Determination of Thermal Diffusivity of Metals at High Temperature

L. Spronck, P. Scarpa (*), C. Defays & W. Legros

Department of Applied Electricity, University of Liège,
Institut Montefiore, Sart Tilman B28, B-4000 Liège, Belgium
(*) Research Associate with the Belgian National Foundation for Scientific Research
EMail: lspronck@montefiore.ulg.ac.be

Abstract

Arc-electrode interactions play an important role during current interruption in a circuit-breaker. This paper describes a method for estimating the thermal diffusivity of the electrode material on the wide range of temperatures encountered during operation. The principle of the proposed method consists in heating the tip of a thin cylindrical material sample with a powerful pulsed laser, and in measuring the temperature rise at two different locations of the sample. The correlation between the recorded signals allows one to obtain the thermal diffusivity of the metal. The proposed method doesn't depend on sensors gain, metal emissivity, ... Moreover, information at different temperatures can be derived by putting the metallic sample inside a furnace. Then, using temperature measurements just under the electrode surface, one can estimate the energy flux flowing from the arc to the electrodes.

1. Introduction

Current interruption in gas circuit-breakers involves the existence of an electric arc appearing between contacts. On one hand, this electric arc nearly behaves as an ideal interrupter due to its ability to rapidly switch from a conducting status to an insulating one, synchronously with the current zero. On the other hand, the electric arc is governed by very complex and highly interacting physical phenomena.

An important aspect, which is often neglected in numerical modelling, concerns the exchanges between the plasma column and the electrodes [Guile1]:
- first, the energy balance of the plasma column is influenced by the amount of heat flowing towards the electrodes;
- then, the metallic vapour emitted by the electrodes mixes with the quenching gas and strongly affects its thermodynamic properties.
Therefore it is interesting to determine the huge energy flux flowing from the arc column to the electrodes. But, on one hand, a purely theoretical approach to quantify that flux seems utopic. On the other hand, a direct measurement is practically impossible due to the extremely high temperature. The retained strategy was to measure the temperature just below the electrode surface, and then, to use it to calculate the energy flux responsible for that temperature rise [Dubois et al.2]. Therefore, to solve the inverse problem [Spronck et al.3], one needs to know the thermal characteristics on the whole temperature range in order to obtain an acceptable accuracy on the estimated flux.

The electrode materials used in practice have to present a complete set of physical properties (electrical conductivity, mechanical strength, ...) to withstand the operating conditions: copper-tungsten compounds are frequently used, with different proportions of the constituents. Unfortunately, information about the thermal diffusivity of those materials is quite rare, especially for temperatures other than the ambient one. Therefore, a procedure to determine the thermal diffusivity has been developed, which associates experimental and numerical approaches.

![Figure 1. Schematic view of the experimental set-up.](image-url)
2. Proposed method

The thermal diffusivity should be estimated on the wide range of temperatures encountered during circuit-breaker operation. Ideally, that technique should also be simple and it should allow an easy and rapid analysis of a given material.

In a previous paper [Spronck et al.], a simple method to determine the thermal diffusivity was proposed: that method gave rather good estimations but several factors could influence the quality of the results (radiation losses, sensor gain, ...)

A significantly improved technique is described in this paper. First a thin cylindrical metal sample is put inside a furnace and heated to a given temperature. Then the tip of the sample is irradiated with a power laser pulse. The incident energy diffuses progressively along the cylinder and the temperature disturbance is measured in two points located at different distances from the extremity of the sample. The pulsed heat source has to be powerful enough to induce detectable temperature increments even for very short pulses. Due to the rapidity of the phenomena, fibre optic infrared thermography is used.

Afterwards, considering the temperature measured at the first point and assuming a given thermal diffusivity, one can calculate the temperature which should have been measured at the second location. Comparison between this computed evolution and the actual record permits one to qualify the validity of the assumed thermal diffusivity.

A procedure of correlation, based on successive trials and errors, finally leads to the actual value of the thermal diffusivity (at the furnace temperature).

3. Experimental set-up

The developed experimental set-up involves (see figure 1):

- a 50 watts RF-excited waveguide CO₂ laser: its output can be modulated by a TTL control signal with frequencies up to 20 kHz and at any duty cycle. Appropriate optics allows one to focus the output beam on the tip of the metallic sample.

- A furnace to heat the metallic sample at the desired temperature.

- the temperature measurement system: since rapidly varying temperatures have to be detected, two infrared thermography systems are used. The light emitted by the sample surface is guided to an InSb detector by an IR optical fibre. To enhance detectivity, the InSb detector is cooled using liquid nitrogen and the preamplifier is included in the Dewar. The distance between the two fibres is adjusted thanks to an accurate positioning system.

To allow comparison with available values, the results reported in this paper concern copper sample. Recorded signals are shown on figure 2 (the furnace temperature is equal to 800 K, the laser pulse lasts 60 ms and the fibres are 2 mm apart).
Figure 2. Temperature measurements (vertical arbitrary scale).

Figure 3. Calculated temperature assuming $\alpha = 105 \times 10^{-6} \text{ m}^2/\text{s}$. 

$T_1(t)$

$T_2(t)$

$T_{2\text{calc}}(t, 105E-6)$
4. Theoretical approach

Since the energy is uniformly injected at a known location (at the tip of the metallic sample), if one knows the temperature evolution at a given location (e.g., at the point aimed by the first fiber), one can compute the temperature evolution at any other location (e.g., in front of the second optic fibre).

This calculation could be done numerically. But an analytical solution is available if one assumes that:

- the sample length is large compared to a thermal characteristic length (calculated while taking into the material thermal properties and the laser pulse duration);
- the diameter of the sample is small compared to its length;
- the temperature disturbance is small enough to neglect the increase of heat losses.

In that case, the problem becomes one-dimensional (see figure 4) and the solution is [Carslaw and Jaeger^5]:

\[ \Delta T(t,x) = \Delta T(t,0) \exp \left( \frac{x^2}{4 \alpha (t - \tau)} \right) \frac{\exp \left[ \frac{x^2}{4 \alpha (t - \tau)} \right]}{(t - \tau)^{3/2}} \]

where:

- \( \Delta T \) represents the temperature increase,
- \( t \) is the time (measured from the beginning of the laser pulse),
- \( x \) is the distance between the considered locations,
- \( \alpha \) is the thermal diffusivity.

Figure 3 presents the temperature which should be measured in front of the second fibre according to the temperature measured in front of the first fibre, while assuming that the thermal diffusivity is equal to 105 \( 10^{-6} \) m\(^2\)/s.

Figure 4. One-dimensional problem.
5. Thermal diffusivity estimation

The estimation of the thermal diffusivity (which is the only undetermined parameter in the above mentioned formula) is based on successive trial and errors, until the signal \(T_2\) corresponding to the second fibre is in agreement with the signal \(T_{2\text{calc}}\) calculated using the temperature \(T_1\) measured at the point aimed by the first fibre.

The synchronism can be easily emphasised by plotting \(T_2\) vs \(T_{2\text{calc}}\): when the agreement is good, the part of the curve corresponding to the temperature rise is superimposed on the part corresponding to the temperature fall (see figure 5). This technique doesn't depend on the sensors gain. Moreover it is very sensitive: small deviations on the value of the thermal diffusivity lead to very different "images". Figure 6 illustrates the effect of a 10% change on the assumed value of the thermal diffusivity.

![Figure 5. Synchronism check (\(\alpha = 105 \times 10^{-6} \text{ m}^2/\text{s}\)).](image)

![Fig. 6. Synchronism check (left: \(\alpha = 95 \times 10^{-6} \text{ m}^2/\text{s}\), right: \(\alpha = 115 \times 10^{-6} \text{ m}^2/\text{s}\)).](image)
Figure 7 presents a comparison between measured and theoretical values of copper thermal diffusivity. The theoretical curve has been obtained by interpolating values found in Zinov'yev. That figure shows that the estimations obtained using the method developed in this paper are excellent. One can observe that the dependence of the thermal diffusivity on temperature is correctly reflected.

\[
\begin{array}{c}
\text{Temperature (K)} \\
600 & 800 & 1000 \\
\end{array}
\]

\[
\begin{array}{c}
\text{Thermal diffusivity (} \times 10^{-6} \text{ m}^2/\text{s}) \\
0 & 50 & 100 \\
\end{array}
\]

\[
\text{reference 6} \\
\text{this paper}
\]

**Figure 7.** Thermal conductivity of copper.

### 6. Conclusions

The results prove the efficiency of the method proposed in this paper: a good estimation of the thermal conductivity of any metal can be obtained for a wide range of temperatures, while involving only reduced experimental time.

The presented method is a significant improvement of the technique described in a previous paper [Spronck et al.]. A few percents accuracy can now be reached since several uncertainties are discarded: sensor gain, metal emissivity, radiation losses, ...

This technique can be applied in various domains involving high temperature metals, to gain information on their thermal properties.
References


