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Proposal for a Modified Fowler-Milne Method to Determine the Temperature Profile in TIG Welding at Low Currents

It is possible to assess the thermal efficiency of welding shielding gases by means of the arc temperature field analysis. Since this approach opens a remarkable study field to assess different shielding gases, giving support for dealing with advantages and disadvantages of commercial gas mixtures, there is a research line under development, which goal is to find techniques to measure arc temperatures. This work describes a proposed method containing different procedures to quantify plasma jet temperature profiles from experimental data. This method was applied on data taken from TIG welding arc, at low current (40 A). This low current was selected to contrast to and amplify the current literature focus, i.e., high currents. The experiment was conducted using emission spectroscopy, picking punctual luminescence from the plasma through an optic system. The TIG arc was stroked on a water-cooled copper plate and shielded by pure argon. The temperature field was determined through the modified Fowler-Milne method. The introduced modification aimed to overcome the limitation that this method has for low radiation intensity presents in low current arcs: the Fowler-Milne method has an intrinsic threshold of 10,000 – 25,000 K. For a 40-A arc, the lower 10,000-K limiting isotherm is reached close to the cathode, restricting the analysis field, especially for the anode region. The proposed modification suggests a linear distribution of the particle density instead of a Maxwellian one, at temperatures below 12,500 K. The experimental temperature field was compared to a previous publication that deals with numerical simulation and the results were found in good agreement, what indicates the supposition of a linear distribution it is not far from the reality.

Keywords*: Welding, emission spectroscopy, modified Fowler-Milne, low currents*

Introduction

The most employed spectroscopy to plasma study is the optical emission spectroscopy (Pang et al., 1993). This is due to the fact that at high temperature regions of arcs, electrons in the last shell are sufficiently excited to emit in ultraviolet (below 400 nm), visible (400-700 nm) and infrared (700-1,000nm) during their return to less energetic levels. Thus, through the optical emission spectroscopy is supposedly possible to determine, for instance, the plasma temperature. There are different methods that could be used, such as the methods that utilise the broadening and/or shifting of spectral lines, the Fowler-Milne method (Thornton, 1993) and the relative intensities for a set of spectral lines that are in the same ionisation stage (Pang et al., 1993).

These methods rely on the need of assuming the plasma in local thermodynamic equilibrium (LTE), i.e., the collisional process is the dominant mechanism and thermal and concentration gradients are small, what is not true close to the cathode and anode. In these regions, the calculated values for temperature are normally overestimated (Vilarinho et al., 2002a). Concerning LTE in low currents, Bott (1966) proposed a lower limit of 35 A above what LTE could be assumed, based on his experiments for 5-mm argon arcs.

Pang et al. (1993) asserts that the relative-intensities method is the simplest and most direct method. However, there is a considerable limitation that is the need of existence of a line set sufficiently spaced for temperature estimation. Vilarinho et al. (2002a) measured the mean temperature using lines 415.9; 420.1; 696.5 and 706.7 nm, which has a energetic gap 1.23 eV, what corresponds to 14,300 K. Another method commonly employed is the Fowler-Milne method.

Nomenclature

A_{mr} = *the transition probability,* s^{-1}
c = *light speed,* $c = 2.9979 \cdot 10^{8}$ *m/s*
E_m = *energetic level, eV*
g_m = *statistical weight, dimensionless*
h = *Planck constant,* $h = 6.626 \cdot 10^{-34}$ *J.s*
I(x) = *spectral intensity profile, counts per second (cps)*
k_B = *Boltzmann constant,* $k_B = 1.380658 \times 10^{-23}$ $J.K^{-1}$
N_m = *particle density,* m^{-3}
r = *radial coordinate, m*
R = *maximum arc radius, m*
T = *temperature, K*
x = *longitudinal coordinate, m*
Z_m = *partition function density, dimensionless*

Greek Symbols

$\varepsilon(r)$ = *radial normalised emission coefficient, dimensionless*
λ_{mr} = *wavelength, m*

Subscripts

m = *upper energetic level*
r = *lower energetic level*

Fowler-Milne Method

Olsen (1959), Haddad & Farmer (1985), Thornton (1993a) and Hiraoka (1998), among others, utilised the Fowler-Milne method to estimate the welding arc temperature. This method is based on Eq. (1). For plasmas in LTE and at constant pressure, this function $\varepsilon(r)$ passes through a maximum value at a well-defined temperature called normal temperature. This maximum occurs because the increase of the exponential factor with the temperature is balanced

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by the reduction of the specie (neutral atom, ion or electron) density due to both expansion and ionisation of the plasma.

$$\varepsilon(r) = \frac{hc}{4\pi}\frac{A_{mr}\, g_m}{\lambda_{mr}}\frac{N_m(T)}{Z_m(T)}e^{-\frac{E_m}{k_B T}} \tag{1}$$

Provided that the axial temperatures of the arc exceed the normal temperature, an off-axis maximum in the radial emission coefficients is observed in the measured spectrum. The temperature at the maximum of the emission coefficients is used to calibrate experimental radial intensity distributions as long as Eq. (1) is known. In short, the Fowler-Milne method is based on the possibility of tracking this off-axis maximum in the radial emission coefficient curve.

A schematic procedure of the Fowler-Milne method is presented in Fig. 1. The first step is to choose a line in a horizontal plane to collect the respective spectra in a transverse scanning and to determine the peak or integral intensity for each point of this line (Fig. 1a to 1b). After that, one must conduct the Abel Inversion (described ahead) for both sides of the experimental curve and get the polynomial interpolation of all points in both sides, Fig. 1c.

An emission coefficient profile is also obtained by Eq. (1), which is compared to the resultant Abel Inversion curve, after normalising both (Fig. 1d). Once the maximum of the experimental (Abel Inversion) curve is found, the emission coefficient values toward the centre of the arc (in Fig. 1d, $R < 1.5$ mm) are compared to the right side of the maximum at the Fowler-Milne curve, i.e., towards higher temperatures (it is implicit that the arc core is hotter than its fringes). From a different perspective, the experimental emission coefficients after the maximum (in Fig. 1d, $R > 1.5$ mm), i.e., toward lower temperatures, should be compared to the left side of the maximum at Fowler-Milne curve. Due to the fact that the maximum intensity does not happen at the arc centre, this method is also called off-axis maximum method.

The Fowler-Milne method has the advantage of eliminating the use of transition probabilities. In addition, this method does not require a measuring apparatus to be calibrated. On the other hand, the partition function $Z_m(T)$ and the particle density $N_m(T)$ of the species must be calculated (Olsen, 1959 and Thornton, 1993). However, the ratio $N_m(T)/Z_m(T)$ is almost independent, so only a small uncertainty in T results (Murphy, 1994).

Olsen (1959) points out that the greatest limitation of this method refers to the lower temperature limit that could be measured, around 10,000 K for argon using Ar I lines. This happens due to the abrupt decay of normalised intensity below 10,000 K (Fig. 1). For this reason, the majority of publications shows minimum isotherms of 10,000 K.

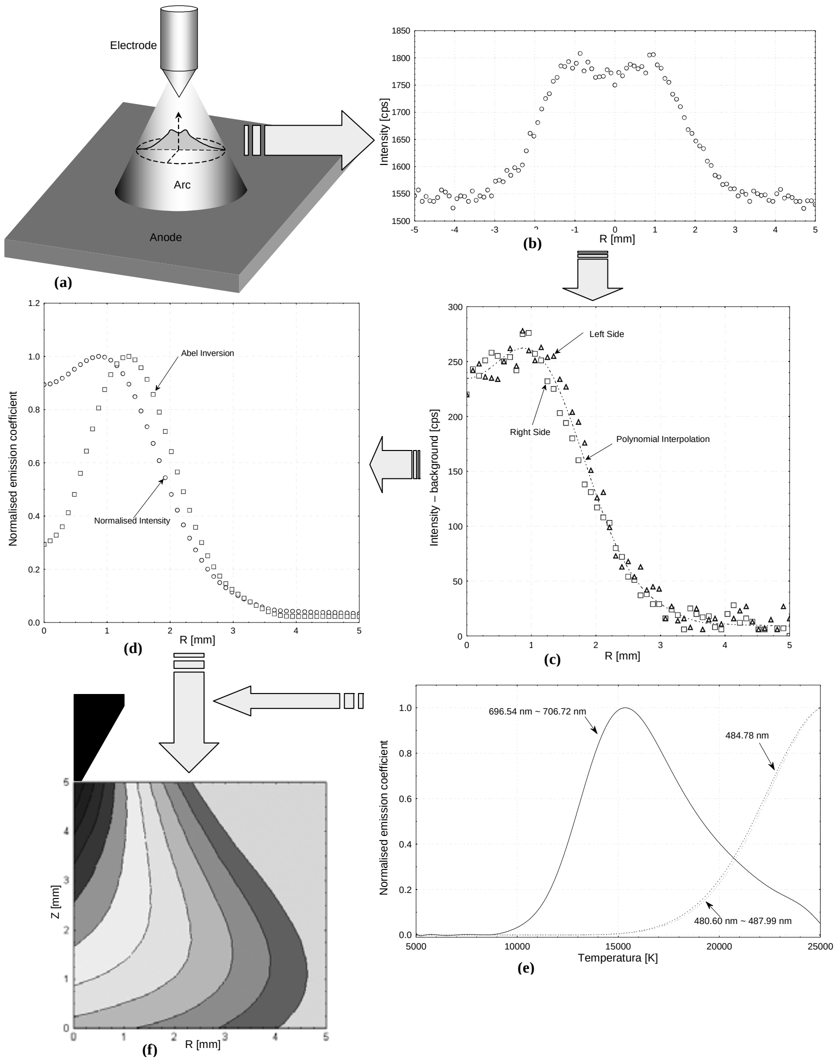


Figure 1. Schematic procedure for the Fowler-Milne method.

An important aspect of the spectroscopic utilisation refers to the way of capturing luminous intensity. One must be aware of the fact that it is a luminous "line" rather than a point that is measured, as shown in Fig. 2. Thus, the spectral intensity will be composed by different energetic states at different temperatures. Supposing an axis-symmetric radial temperature, i.e., the intensity distribution is the same for both directions x and y, it is possible, mathematically, to eliminate this effect using the Abel Inversion, given by Eq. (2).

$$\varepsilon(r) = -\frac{1}{\pi}\int_r^R \frac{1}{\sqrt{x^2 - r^2}}\frac{dI(x)}{dx}dx \qquad (2)$$

This equation must be solved numerically from the experimental data. There are different methods to deal with it, the most common are Nestor-Olsen (Nestor & Olsen, 1960), Barr (Barr, 1962), Herlitz (Herlitz, 1963) and Minerbo (Minerbo & Levy, 1969). Besides these methods, it is possible to find different approaches in the literature, for instance, Park & Moore (1970), Snow (1972), Anderssen (1976), Deutsch & Beniaminy (1982) and Vilarinho et al. (2002b).

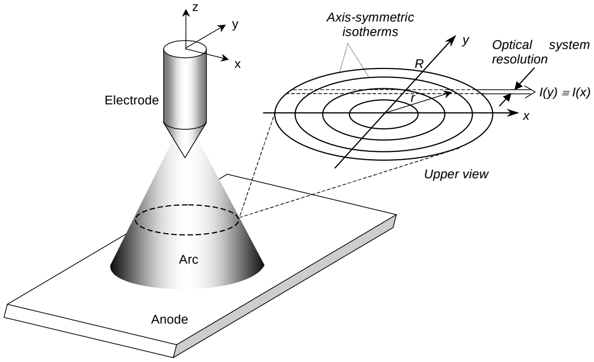


Figure 2. Example of an arc transverse section.

In order to utilise any spectroscopic method, one must know to which element a given line belongs to. This could be done using a database, for instance Reader & Corliss (1998). It should be pointed out that the most popular bibliographic references (Haddad & Farmer, 1984 and 1985; Lacroix et al., 1997 and Hiraoka, 1998) resort to far-date spectral data (Olsen, 1959 and 1963). Another limitation of the previously published data is the lack of automatic identification of spectral lines and determination of its physical constants. Vilarinho et al. (2002a) proposed computational routines to deal with this problem.

In view of the limitations of previous studies for high welding currents (above 100 A), this work aims to investigate the temperature field at a lower current (40 A) by applying a proposed modified Fowler-Milne method to calculate isotherms lower than 10,000 K.

Methodology

Proposal for a Modified Fowler-Milne Method

As it was stated, the Fowler-Milne has an intrinsic lower limit of 10,000 K. This is due to the fact that a Maxwellian distribution is assumed to characterise the particle/specie density. Griem (1997) states that it could be even assumed a Fermi distribution. Since data from literature that could stand different particle density distribution for low currents was not found, this distribution was assumed here as linear for low temperatures, i.e., it is proposed here a mixed Linear-Maxwellian distribution as shown in Fig. 3. As seen, the employed linear curve ranges from 12,500 K (which corresponds to an ionisation degree of ~10%) until 5,000 K (lower limit where physical constants are available). Although one could propose a mathematical/physical justification for this assumption, the strategy to validate or not this assumption will be a possible confirmation with the results at the end.

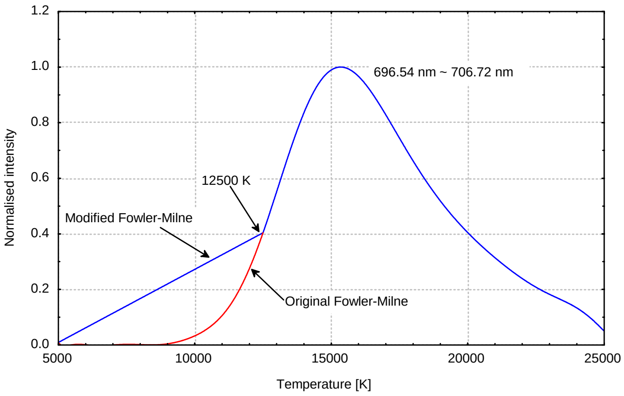


Figure 3. Proposed modified Fowler-Milne method.

Experimental Rig

The experimental rig used in this work is schematically presented in Fig. 4. The arc was established using a constant current electronic power supply (inverter) and a TIG torch with a 1.6-mm-diameter, 60º-tapered, AWS EWTh-2 class electrode (tungsten doped with 2% of thoria). The arc length was kept 4 mm long and commercially pure Argon at 8 l/min was employed to protect the arc. The arcs ran over a water-cooled copper plate, acting as anode. The plate refrigeration aimed to prevent metal evaporation and, consequently, arc medium contamination. It is important to point out that the whole set has a considerable mass and low rigidity, in order to prevent vibration effects. This experimental rig is better described in Vilarinho et al. (2002a).

An optical fibre was used to capture the luminous intensity from the arc. It was kept fixed in a focusing device, which was hold by a three-axis translation system (step of 0.38 mm/turn). This device was built to provide an arc magnification of three times and so to improve the spatial resolution. Since the optical fibre has a diameter of 400 μm, this system has a resolution of 400/3 μm, i.e., 133 μm. It is important to emphasise that a fibre with 250-μm diameter would have an error of 3.5% (Vilarinho et al., 2002b).

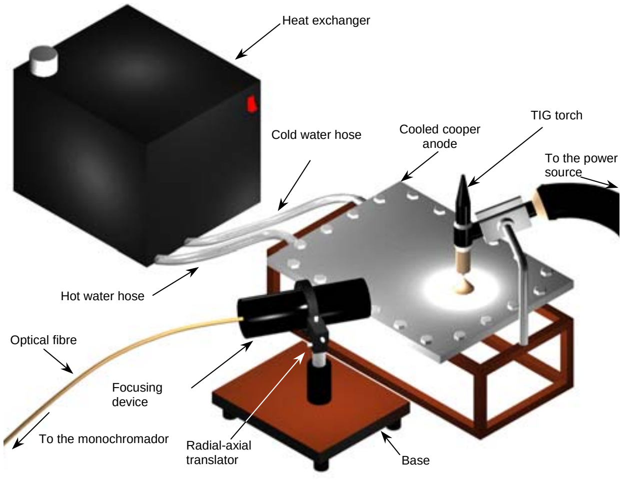


Figure 4. Schematic view of the experimental rig.

In order to quantify the plasma temperature field, 24 run-points disposed as shown in Fig. 5 were employed. Since the Abel inversion requires an axis-symmetric arc, half of the arc was scanned. This point distribution was employed from previous trials. In order to clarify the nomenclature employed here, runs from #01 to #04 will be denominate Row #1; runs from #08 to #05 will be called Row #2 and so on up to Row #5.

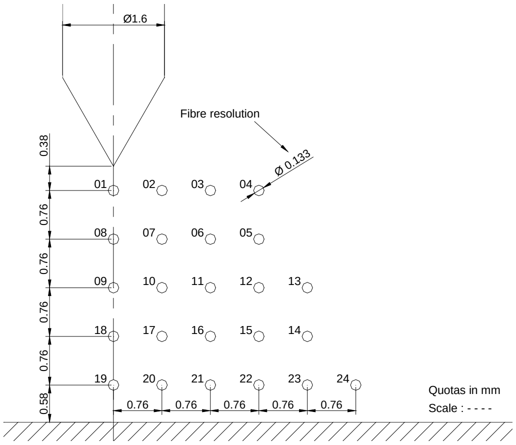


Figure 5. Run positions for arc temperature mapping.

The current was kept constant at 40 A. As said before, this value was employed despite of the fact of a lack of literature data for low currents. Therefore, researching this current magnitude can be of extra value for the study on physics of arc. The luminous entrance in the spectrometer was set by its slit in 12 μm with an integration time of 0.01 s.

Some initial investigations were conducted to assess the possibility of using the relative-intensities method, such as in Vilarinho et al. (2002a). The 415.9, 420.1, 696.5 and 706.7 spectral lines were scanned. However, the temperature is so high that in the central points of Fig. 5 (#01, 08, 09,18 and 19), the 415.9 and 420.1 were not found, restraining the application of the relative-intensities method. This is due to the fact that, for highly ionised argon, the neutral population (Ar I) in this region (400-500 nm) is overcome by its ions (Ar II). It is important to point out that 696.5 and 706.7 lines are still visible, because they are in another wavelength range, far from the Ar II range. Another tried approach for using the relative-intensities was to search for Ar II lines, since with the relative-intensities method one cannot pick up any lines. There is a criterion stating that there must be an energetic gap between the lines (Griem, 1997). This energetic gap is the difference between the upper energetic levels of each line. They are on databases and are expressed in eV (1 eV = 11,600 K). But this task was unfruitful.

The second approach was to employ the original Fowler-Milne, but, as expected, the built program (denominated “Fowlermilne.m”) calculated all temperature in the arc fringes (normalised intensity below 0.075) as approximately 10,000 K. Thus, the proposed modified Fowler-Milne was employed, in which two different regions around 480.60 nm and 696.54 nm were acquired. The intensities of these lines were normalised (maximum value equal to 1.0) and the Abel inversion was used, through the program “Abel.m” (Vilarinho et al., 2002b). The inversion was performed for each of the five rows in which the experimental points are distributed (Fig. 3), totalling five inversions. One example is shown in Fig. 6.

After the Abel inversion, the obtained values were again normalised, since as it is shown in Fig. 6, they are not more normalised after the inversion. With this normalisation and the proposed modified Fowler-Milne, the temperature isotherms were built using an average of three measurements and a least square adjust.

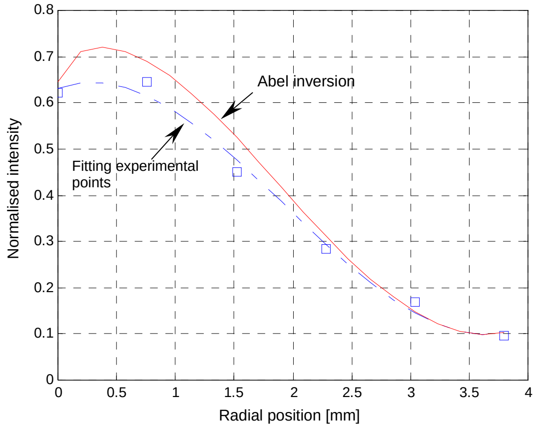
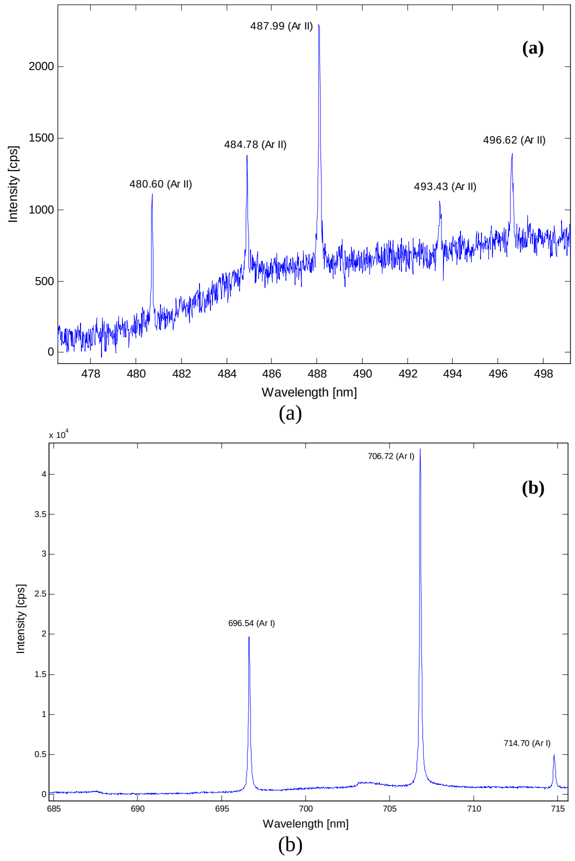


Figure 6. Abel inversion curve (straight line) obtained on the Row #5 data. Dotted-dashed line represents the fitting experimental curve.

Results and Discussion

An example of obtained spectra is presented in Fig. 7, which presents the spectrum of Point #01 (Fig. 5). Reporting now all spectra, it was possible to notice the presence of Ar II lines only for Points #01 and #08, for which is predicted a temperature at least over 15,000 K (according to Fig. 1e). Considering now Ar I lines (696.54 and 706.72 nm), they present the profile expected for the Fowler-Milne method, i.e., increasing until ~15000 K and decreasing after that.



(a)

(b)

Figure 7. Example of an obtained spectrum during mapping of Point #01.

Following the presented procedure for the proposed Fowler-Milne method, temperature maps for both 696.54 and 706.72-nm lines were obtained. These maps are shown in Fig. 8. Their disposition is such that one can compare both plots in order to gather more information about the LTE. Even better comparison could be conduct if all rows of points were plotted separately, like in Fig. 9. In this figure, each plotted curve refers to each of the five rows of runs.

Comparing both maps (obtained by 696.54 and 706.72 nm-lines) is possible to assert that there is a good agreement between them and the small-presented difference cannot be attributed to departures from the LTE. It is likely due to experimental errors (stipulated here as ± 500 K). Even in the arc fringes, where some authors (Thornton, 1993, for instance) argue against the existence of the LTE, good agreement between the two maps was found.

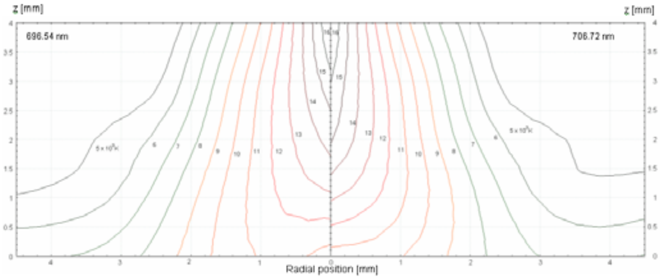


Figure 8. Comparison between isotherms obtained from 696.54 and 706.72 nm lines.

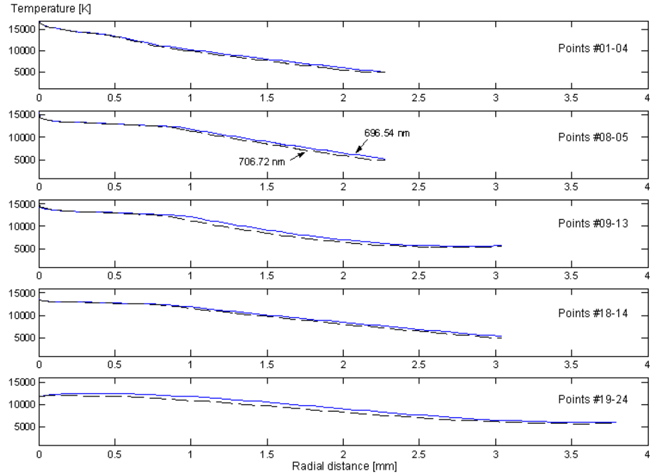


Figure 9. Comparison between temperatures obtained for the five rows of experimental points.

As it was said, no previous work dealing with welding arcs at low current were found, what brings difficulty to validate the proposed method. At least, it is possible to assert that the maximum value found for the temperature (16,000 K) is at the same order that values found for 100-A argon arc. For instance, both Haddad & Farmer (1985) and Thornton (1993) found 20,000 K, whereas Hiraoka (1998) found 18,000 K.

Another possibility to validate the technique is to compare the results to numerical simulations. Comparing the temperature map calculated in Fig. 8 with simulations conducted by Vilarinho (2001), one will find differences in temperature in the order of 13.4 %. This could be considered a good agreement, especially if limitations on simulation (for instance, reliable boundary conditions) were admitted.

Thus, it is possible to state that the proposed Fowler-Milne method was found consistent, since two distinct maps, calculated by two different Ar I lines, presented good agreement with the simulations presented in Vilarinho (2001). Possible sources of errors in the presented method could be the arc fluctuation, especially due to the 30-min period of continuous running, numerical errors, due to the data treatment, and inherent errors, due to the minimum quadratic adjust. It is a proposal for the near feature to verify these sources.

Conclusions

The proposed modified Fowler-Milne method, based on a linear distribution of the particle density instead of a Maxwellian one, at temperature below 10,000 K, showed very useful for calculating the temperature field for welding arcs at low current (40-A argon arc in this work), in contrast to the normal Fowler-Milne method, which led to error at such low temperature profile calculations.

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