Thermal properties of metals alloy by electrical pyroelectric method (EPE)

N. Bennaji\textsuperscript{1}, I. Mellouki\textsuperscript{1}, N. Yacoubi\textsuperscript{1}

\textsuperscript{1} U.R. Photopyroelectric, IPEIN, BP 62 Merazka 8000, Nabeul, Tunisia

E-mail: bennajin@yahoo.fr

Abstract. In present work, we propose a new technique based on uniform electrical heating of pyroelectric detector which investigated simultaneous thermal conductivity and diffusivity of samples. A new one-dimensional theoretical model was developed to determine thermal proprieties of steel alloy. The obtained values of thermal conductivity are 13 W m\(^{-1}\)K\(^{-1}\), 18 W m\(^{-1}\)K\(^{-1}\) and 24 W m\(^{-1}\)K\(^{-1}\) and of thermal diffusivity are \(7 \times 10^{-6} \text{m}^2\text{s}^{-1}\), \(15 \times 10^{-6} \text{m}^2\text{s}^{-1}\) and \(8 \times 10^{-6} \text{m}^2\text{s}^{-1}\) respectively for sheet steel, galvanized steel and stainless steel. These results are given with an uncertainty at the 1\(\sigma\) level.

1. Introduction
In this paper, we investigated thermal properties of metals alloy using Electrical-PyroElectric (EPE) technique by heating uniformly the sample. The sample covered by a very thin PVDF film (PolyVinylidene Fluoride) is heated by an external electrical modulated power. The generated thermal wave will propagate in the Pyroelectric thin film and induce a temperature gradient [1] by fitting the experimental pyroelectric signal with theory one can deduce simultaneously the thermal diffusivity and the thermal conductivity values of sheet steel, galvanized steel and stainless steel. Good agreement with values reported in the literature [2] is obtained.

2. Experimental set-up
The schematic of pyroelectric detector design built for this technique is shown in fig. 1. The sample is in good thermal contact with a 125-µm-thick Mylar layer. This layer is placed between the sample and PVDF metalized thin film to insure electrical measurement. The PVDF sensor of 25µm-thick is put on a copper heatsink of 6mm-thick [3].

Thermal properties of substrate, PVDF film, Mylar layer and air are gathered in table 1 [4,5,6].

The Electrical-PyroElectric experimental setup system is shown in fig. 2. The sample is heated by an electrical power with pulses generator modulated at frequency f. The output from the pyroelectric detector is fed into a low-noise preamplifier for signal amplification. Experimental data were performed by a lock-in amplifier (model EG & G 5210) connected to a personal computer via RS232 interface.
3. Theoretical model

The temperature expression \( T_p (\phi) \) at PVDF film is obtained by resolution of heat equations in different media: air, sample, Mylar layer, PVDF film and backing [7]. The schematic diagram of EPE model is shown in fig. 3.

![Schematic diagram of EPE model](image)

Figure 1. Schematic of pyroelectric detector.

| Sample      | Thermal conductivity | Thermal diffusivity |
|-------------|----------------------|---------------------|
| Air         | 0.025 Wm\(^{-1}\)K\(^{-1}\) | \(2 \times 10^{-5} \text{m}^2\text{s}^{-1}\) |
| Mylar layer | 0.04 Wm\(^{-1}\)K\(^{-1}\) | \(150 \times 10^{-4} \text{m}^2\text{s}^{-1}\) |
| PVDF film   | 0.13 Wm\(^{-1}\)K\(^{-1}\) | \(6.3 \times 10^{-8} \text{m}^2\text{s}^{-1}\) |
| Copper      | 390 Wm\(^{-1}\)K\(^{-1}\)  | \(4 \times 10^{-4} \text{m}^2\text{s}^{-1}\) |

Table 1. Thermal properties used in the theoretical model.

![Schematic diagram of Electro-Pyroelectric experimental setup](image)

Figure 2. Schematic diagram of Electro-Pyroelectric experimental setup.

Figure 3. Studied system configuration.
In stead, we consider uniform heating of the sample, the one-dimensional heat treatment is justified, heat equations governing the change of the temperature in each medium \( i \) constituting the detector are:

\[
\frac{\partial^2 T_i}{\partial x^2} = \frac{1}{D_i} \frac{\partial T_i}{\partial t} \quad \text{if} \quad x \in [0, \ell_i]
\]

\[
\frac{\partial^2 T_s}{\partial x^2} = \frac{1}{D_s} \frac{\partial T_s}{\partial t} - \frac{Z I_e^2}{v \times K_s} \quad \text{if} \quad x \in [-\ell_s, 0]
\]

\[
\frac{\partial^2 T_g}{\partial x^2} = \frac{1}{D_g} \frac{\partial T_g}{\partial t} \quad \text{if} \quad x \in [-\ell_s - \ell_g, -\ell_s]
\]

\[
\frac{\partial^2 T_p}{\partial x^2} = \frac{1}{D_p} \frac{\partial T_p}{\partial t} \quad \text{if} \quad x \in [-\ell_s - \ell_g - \ell_p, -\ell_s - \ell_g]
\]

\[
\frac{\partial^2 T_b}{\partial x^2} = \frac{1}{D_b} \frac{\partial T_b}{\partial t} \quad \text{if} \quad x \in [-\ell_s - \ell_g - \ell_p - \ell_b, -\ell_s - \ell_g - \ell_p]
\]

Where \( T_i, D_i \) and \( \ell_i \) are respectively temperature, thermal diffusivity and thickness of medium \( i \) \((i=a, s, g, p, b)\), where \( a, s, g, p \) and \( b \) are respectively air, sample, Mylar layer, PVDF film and backing. The thermal diffusivity \( D_i \) is related to thermal conductivity \( K_i \), by

\[
D_i = \frac{\rho_i c_i K_i}{\rho_i c_i}
\]

where \( \rho_i c_i \) is the volumic specific heat. \( Z \) is the electrical impedance, \( v \) is volume of the sample and \( I_e \) is the intensity of current. The spatial average of temperature \( T_p(x, \omega) \) of PVDF film given by resolution, are:

\[
\langle T_p(\omega) \rangle = \frac{2Z I_e^2}{C_{th} \omega^2} f_p \sigma_p \times \frac{1}{(1 - e^{-\mu_i t})} \times \left( b_{y_p + 1}(e^{\sigma_i t} - 1) + (b_{y_p - 1})(e^{-\sigma_i t} - 1) \right) \left( (b_{y_f + 1})e^{\sigma_i t} - (b_{y_f - 1})e^{-\sigma_i t} \right)
\]

\[
= \left( b_{y_f + 1} \right) \left( (b_{y_f + 1})e^{\sigma_i t} + (b_{y_f - 1})(b_{y_p + 1})e^{-\sigma_i t} \right) \left( e^{\sigma_i t} - e^{-\sigma_i t} \right)
\]

\[
= \left( b_{y_f + 1} \right) \left( (b_{y_f + 1})e^{\sigma_i t} + (b_{y_f - 1})(b_{y_p + 1})e^{-\sigma_i t} \right) \left( e^{\sigma_i t} - e^{-\sigma_i t} \right)
\]

Where \( \sigma_i = \frac{1 + j}{\mu_i} \), \( \mu_i = \left( \frac{\pi f}{D_i} \right)^{1/2} \). \( \mu_i \) is the thermal diffusion length of medium \( i \). \( C_{th} \) is specific heat capacity of sample, \( b_{y_f} = \frac{k_i \sigma_j}{k_j \sigma_i} \) is thermal transport coefficients and \( \omega = 2\pi f \) \(( f \) is the modulation frequency). So the expression of the pyroelectric signal is given by the following [8,9].

\[
\langle V_p(\omega) \rangle = \frac{j\omega A \Delta S \Phi(\omega)}{C_p C_{th} \left( j\omega + \frac{1}{\tau_{th}} \right) \left( j\omega + \frac{1}{\tau_p} \right)} \langle T_p(\omega) \rangle
\]

In this expression \( \Delta, A, \Delta, C_{th} \) and \( C_p \) are respectively pyroelectric coefficient of PVDF sensor, gain of amplifier, surface of the sample, specific heat capacity of detector and pyroelectric material.
\[
\frac{j \omega}{j \omega + \frac{1}{\tau_{th}}} = (j \omega + f_{th})(j \omega + f_{s})(j \omega + f_{p})(j \omega + f_{b})
\]

where \( f_{th} = \frac{D}{\ell_i^2} \) is the thermal cut-off frequency related to layer \( i (s, g, p, b) \) [11].

As pyroelectric signal is a complex number it may be written as \( V_i(\omega) = |V_i(\omega)| \exp(j \varphi(\omega)) \), where \( |V_i(\omega)| \) and \( \varphi(\omega) \) are respectively the amplitude and phase of the pyroelectric signal. These expressions are function of the thermal properties of sample and modulation frequency.

4. Experimental results

Theoretical and experimental curves of phase and amplitude of the pyroelectric signal according to the root square of frequency are obtained by both software such as the Microcal Origin and Maple. The curves of figures 4, 5 and 6 represented experimental and theory variations respectively of the pyroelectric amplitude and phase variations according to the square root frequency of sheet steel of 700-μm-thick, galvanized steel of 800-μm-thick and stainless steel of 600-μm-thick, in frequencies range from 1Hz to about 50KHz.

The best coincidence between theoretical and experimental curves for amplitude and phase of the pyroelectric signal permit to determine simultaneously the thermal conductivity and the diffusivity of the sample. Table 2 summarizes the obtained thermal conductivity and thermal diffusivity by EPE technique using electrical heating. Uncertainties are evaluated by statistical calculation [12], when thermal properties varied, while keeping the best coincidence between experimental and theoretical pyroelectric signal curves.

![Figure 4](image1.png)

**Figure 4.** Pyroelectric amplitude and phase variations according to the square root frequency of sheet steel for different value of thermal diffusivity.

![Figure 5](image2.png)

**Figure 5.** Pyroelectric amplitude and phase variations according to the square root frequency of galvanized steel for different value of thermal conductivity.
In this paper we have presented a new method based on the pyroelectric technique to determine the thermal diffusivity and thermal conductivity of metals alloys. The main advantage lies in its simplicity, non destructive character and its high sensitivity for thermal properties. The obtained values of thermal diffusivity and thermal conductivity for sheet steel, galvanized steel and stainless steel were in good agreement with those found in the literature. In the future, this method will be applied to semi-conductor samples in order to obtain their thermal and electrical properties, and will compare to other photothermal technique such as “Mirage Effect”.

5. Conclusion
In this paper we have presented a new method based on the pyroelectric technique to determine the thermal diffusivity and thermal conductivity of metals alloys. The main advantage lies in its simplicity, non destructive character and its high sensitivity for thermal properties. The obtained values of thermal diffusivity and thermal conductivity for sheet steel, galvanized steel and stainless steel were in good agreement with those found in the literature. In the future, this method will be applied to semi-conductor samples in order to obtain their thermal and electrical properties, and will compare to other photothermal technique such as “Mirage Effect”.

Table 2. Thermal properties of metals alloy.

| Sample       | Thickness | Thermal conductivity | Thermal diffusivity          |
|--------------|-----------|----------------------|------------------------------|
| Sheet steel  | 0.7 mm    | 13 ± 0.5 Wm⁻¹K⁻¹    | (7 ± 0.2)10⁻⁶ m²s⁻¹           |
| Galvanized steel | 0.8 mm   | 18 ± 1 Wm⁻¹K⁻¹      | (15 ± 0.3)10⁻⁶ m²s⁻¹          |
| Stainless steel | 0.6 mm   | 24 ± 0.3 Wm⁻¹K⁻¹    | (8 ± 0.01)10⁻⁶ m²s⁻¹          |

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