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The development measuring skill for the thermal conductivity of heat pipe, graphite sheet and vapour chamber

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The development measuring skill for the thermal conductivity of heat pipe, graphite sheet and vapour chamber

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Abstract. This research designed a set of experimental instruments (TDMI) to measure the thermal diffusivity α of the material. TDMI is calibrated by pure substance such as copper, tin, lead, Aluminium 6061 etc., after done the calibration, the thermal conductivity of heat pipe、 graphite sheet and vapour chamber also be measured. The repeatability error in this experiment, are within 5%. Compared with the thermal diffusivity data of those the pure substance from handbook while for the accurate relative error were within 10% as well.

1. Introduction

D5470 is useful for thermal conductivity measurement of pure substances such as copper, aluminum or homogeneous substances such as TIM. This K value is fix regardless of the X, Y and Z directions. [1, 2]. However, the K value of a non-uniform two-phase flow heat-conducting material such as a heat pipe, a vapor chamber or a brittle material such as graphite sheet cannot be obtained by a simple Fourier law. The heat transfer principle of graphene and vapor chamber is the same as that of heat pipe but the direction of heat conduction is different. The heat transfer mode of heat pipe is one-dimensional, while the heat transfer mode of vapor chamber could be two-dimensional mode. The thermal conductivity k represents whether the material is a good heat conductor, and the large k value represents the larger the power value that the object can transmit, but the time required to reach this final temperature cannot be determined. The thermal duffusivity α (cm^2/s) of the material represents the area where the heat can diffuse in the same power and unit time. Thermal duffusivity α represents the time required to reach the final temperature of the substance is shorter. The k value is the most direct description of the thermal conductor behavior of the material. Most of it measured by Fourier's theorem. However, Fourier's law is achievable for applied only solid heat conduction with the heating area must be the same as the heat dissipation area. For non-uniform device such as heat pipes or vapor chamber, the function of heat dissipated utilize the latent heat of working fluid, the convection heat transfer. In addition, a fragile material such as graphite sheet, or the heating area and the heat dissipating area are different; there exist a thermal diffusion problem; for measuring the thermal conductivity, k of these particular material, Angstrom method will be a good method. Angstrom's theory is input a heat to a one-dimensional strip test object in a periodic pattern. When the periodic sinusoidal is propagated from one side to another side, by measuring the distance and the wave amplitude of these two measuring points, the thermal diffusivity α[3-6] of the object to be tested can be inferred. Angstrom is one-dimensional control volume governing equation can be expressed as

equation (1). After the calculation of the separation variable is simplified, the thermal diffusivity of the object to be tested be able calculated by equation (2). According to the Angstrom method, the thermal diffusivity α_{1D} of the one-dimensional test object can be calculated by using the temperature change M, N, the delay time Δt and the distance L between T_c and T_x in the heat balance process. Table 1 shows the symbols of the Angstrom method. In the heat transfer analysis, the thermal diffusivity α_{1D} is the ratio of the thermal conductivity K to the density ρ and the specific heat C, as shown in equation (3).

$$-\left(\frac{\partial T}{\partial t}\right) + \alpha_{1D}\left(\frac{\partial^2 T}{\partial x^2}\right) - \frac{h}{B\rho C_P}(T - T_a) = 0 \qquad (1)$$

$$\alpha_{1D} = \frac{L^2}{2\Delta t(\ln\frac{M}{N})} \qquad (2)$$

$$\alpha_{1D} = \frac{k_{eff}}{\rho C} \qquad (3)$$

Table1. Nomenclature of Angstrom method

symbol	description	symbol	description
2B	Thickness of test sample (cm)	α_{1D}	Thermal diffusivity of one dimension (cm^2/s)
A_S	Surface of test sample (cm^2)	C	Specific heat of test sample (J/g-k)
L	Distance between T_c and T_x (cm)	Δt	The delay time of sine wave cycle from T_c to T_x (s)。
M/N	Amplitude ratio of T_c to T_x	k_{eff}	The effective thermal conductivity (W/cm-k)
ρ	Density of test sample (g/cm^3)	M	Amplitude of the sine wave temperature change of T_c
		N	Amplitude of the sine wave temperature change of T_x

2. Experimental device and system

2.1. Thermal diffusivity (α) measuring instrument TDMI

Figure 1 is schematic diagram of thermal diffusivity measurement [7], the heat source input sine wave heating power, and the control method is to use the thermoelectric chip to achieve a periodic heating sine wave temperature curve. The test piece is placed on the heated copper block and two temperature-detecting points T_c and T_x are respectively installed on the piece to be tested. It should be notice that the heating method must be a point heat source; the contact point of the test sample and the copper block should be as small as possible. The thermal diffusion measurement platform TDMI is mainly composed of two parts: (1) the power supply and (2) the thermal diffusion-measuring platform of the instrument shown in Figure 2.

2.2. Calibration of TDMI

In order to verify the accuracy of the TDMI, standard calibration experiments must carried out. The calibration based on pure metals such as copper, tin, lead and aluminium. The standard values of the thermal diffusivity of these metals be able to find in the literature. After measuring the thermal diffusivity α of these metals by the instrument, and comparing with the standard value, the reliability and accuracy of TDMI should verify. The data measurement is in the form of full blind test. First, it must be determined that the experimental data is repeatable. Therefore, it is necessary to perform repeatability error analysis on the acquisition of experimental numbers. Repeatability error shown as equation (4) refers to repeating several measurements by the same person during the experiment, and comparing each measured result with the overall average. The relative error is of course as low as possible. If the repeatability error is too large, it means the measured data is floating and indicates that the data in this range is low in reference and the instrument test is unstable. Accuracy error refers to the relative error between the test result and the standard value of the gold sample as shown in equation (5). The method first selects several pure materials with known thermal diffusivity as golden

samples, and compares the test results with the standard values of the test pieces to determine whether the instrument is accurate or not. If the accuracy error is too large, it means Instrument test results are not credible.

$$\varepsilon_{rep} = \frac{|\alpha - \alpha_{ave}|}{\alpha_{ave}} \times 100\% \tag{4}$$

$$\varepsilon_{std} = \frac{|\alpha - \alpha_{std}|}{\alpha_{std}} \times 100\% \tag{5}$$

$\alpha_{ave} = \frac{\sum_i^n \alpha_i}{n}$: Average of several measurements repeated. α_{std} : the standard value of the test piece.
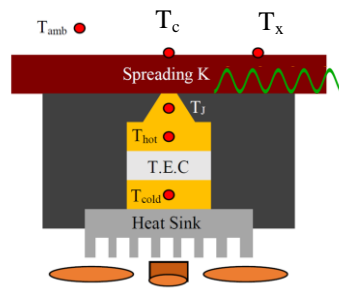

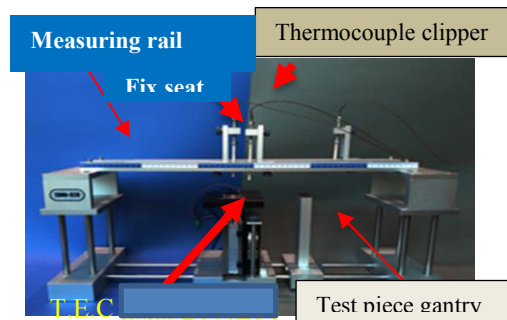**Figure 1.** Schematic diagram of thermal diffusivity measurement

Figure 2. Heating platform for thermal diffusivity measurement system

3. Experiment results and discussion

3.1. The experiment verification of repeatability error
Table 2 shows the repeatability error $\varepsilon_{rep,i}$ is less than 5%. Results shows TDMI doing Well, the experimental data is highly reliable.

Table 2. Repeatability error analysis of Copper ($\alpha_{std, cu}$=1.17cm2/s)

L (mm)	W (mm)	T (mm)	τ=T/W	$\varepsilon_{cu,rep,1}$%	$\varepsilon_{cu,rep,2}$%	$\varepsilon_{cu,rep,3}$%
100	10	0.4	0.04	0%	0.84%	0%
100	20	0.4	0.02	0%	0.91%	0.91%
100	30	0.4	0.01	1.63%	0%	1.63%
100	40	0.4	0.01	3.38%	3.38%	3.38%
100	50	0.4	0.01	2.97%	3.44%	3.44%

3.2. The experiment verification of accuracy error
Table 3 shows the accuracy error analysis of copper in TDMI test. The diffusivity of pure copper $\alpha_{std,cu}$ is 1.17 cm^2/s. The average value of the experimental amount of 3 times is expressed by $\alpha_{cu,avg}$, when τ<0.02, region is " A"; when 0.02≤τ≤075, regionis " B"; while 0.075<τ, region is " C". The red font dimension in the table are the accuracy error after partition correction. Table 2 shows that the accuracy error of copper is controlled within 10% after partition correction, as shown by the red character. Therefore, the thermal diffusivity correction is based on the measuring length 3 cm and the judgment distribution of one-dimensional and two-dimensional. The criterion for the judgment is the thickness-to-width ratio of the test sample as an index, the thickness of the test sample T must less than 5 mm or less.

(I) When $0.02 \leq \tau \leq 0.075$, it is "B"region, one-dimensional mode is adopted, $\alpha_{M,1D} = \frac{L^2}{2\Delta t(\ln\frac{M}{N})}$ (6)

(II) When τ<0.02, it is "A"region, expressed as $\alpha_{M,1D\times2}$, $\alpha_{M,1D\times2} = \alpha_{M,1D} \times 2$ (7)

(III) When $\tau > 0.075$, it is "C" region, expressed as $\alpha_{M,1D\times0.5}$, $\alpha_{M,1D\times0.5} = \alpha_{M,1D} \times 0.5$ $\qquad$ (8)

Table 3. Accuracy error analysis of pure copper diffusivity ($\alpha_{std,\,cu}$=1.17cm^2/s)

No	$\tau = \dfrac{T}{W}$	Zone	$\alpha_{cu,avg}$	1-D mode (B)	2-D mode (A)	0.5D mode (C)
				$\varepsilon_{cu,std,1D}$	$\varepsilon_{cu,std,1DX2}$	$\varepsilon_{cu,std,1DX0.5}$
1	0.04	B	1.198	2.4%	104.7%	48.803%
2	0.02	B	1.094	6.4%	87%	53.24%
3	0.013	A	0.615	47%	5.12%	73.71%
4	0.01	A	0.60	48%	2.564%	74.35%
5	0.008	A	0.5826	50%	0.41%	75.1%

3.3. Experimental results and analysis of graphite sheets

The main structure of the graphite sheet is a layer of PET material on the bottom layer, and then coated with graphene or graphite powder called graphite layer. Some of the manufacturers may have resin film on the graphite. The parallel thermal resistance is shown as in equation (9), If the thermal resistances expressed in the Fourier form, the total thermal conductivity $K_{eff,total}$ of the graphite sheet can simplify to equation (10). Table 4 shows the thermal diffusivity measurement results of the graphite sheets E and F and G. The thermal diffusivity of the graphite sheet for E, F, G are 1.43, 1.58 and 4.12 respectively. The total effective thermal conductivity of the graphite sheet E, F, G are 252, 328 and 590. The effective thermal conductivity of the graphite layer E is 452, F is 491 while for G is 1060.

$$\frac{1}{R_{th,total}} = \frac{1}{R_{th,PET}} + \frac{1}{R_{th,c}} + \frac{1}{R_{th,resin}} \qquad (9)$$

$$k_{eff,total} = k_{PET} \times AF_{PET} + k_{eff,C} \times AF_C + k_{resin} \times AF_R \qquad (10)$$

Table 4. Diffusivity measurement results of graphite sheets E, F and G (Test sample L=200mm, W=200mm)

sample	τ (H_{total}/W)	Zone	α_2 (cm^2/s)	graphite sheet K_{total} (W/m-k)	graphite layer $K_{eff,}$ (W/m-k)
sheet E	0.0015<0.02	A	1.43	$K_{eff,total,E}$=252	$K_{eff,total,C,F}$=452
sheet F	0.002<0.02	A	1.58	$K_{eff,total,F}$=328	$K_{eff,total,C,F}$=491
sheet G	0.0015<0.02	A	4.12	$K_{eff,total,G}$=590	$K_{eff,total,C,G}$=1060.9

3.4. Experimental results and analysis of the vapor chamber

The vapor chamber in this experiment has three kinds of VC-A, VC-B and VC-C, as shown in Fig. 3, Fig. 4 and Fig. 5, the dimensions are 90×90×2.35mm^3, 100×100×8mm^3 and 90×90×0.85 mm^3. VC-A is a uniform shape vapour chamber with a thickness of 2.5mm. VC-B is an irregularly shaped vapour chamber with a thickness 8mm in the middle of the upper lid and the lower lid. VC-C is ultra-thin vapour chamber with thickness of 0.86mm.Table 5 shows the thermal diffusivity of "VC-A" for x-direction is α_x=1.99, while for Y-direction is α_y=1.77 and α_{total}=3.76. The thermal diffusivity of "B" for x-direction is α_x=0.55, while for Y-direction is α_y=0.54 and α_{total}=1.09. The thermal diffusivity of "C" for x-direction is α_x=0.48, while for Y-direction is α_y=0.37 and α_{total}=0.85. Convert the thermal diffusivity data to the thermal conductivity, that is equivalent to K_{VC-A}=19288, K_{VC-B}=4330 and K_{VC-C}=1614

Figure 3. Vapor chamber VC-A   **Figure 4.** Vapor chamber VC-B   **Figure 5.** Vapor chamber VC-C

Table 5. Thermal diffusivity of VC-A ,VC-B and VC-C measured with two-dimensional mode

item	VC-A	VC-B	VC-C
$\rho(g/cm^3)$	$\rho_{ave,VC-A}$ =5.70	$\rho_{ave,VC-B}$ =4.43	$\rho_{ave,VC-C}$ =6.49
$C(J/g \cdot {}^{\circ}C)$	4.5	4.505	1.463
$L \times W \times T$ (mm^3)	90×90×2.35	100×100×8	90*90*0.85
$\tau = T/W$	$\tau=2.5/90=0.0261$	$\tau=8/100=0.08$	$\tau=0.85/90=0.0094$
mode	Two-dimension Zone	Two-dimension Zone	Two-dimension Zone
α (cm^2/s)	$\alpha_{total}=3.76$	$\alpha_{total}=1.085$	$\alpha_{total}=0.85$
$K_{VC,TDMI}$ (W/m-k)	K_{VC-A} =19288	K_{VC-B}= 4330.7	K_{VC-C}= 1614.1

4. Conclusion

4.1 According to the TDMI instrument, it is necessary to determine whether the experimental condition is a one-dimensional mode or a two-dimensional mode first. Generally, a width W is larger than 5cm defined a two-dimensional mode, and W=5 cm or smaller is a one-dimensional mode. The one-dimensional mode uses the aspect ratio as the criterion for the correction. The basis of the judgment is that the thickness-to-width ratio τ of the test piece is an index, and the material is applicable with thickness no larger than 5 mm

4.2 The K value (vertical phase) of the natural graphite measured by D5470 in the general literature is about 25 (W/m-k), and the k value in the horizontal direction is between 500 and 1200 (W/m-k). The effective thermal conductivity of three typical graphite layers have been measured by TDMI which are 452(W/m-k), 491(W/m-k) and 1060.9(W/m-k) respectively. The TDMI, designed with the Angstrom principle provides a relatively inexpensive, fast and simple measuring method of the effective thermal conductivity of graphite sheets and graphite layers.

4.3 TDMI can also calculate its thermal conductivity after two-dimensional correction. Since there is no standard thermal diffusivity value of the vapor chamber, it can only use as a reference. In this study, three pieces of vapor chamber VC-A, VC-B and VC-C were measured which are 20,000(W/m-k), 4000(W/m-k) and 1600(W/m-k) respectively.

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