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The ac-Heated Strip Technique for the Measurement of Thermal Properties of Thin, Solid Nonconducting Layers[1]

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The differential equation describing the temperature oscillations generated by a metallic strip of thickness $2L_1$, coated with a thin nonconducting layer of thickness δ and heated by an ac current, was solved with and without reference to the heat transfer by radiation from the outer surface of the coating layer. The solution obtained shows that for $L_1/\delta > 5$, the measurement of the amplitude (and phase) of the temperature oscillations of the strip allows the following thermal properties to be measured: thermal diffusivity (a), volumetric heat capacity (ρC_p), and thermal conductivity (λ) coefficients of the thin nonconducting layers investigated when the layer thickness is less than the thickness (Λ) at which the temperature oscillations are practically damped in the material of the coating layer ($\delta < \Lambda$). For thin films ($\delta \ll \Lambda$), a simple formula is obtained which allows the volumetric heat capacity of the film material to be determined alone. On the other hand, when the coating layer is very thick ($\delta \gg \Lambda$), only the thermal activity coefficient ($\lambda/\sqrt{a}$) can be determined. To test this technique, thin layers of polyethylene and polystyrene were investigated. Bulk specimens were investigated by the ac-heated wire technique. Both sets of results obtained are in good agreement with each other and with published data. The setup described was then used to measure the thermal properties of thin layers of Synthesite AC-43 (440 to 80°C) and Krylon (40 to 160°C). The results are reported. It is worth mentioning that this technique can be used for the estimation of the thickness of opaque thin layers of nonconducting solids, provided that their thermal properties are known. The thermal properties mentioned can be measured applying the ac-heated wire technique, but for bulk material.

KEY WORDS: ac-heated strip; insulating layer; metal strip; thermal properties; thin film.

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1. INTRODUCTION

The ac-heated metallic strip (wire) technique has been successfully applied to measurements of thermal properties—thermal diffusivity (a), volumetric heat capacity (ρC_{p}), and thermal conductivity (λ)—of liquids and solids [1–3].

The measurement of power and amplitude of the temperature oscillations of a metallic wire immersed in the liquid investigated provides the thermal properties mentioned. The liquid is assumed to be an infinite medium; however, the so-called temperature waves are totally damped in a thin liquid layer. This technique can be used to measure the mentioned thermal properties of solids, provided there is perfect contact between the strip and the solid.

In another important case, the strip is coated with the investigated nonconducting solid material in the form of a thin layer or a thin film. This problem is of great interest [4–6] for numerous high-technology applications. In addition, such a configuration has been recommended for the investigation of the thermal properties of conducting liquids [7].

In this work, this problem has been solved in the case where the radiative heat transfer from the outer surface of the coating layer is negligible and for the case when this heat transfer is considerable (at high temperatures). The experimental test of the technique described was carried out with the setup described in Ref. 1. The mentioned thermal properties of Synthesite and Krylon are reported.

2. THEORY

The differential equation governing the temperature oscillations of a metallic strip immersed in the investigated liquid and heated by an ac current is expressed as follows:

$$\partial^2\theta/\partial x^2-(2i\omega/a)\,\theta=0 \tag{1}$$

where

$\theta=$ amplitude of the temperature oscillations of the metallic strip (K)

$\omega=$ angular frequency ($\mathrm{rad\cdot s^{-1}}$)

$a=$ thermal diffusivity coefficient ($\mathrm{m^2\cdot s^{-1}}$)

The solution to Eq. (1) is written in the form

$$\theta=\mathrm{A}e^{(\sqrt{2i\omega/a})\,x}+\mathrm{B}e^{-(\sqrt{2i\omega/a})\,x} \tag{2}$$

where A and B are constants, to be determined from the boundary conditions, depending on whether or not we take the radiative heat transfer from the outer surface of the coating layer into consideration.

Let us first consider the case in which the radiative heat transfer from the outer surface of the coating layer is too small to affect the amplitude of temperature oscillations of the metallic strip.

2.1. Negligible Radiation

In this case, we have two boundary conditions (Fig. 1):

$$W/s = (2m'c'i\theta\omega/s) - 2\lambda\, \partial\theta/\partial x|_{x=L_1} \tag{3}$$

$$\partial\theta/\partial x|_{x=L_2} = 0 \tag{4}$$

where

W = heat per unit length of the strip ($J \cdot m^{-1}$)

m' = mass per unit length of the strip ($kg \cdot m^{-1}$)

c' = specific heat of the strip material ($J \cdot kg^{-1} \cdot K^{-1}$)

$2L_1$ = thickness of the strip (m)

$2L_2$ = thickness of both the strip and the coating layer (m)

δ = thickness of the coating layer (m)

s = surface area of the strip (m^2)

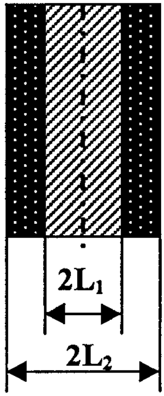


Fig. 1. Geometry of the metallic strip and coating.

Equation (3) is the energy balance condition at the strip–layer interface. Equation (4) describes the adiabatic condition on the outer surface of the thin layer investigated.

Then we get the following formulae for A and B:

$$\mathrm{A} = \frac{We^{-2(\sqrt{2i\omega/a})\,L_2}}{\begin{pmatrix} 2m'c'i\omega(e^{2(\sqrt{2i\omega/a})\,\delta} + e^{-2(\sqrt{2i\omega/a})\,\delta}) \\ -2\lambda s\sqrt{(2i\omega/a)}\,(e^{2(\sqrt{2i\omega/a})\,\delta} - e^{-2(\sqrt{2i\omega/a})\,\delta}) \end{pmatrix}}$$

$$\mathrm{B} = \frac{We^{2\sqrt{(2i\omega/a)}\,L_2}}{\begin{pmatrix} 2m'c'i\omega(e^{2(\sqrt{2i\omega/a})\,\delta} + e^{-2(\sqrt{2i\omega/a})\,\delta}) \\ -2\lambda s\sqrt{(2i\omega/a)}\,(e^{2(\sqrt{2i\omega/a})\,\delta} - e^{-2(\sqrt{2i\omega/a})\,\delta}) \end{pmatrix}}$$

Equation (2) is then written

$$\theta = \frac{w}{(2m'c'i\omega) - 2\lambda s\sqrt{(2i\omega/a)}\,\dfrac{(e^{(\sqrt{2i\omega/a})\,\delta} - e^{-(\sqrt{2i\omega/a})\,\delta})}{(e^{(\sqrt{2i\omega/a})\,\delta} + e^{-(\sqrt{2i\omega/a})\,\delta})}} \tag{5}$$

Let us introduce the following notation:

$$\theta_0 = W/2m'c'\omega; \qquad \chi_1 = (\sqrt{2i\omega/a})\,L_1; \qquad \chi_2 = (\sqrt{2i\omega/a})\,L_2$$

$$\chi_3 = (\sqrt{2i\omega/a})\,\delta; \qquad \chi_4 = (\chi_3/\sqrt{2}); \qquad \mu = (2\sqrt{2}\,\eta), \qquad \zeta = \delta/L_1$$

$$\phi_1 = \cos\chi_4(e^{\chi_4} - e^{-\chi_4}), \qquad \phi_2 = \sin\chi_4(e^{\chi_4} + e^{-\chi_4})$$

$$\phi_3 = \cos\chi_4(e^{\chi_4} + e^{-\chi_4}), \qquad \phi_4 = \sin\chi_4(e^{\chi_4} + e^{-\chi_4})$$

$$\phi_5 = (\phi_1\phi_3 + \phi_2\phi_1)/(\phi_3^2 + \phi_4^2)$$

$$\phi_6 = (\phi_2\phi_3 + \phi_1\phi_4)/(\phi_3^2 + \phi_4^2)$$

$$\phi_7 = (\phi_5 - \phi_6), \qquad \phi_8 = \phi_5 + \phi_6$$

θ_0 = the temperature oscillation of the bare strip at the same thermal power

Finally, we get the following formula for the reduced temperature oscillations of the strip:

$$\theta/\theta_0 = \frac{1}{\{(1/\mu\chi_2)\,\phi_7^2 + (1 + (1/\mu\chi_2)\,\phi_8)\}^{1/2}} \tag{6}$$

The phase angle between power and strip oscillations is expressed as follows:

$$\varphi = \arctan \frac{1 + (1/\mu\chi_2)\,\phi_8}{(1/\mu\chi_2)\,\phi_7} \tag{7}$$

When the temperature oscillations are established in a continuous medium, they are practically damped at a distance called the effective layer thickness (Λ).

This thickness at a certain frequency is calculated according to the following formula [8, 9]:

$$\Lambda = 2\pi(\sqrt{a/2\omega}) \tag{8}$$

To estimate this distance, let us take $a = 10^{-7}$ to $10^{-8}\,\mathrm{m}^2 \cdot \mathrm{s}^{-1}$ and frequency $f = 50\mathrm{Hz}$; then we get $\Lambda = 0.05$ to 0.15 mm.

With this in mind, let us consider three special cases: bare strips, thin films, and thick layers.

2.1.1. *Bare Strips*

In this case, we get the following formula for the temperature oscillations of the bare strip:

$$\theta = \theta_0 = W/(2m'c'\omega) \tag{9}$$

This formula is important, because it allows *in situ* determination of the volumetric heat capacity of the strip material.

2.1.2. *Thin Films*

When the coating layer is very thin ($\delta \ll \Lambda$), Eq. (6) reduces to the following form:

$$\theta/\theta_0 = 1/(1 + (\zeta/\eta)) \tag{10}$$

In this case, this technique allows the measurement of the volumetric heat capacity of the investigated material alone. This can be realized by selecting low frequencies and/or thin films.

2.1.3. *Thick Layers*

When the layer investigated is very thick, $\delta \gg \Lambda$, this technique allows measurement of only the ratio $b = \lambda/\sqrt{a}$, which is called the thermal activity [7].

2.2. Considerable Radiation

If radiation is to be considered (at high temperatures), the formalism is retained, except for Eq. (4), which has to be replaced by the following equation [8]:

$$-\lambda\, \partial\theta/\partial x = \alpha\theta|_{x=L_2} \tag{11}$$

where $\alpha = (4\varepsilon\sigma T^3)$ is the coefficient of heat transfer by radiation from the outer surface of the coating layer, ε is the emissivity of the coating material, σ is the Stefan–Boltzmann constant, and T is the mean temperature.

Then we get the following expression for the temperature oscillations of the strip:

$$\theta = \frac{w}{(2m'c'i\omega) - 2\lambda s\sqrt{(2i\omega/a)}\,\dfrac{(e^{\sqrt{2i\omega/a}\,\delta} - Ze^{-\sqrt{2i\omega/a}\,\delta})}{(e^{\sqrt{2i\omega/a}\,\delta} + Ze^{-\sqrt{2i\omega/a}\,\delta})}} \tag{12}$$

where

$$Z = \frac{\lambda\sqrt{(2i\omega/a)} - \alpha}{\lambda\sqrt{(2i\omega/a)} + \alpha}$$

Let us further introduce the following notation:

$$\zeta = \mathrm{Bi}/\chi_4; \qquad \text{where} \quad \mathrm{Bi} = \alpha\delta/\lambda \text{ (Biot number)}; \text{ and } \nu = \delta/L_2$$

$$A_1 = (2-\zeta^2)/(2+\zeta^2)$$

$$B_1 = 2\zeta^2/(2+\zeta^2)$$

$$\phi_9 = e^{\chi_4}\cos\chi_4 + e^{-\chi_4}(A_1\cos\chi_4 + B_1\sin\chi_4)$$

$$\phi_{10} = e^{\chi_4}\sin\chi_4 + e^{-\chi_4}(B_1\cos\chi_4 - A_1\sin\chi_4)$$

$$\phi_{11} = e^{\chi_4}\cos\chi_4 - e^{-\chi_4}(A_1\cos\chi_4 + B_1\sin\chi_4)$$

$$\phi_{12} = e^{\chi_4}\sin\chi_4 + e^{-\chi_4}(B_1\cos\chi_4 + A_1\sin\chi_4)$$

$$\phi_{13} = (\phi_9\phi_{11} - \phi_{10}\phi_{12})/(\phi_9^2 + \phi_{10}^2)$$

$$\phi_{14} = (\phi_9\phi_{12} + \phi_{10}\phi_{11})/(\phi_9^2 + \phi_{10}^2)$$

For the amplitude of the temperature oscillations of the strip, we then get

$$\theta/\theta_0 = 1/\{((\nu/\mu\chi_2)\,\phi_{13})^2 + (1 + (\nu/\mu\chi_2)\,\phi_{14}^2)\}^{1/2} \tag{13}$$

For the phase difference between current and temperature oscillations, we get

$$\varphi = \arctan\{(1/(\nu/\mu\chi_2)\,\phi_{14}\}/\{(\nu/\mu\chi_2)\,\phi_{13}\} \tag{14}$$

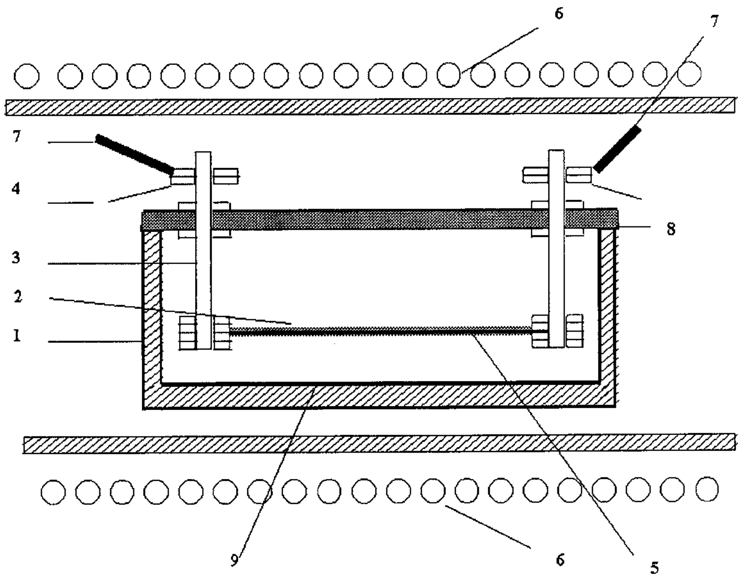
3. RESULTS AND DISCUSSION

Analysis of Eq. (6) shows that for the determination of $\chi_4 - (\zeta > 5)$ and, consequently, of the mentioned thermal properties, a, ρC_p, and λ, the best range for θ/θ_0 is realized when $\chi_4 = 0.1$ to 0.8. Further analysis of Eq. (7) shows that measuring θ with an error of 1% will produce an error of 1.2% for the determination of χ_4. Moreover, from Eq. (7), an error of 1° in the measurement of φ leads to an error of 0.8% in the determination of χ_4.

The coated strip was connected between two stainless-steel electrodes mounted on a ceramic lid of the experimental (ceramic/stainless-steel) cell as shown in Fig. 2. The cell was then mounted inside an electric furnace that provides the mean temperature of the sample and is powered by a 10-kW variac connected through an isolation transformer. The temperature of the furnace was regulated to 0.2°C and measured by means of a digital thermometer. The experimental cell and the electric furnace were mounted in a water-cooled metallic chamber, placed on a metallic base of 40-cm diameter that contains all the electric leads, as shown in Fig. 3. The chamber and base were evacuated to 10^{-2} to 10^{-3} mm Hg.

The block diagram of the experimental setup used for the realization of these measurements is shown in Ref. 1. The strip was connected as one arm of an ac bridge consisting of two precise shielded decade resistance boxes and a standard resistor. The bridge was fed by an ac signal generated by a signal generator and an audio amplifier. The signal frequency was measured by a digital frequency meter. When the bridge was completely balanced at a frequency f (60 to 120 Hz), which was judged by the shape of the signal from the diagonal of the bridge on the screen of an oscilloscope, and the third harmonic signal was amplified, filtered, and displayed on the screen of another identical oscilloscope. For more control, the output signal of the amplifier was displayed on the screen of the same oscilloscope. Then the third harmonic signal was adjusted to be enveloped by two horizontal lines generated on the second channel of the second oscilloscope from another function generator. Then the amplitude of this signal ($E_{3\omega}$) was measured by means of an accurate digital multimeter.

Readings of multimeters of the voltages across the bridge, the standard resistor, the platinum wire, and $E_{3\omega}$ were recorded, along with the values of the readings of the decade resistance boxes. The amplitude of the third harmonic $E_{3\omega}$ was then accurately calibrated by means of a potential



1- Ceramic (or stainless steel) cell.
2- Sample.
3- Stainless steel electrode.
4- Potential leads.
5- Metallic wire.
6- Furance.
7- Current leads.
8- Silicon rubber.
9- Resistive coating

Fig. 2. Sample mounting.

divider consisting of two precise shielded decade resistance boxes. Measurement of power was carried out with multimeters connected across the standard resistance and the strip. A detailed analysis of the circuit was carried out to consider the internal resistor of the power amplifier, the output amplifier, and all other elements of the circuit. This proved to be quite essential to get the correct values of the temperature oscillations amplitude and power. Calibration of the third harmonic signal was carried out in two ways, either by means of the mentioned potential divider or by means of the ac bridge itself replacing the strip by an equivalent resistance and unbalancing the bridge until the same value of $E_{3\omega}$ is obtained. The coefficient of the change of resistance of the strip with temperature was measured in a separate experiment.

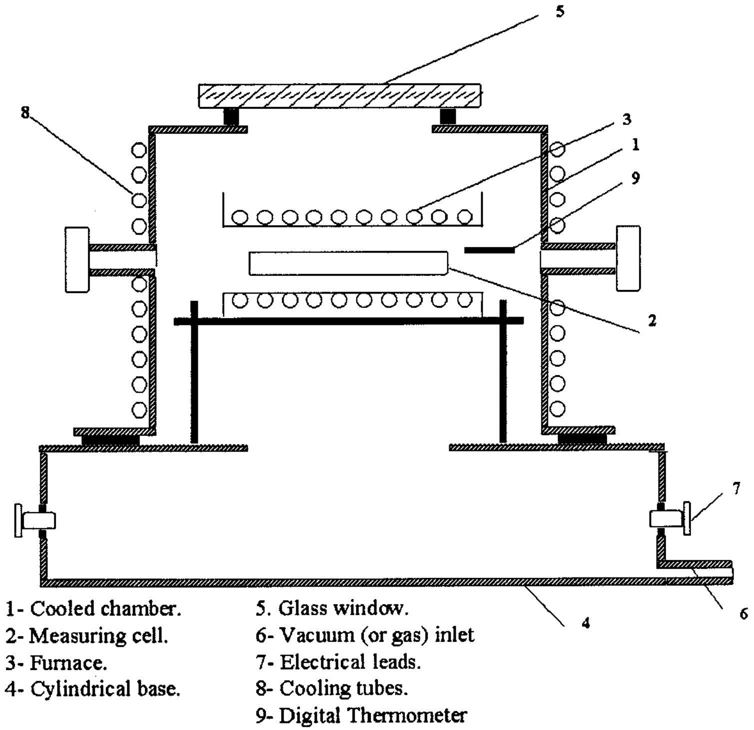


Fig. 3. Vacuum chamber.

To test this technique, thin polyethylene and polystyrene strips of thickness 0.02 to 0.03 mm, coated with conducting films of thickness 0.003 to 0.005 mm, were investigated. Bulk materials were investigated with the ac-heated wire technique, with a platinum wire of 0.05-mm diameter as described in Ref. 1. The results obtained for bulk samples differed from those for thin layers by 2 to 3%.

Table I gives the results of measurements of the thermal diffusivity (a), volumetric heat capacity (ρC_p), and thermal conductivity (λ) of polyethylene samples. The results obtained for thermal diffusivity are 5% lower than those obtained by Zhang et al. [10]. For volumetric heat capacity our data are 8% higher than those obtained by Zhang et al. [10] at 30°C but coincide with the same data at 100°C. For thermal conductivity, the results obtained are 6% lower than the results of Zhang et al. [10] and Eiermann and Hellwege [11] at 35°C but agree well with the same data at 90°C. Our data are 34% higher than those of Kline [12], which are lower than all the other mentioned references.

Table I. Thermal Properties of Polyethylene

	a ($10^{-7}\,m^2 \cdot s^{-1}$)		ρC_p ($10^6\,J \cdot m^{-3} \cdot K^{-1}$)		λ ($W \cdot m^{-1} \cdot K^{-1}$)	
Temp. (°C)	Film	Bulk	Film	Bulk	Film	Bulk
30	2.6	2.64	1.53	1.5	0.39	0.39
35	2.5	2.55	1.4	1.43	0.35	0.35
40	2.44	2.40	1.38	1.39	0.33	0.33
45	2.3	2.34	1.34	1.37	0.31	0.31
50	2.24	2.25	1.33	1.34	0.33	0.33
55	2.09	2.13	1.34	1.32	0.28	0.28
60	2.1	2.10	1.32	1.31	0.27	0.27
65	2.08	2.05	1.26	1.30	0.26	0.26
70	2.06	2.03	1.27	1.29	0.25	0.25
75	2.04	2.01	1.26	1.28	0.25	0.25
80	1.98	1.96	1.25	1.27	0.25	0.25
85		1.92		1.25		0.24
90		1.87		1.24		0.23
95		1.85		1.22		0.22
100		1.83		1.21		0.22

Table II lists the results of measurements of the thermal diffusivity (a), volumetric heat capacity (ρC_p), and thermal conductivity (λ) of LD polystyrene samples. The results obtained for thermal diffusivity are 15% lower than those obtained by Zhang et al. [10] at 30°C and 20% higher than data obtained by Morikawa [13] and coincide with both at 100°C. For volumetric heat capacity our data are 8% higher than those obtained by Zhang et al. [10] at 30°C but coincide with the same data at 100°C. For thermal conductivity, the results obtained are 4% lower than the results of Zhang et al. [10] and fall between data obtained by Lobo and Cohen [14] and Dashora and Gupta [15] and Underwood and McTaggart [16] in the temperature range investigated.

Tables III and IV list the results of measurements of the thermal diffusivity (a), volumetric heat capacity (ρC_p), and thermal conductivity (λ) coefficients of thin layers of Synthesite and Krylon. Measurements were also made with bulk specimens in nitrogen atmosphere. The results obtained for bulk samples differed from those for thin layers by 1 to 2%.

Synthesite AC-43 is a polymer used for the insulation of electric wires. It has the advantage that it dries in a few hours and it can withstand temperatures up to 120°C. The measurements were performed up to 65°C, still well below the softening temperature. No reference data were found for

Table II. Thermal Properties of Polystyrene

	a ($10^{-7}\ m^2 \cdot s^{-1}$)		ρC_p ($10^6\ J \cdot m^{-3} \cdot K^{-1}$)		λ ($W \cdot m^{-1} \cdot K^{-1}$)	
Temp. (°C)	Film	Bulk	Film	Bulk	Film	Bulk
30	1.69	1.71	1.039	1.023	0.179	0.179
35	1.64	1.66	1.038	1.032	0.167	0.171
40	1.61	1.63	1.041	1.030	0.167	0.168
45	1.60	1.62	1.043	1.031	0.166	0.167
50	1.57	1.59	1.042	1.033	0.163	0.164
55	1.54	1.57	1.043	1.035	0.160	0.162
60	1.53	1.58	1.044	1.036	0.159	0.163
65	1.50	1.54	1.042	1.039	0.156	0.160
70	1.45	1.48	1.041	1.033	0.151	0.153
75	1.41	1.47	1.040	1.040	0.147	0.153
80	1.48	1.52	1.039	1.044	0.154	0.158
85	1.45	1.48	1.045	1.051	0.151	0.155
90	1.42	1.48	1.048	1.061	0.148	0.157
95		1.44		1.09		0.157
100		1.38		1.08		0.149
105		1.36		1.12		0.152
110		1.33		1.08		0.143

this material. Our aim was to compare the bulk and the thin layer results of measurement.

Krylon is a high-temperature polymer used for filling holes and cracks in metal parts at high temperature up to 600°C. It also has the advantage that it dries in a few minutes. The measurements were performed at temperatures up to 160°C, still well below the softening temperature. No reference data were found for this material. Our aim was to compare the bulk and the thin layer results of measurement.

Table III. Thermal Properties of Synthesite AC-43

Temp. (°C)	a ($10^{-9}\ m^2 \cdot s^{-1}$)	ρC_p ($10^6\ J \cdot m^{-3} \cdot K^{-1}$)	λ ($W \cdot m^{-1} \cdot K^{-1}$)
40	4.1	5.2	0.022
45	3.9	5.1	0.021
50	3.8	5.0	0.020
55	3.6	4.9	0.018
60	3.5	4.8	0.016
65	3.4	4.7	0.016

Table IV. Thermal Properties of Krylon

Temp. (°C)	a ($10^{-8}\,m^2 \cdot s^{-1}$)	ρC_p ($10^6\,J \cdot m^{-3} \cdot K^{-1}$)	λ ($W \cdot m^{-1} \cdot K^{-1}$)
60	1.78	4.6	0.082
80	1.72	4.4	0.076
100	1.60	4.3	0.069
120	1.55	4.2	0.065
140	1.24	4.1	0.051
160	1.12	4.0	0.045

The analysis of the data obtained for thermal diffusivity showed that the relative standard deviation of the experimental points for the solid phase varied from 1.3 to 1.7%. The combined standard uncertainty associated with the measurements was determined to be 2.7%, and the expanded uncertainty 5.4%, for a 0.95 confidence level. For the volumetric heat capacity the relative standard deviation of the experimental points for the solid phase varied from 1.5 to 2.8%. The combined standard uncertainty associated with the measurements was determined to be 3.1%, and the expanded uncertainty was 5.6%, for a 0.95 confidence level. For thermal conductivity measurements, the relative standard deviation of the experimental points for the solid phase varied from 1.2 to 1.9%. The combined standard uncertainty associated with the measurements was determined to be 2.7%, and the expanded uncertainty 5.4%, for a 0.95 confidence level.

4. SUMMARY AND CONCLUSION

The ac-heated strip technique can be used for accurate measurements of thermal properties—thermal diffusivity (a), volumetric heat capacity (ρC_p), and thermal conductivity (λ) coefficients of a thin insulating layer deposited on a thin metallic strip, provided that the layer thickness is less than the effective layer thickness of the established temperature oscillations, which in turn depends upon the frequency of the applied current. This can be easily achieved by varying the working frequency for a preselected thickness of the insulating layer ($\delta < \Lambda$). It is worth mentioning that this technique can be used to estimate the thickness of the solid layer, if the thermal properties of the layer investigated are known. This is similar to the optical interference techniques for determination of the thickness of transparent thin films. The ac-heated strip technique can be used for opaque layers.

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