COMPARISON OF OPTICAL AND ELECTRICAL TEMPERATURES IN ATMOSPHERIC PRESSURE (TIG) ARCS

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Abstract. *Atmospheric pressure argon arcs were investigated by emission spectroscopy and electric exploration techniques in the range of 50-200 A. The first technique gives temperature maps for arc currents in good agreement with previously published data. An extensive study on Langmuir probes in arcs was performed and a multi-wire apparatus was constructed. Because the probe characteristic curve is distorted at high pressure, only the ion saturation part of this curve is available under these conditions and temperatures are obtained from the inversion of the ion saturation current. However, the values obtained are systematically lower than the optical spectroscopy determinations. This is attributed to the recombination between ions and electrons, reducing the particle number. Since the temperature is proportional to the particle density, recombination lowers the temperature.*

Keywords*. Arc Physics, Spectroscopy, Langmuir Probe, Temperature.*

1. Introduction

The structure of a discharge may be defined in terms of its temperature, pressure and particle flux distributions, which in many cases are time dependent. Considerable difficult is encountered both with measurement and accurate interpretation of the data. However, atmospheric plasmas in industrial applications may be simplified to consider the effect of successive stepwise departures from an idealised condition. Such an approach is proposed here, to build on the limited but valuable understanding of the physics of welding arcs.

The welding arc is a relatively small region characterised by high temperatures (around 20,000 K), strong luminous radiation, intense matter flux and high physical property gradients. Thus, the arc study, both theoretical and experimental, is very complex and although a large literature about it can be found, many aspects remain unclear (Modenesi, 1996). Theoretical studies are done through the arc modelling, either analytical or numerical models. They are described in Vilarinho (2002). Experimental studies can be conducted by direct (invasive) or indirect (non-invasive) methods. Examples of direct methods are the Langmuir probe, the enthalpy probe and PIV technique (Particle Image Velocimetry). Regarded indirect techniques, there are different ones that can be used (Arzimovich, 1965; Shaw, 1975a and 1975b; Bálsamo et al., 2000; Boulos, 2001 and Vilarinho, 2001). For instance, electrical signal analysis, shadowgraph, calorimetry, electrode analysis, schlieren, interferometry, radio waves measurement, inverse methods, x-rays and spectroscopy. A more recent technique has been proposed by Murphy (1999) for temperature calculation basing on colour separation, i.e., different wavelengths mean different colours and different temperatures.

Among the different cited techniques, the ones, which can directly assess the gas thermal properties (temperature, ionisation, etc), are outstanding, since the thermal efficiency of a shielding gas is one of the main factors that affect the welding process (Jönsson et al., 1995). The efficiency of this energy transfer depends, in general terms, on the arc current, the arc length and the gas composition, but the one common parameter, which is influenced by all these variables, is the arc temperature distribution (Gick et al., 1973). Thus, this work deals with techniques that can directly assess the arc temperature distribution namely, optical emission spectroscopy and Langmuir probes, in order to provide a comparison between a non-invasive (spectroscopy) and an invasive technique (probe).

The study programme will focus on the Tungsten Inert Gas (TIG) discharge typically used for welding applications, although the results and the insights gained should be applicable to a much wider range of discharge conditions, most notably those used in technologies such as waste destruction and chemical manufacturing. Specifically, the TIG process is employed for the welding of materials and components where close control over heat transport to the workpiece and subsequent thermal history are required. The range of applications includes complex or expensive aerospace components (turbine blades, engine components, tubing etc), machine tools, ultra-clean pipelines for electronic and medical applications and critical welds in large structures or components (root welds). Materials commonly welded include titanium and its alloys, aluminium alloys, carbon manganese steels, stainless steels and nickel-based alloys.

1.1. Optical emission spectroscopy

Through the optical emission spectroscopy is possible to determine 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 relative intensities and the Fowler-Milne method. This paper is focused on the latter one, because of its larger utilisation and relatively straightforward application.

Among others, Olsen (1959), Haddad & Farmer (1985), Thornton (1993), Haidar & Farmer (1993), Sabsabi et al. (1994), Hiraoka (1998) and Tsukamoto et al. (1998) utilised the Fowler-Milne method to estimate the welding arc temperature. This method is based on Equation 1 and it was initially proposed by Fowler & Milne (1924). For plasmas in the Local Thermodynamic Equilibrium (LTE) and at constant pressure, this function passes through a maximum at a well-defined temperature called normal temperature. This maximum occurs because the exponential factor increase with the temperature is balanced by the specie density reduction due to both expansion and ionisation of the plasma.

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

where, $\varepsilon(r)$ is radial emission coefficients determined after the Abel inversion;
k_{mr} is a constant that represents radiation losses between the arc and monochromator;
h is the Planck constant ($h = 6.626 \cdot 10^{-34}$ J.s);
c is the light speed ($c = 2.9979 \cdot 10^{8}$ m/s);
λ_{mr} is the wavelength (m);
A_{mr} is the transition probability (s^{-1});
g_m is the statistical weight;
$N_m(T)$ is the particle density (m^{-3});
$Z_m(T)$ is the partition function;
E_m is the line energetic level (eV);
k_B is the Boltzmann constant ($k_B = 1.380658 \times 10^{-23}$ J.K^{-1}) and
T is the temperature (K).

Provided that the axial temperature of the arc exceeds the normal temperature, an off-axis maximum in the radial emission coefficients is observed. The temperature at the maximum of the emission coefficients is used to calibrate experimental radial intensity distributions provided the form of Equation 1 is known.

A schematic procedure of the Fowler-Milne method is presented in Vilarinho & Scotti (2003). The first step of the method is to choose a line (a specific wavelength) and collect the spectra and determine the peak or integral intensity for each point through a horizontal plane. After that, one must proceed to the Abel Inversion and compare the normalised emission coefficient profile to the profile obtained by Equation 1. Once the maximum of the experimental inverted curve is found, the emission coefficient values toward the centre of the arc are compared to values at the right side of the maximum of the Fowler-Milne curve, i.e., at higher temperatures. It is implicit the assumption of the arc core is hotter than fringes. Conversely, the maximum of the experimental emission coefficients after the maximum should be compared to the left side of the Fowler-Milne curve. Due to this fact, i.e., the maximum intensity does not happen in 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 and also it does not require the measuring apparatus to be calibrated. In exchange, the partition functions and number densities of the species must be calculated (Olsen, 1959 and Thornton, 1993). However, the ratio $N_m(T)/Z_m(T)$ is almost independent of temperature, so only a small uncertainty in T results (Murphy, 1994).

Despite all the knowledge accumulated so far, divergences among different researchers still exist and a thorough analysis of the experimental procedure (more updated physical data, computer programs, error analysis, etc) needs to be carried out. Thus, the aim of the present spectroscopy experiment is to deal with these issues, hoping to clarify doubts and provide further steps into the use of spectroscopy in welding.

1.2. Langmuir probes

One of the earliest methods used in the study of the plasma of gas discharges was that of inserting an insulated solid electrode, or probe, in the discharge and measure the potential the probe assumes (Cobine, 1958). Mott-Smith & Langmuir (1926) were the pioneers in this technique, presenting the starting theory for low-pressure plasmas, where probes are traditionally employed. After them, some books dedicated to this subject were published (Swift & Schwar, 1970 and Chung et al., 1975). Former reviews about probes are due to Kagan & Perel (1964) and Clayden (1968), although more recently reviews were also conducted (Benilov, 1989; Allen, 1995 and Fanara, 2001).

A Langmuir or electrostatic probe consists of one (single probe) or more conductors (double and triple probe – Leveroni & Pfender, 1989) exposed to the plasma. This electrode can be a disk, cylinder or sphere and it is usually as small as it can be manufactured. Comprehensive analyses of probe dimension effects were conducted by some authors, such as Waymouth (1964), Little & Waymouth (1966), Shunko (1990) and Sheridan (2000).

It should be pointed out that the potential assumed by an insulated probe immersed in a plasma (referred here as V_p) does not coincide with the actual plasma potential (V_{pl}) at the given point, because of the sheath formation (Cobine, 1958, and more recently a review can be found in Riemann, 1991). The presence of the sheath generates a potential fall around the probe (V_s) and $V_p = |V_{pl} - V_s|$. In floating conditions, this sheath voltage is called the floating potential, e.g. $V_s = V_f$.

Instead of just keeping the probe insulated, i.e., in floating condition, one can vary its potential with respect to the one of the electrodes (Figure 1) and study the probe current as a function of its potential (biased probe). The curve so constructed is known as 'IV' or characteristic curve.

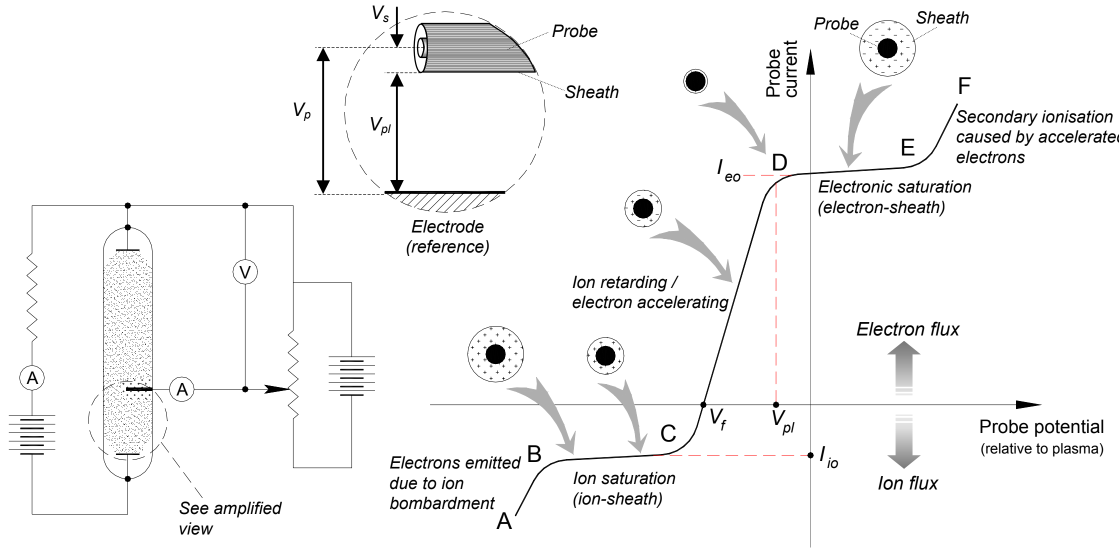

Figure 1. Probe characteristic curve (right) obtained by the single probe circuit (left) and the detailed involved voltage drops: V_f – floating potential (to be rigorously scientific, the correct term is "the probe potential in floating conditions"); V_{pl} – plasma potential; V_p – probe potential and V_s – sheath potential.

While it is quite difficult to exhaust the tremendous amount of literature existing on the subject as taken in general terms, a very limited selection of published works is available on the use of this technique for arc plasma diagnostics and TIG arcs in particular (Fanara, 2001). The large literature involves several probe-operating regimes. Nevertheless, there are few publications dealing with probes in atmospheric plasmas during welding. One of the earliest publications is due to Gillette & Breymeier (1951). After that, Petrie & Pfender (1970), Gick et al. (1973), Allum et al. (1977), Allum (1982) and Fanara & Richardson (2001) also presented some results. The common sense among them is the fact that there is a lack of probe theory that deals with atmospheric-pressure flowing plasmas. Swift & Schwar (1970) underline the difficulties when dealing with high-pressure plasmas, where the effect of collisions makes the interpretation of the characteristic curve rather involved if not impossible (Schott, 1968).

Tracing a parallel with low-pressure theory, Gick et al. (1973) presented a temperature map, in which values are lower than the ones obtained by spectroscopy. Gick et al. (1973) calculated this temperature map using a random-ion-flux model for the ion-saturation current (Equation 2).

$$I_{isat} = \frac{N(T) \cdot e \cdot \langle v \rangle \cdot S}{4}, \qquad (2)$$

where, N(T) is the ion density (equal to the electron density, for single ionised plasma);

<v> is the mean thermal (Maxwellian) velocity of the ions given by $\langle v \rangle = \sqrt{\frac{8 k_B T_i}{\pi m_i}}$;

S is the probe surface area given by $S = 2\pi r_p L_p$;

L_p is the characteristic probe length, estimated here as $L_p = 2R_{arc}$.

Although Langmuir probes have been extensively studied in low-pressure discharges, further analysis is needed in high-pressure arcs. Thus, the present study aims to show some results for welding arc at different currents, using the presented theory.

2. Experimental procedures

2.1. Optical emission spectroscopy

The experimental arrangement comprises an arc generation and manipulation system, an optical assembly for light capture and focusing, a monochromator and detector (Figure 2). Light from the arc is imaged at a 1:1 ratio on to a 50-μm diameter pinhole. Light from the pinhole is collected by a second lens and imaged to the monochromator. The monochromator (Spex model 1704) has a 1m focal length and a reciprocal linear dispersion of 0.8 nm/mm for first order images. Two-dimensional mapping of the arc is carried out by moving the arc through the focal plane of the fixed optical path by means of precision stepper motors (1 μm/step). This arrangement provides a spatial resolution of 50 μm, determined by the pinhole diameter.

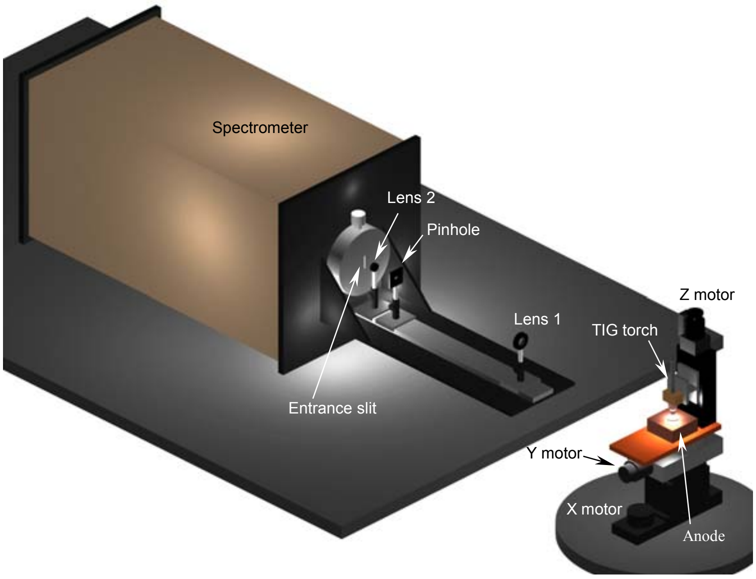

Figure 2. Experimental rig for optical emission spectroscopy.

A DC arc was struck between a tungsten electrode (cathode) and a copper anode. The cathode is a 3.2-mm diameter, 2 % thoriated (AWS EWTh-2), typically ground to a 60º include angle and truncated to a 0.2-mm flat tip. According to Thornton (1993b) the flat tip is preferable because firstly, if the tungsten were too sharp it would frequently become stuck to the anode during touch striking of the arc. Secondly, although the tungsten electrodes were accurately machined to give the correct tip angle, difficulty was experienced with reproduction of detailed tip profiles. Thirdly, a very sharp electrode tip was found to erode very quickly during operation, what leads to a changing arc profile during the measurements.

The anode was a 36-mm diameter and 6-mm-thick oxygen free copper disk that can be readily substituted for each run. The anode block is cooled in order to prevent melting and to avoid evaporation, which would alter the thermal and physical properties of the arc (metal vapour impurities have a lower ionisation potential). A steel anode was also employed to verified the effect of the anode in the arc temperature for 50 A (higher currents were not run for the steel anode due to anode melting).

A transistor series regulated power supply was used (model GEC AWP H350sr). This power supply was used to provide a highly uniform output (current ripples less than ± 0.1 A). A typical sequence for striking an arc was to turn on the power supply and move the torch (Z axis – Figure 2) by software in steps of 0.1 mm. As soon as the short-circuit occurred between the electrode and the anode, the electrode was lifted up and the arc established. The short-circuit current setting of the power supply was limited to 10 A to prevent damage to the tungsten electrode.

The system alignment is described in Vilarinho (2002), as well as the initial investigation to determine the optimum configuration (set-up) for the spectrometer. The final parameters were an integration time of 0.5 s; a dark offset off; full CDD area and entrance slit as 50 μm.

After the determination of the anode reference, the data collection starts. Some programs were written to automatically move the whole system (anode and cathode blocks). A spatial resolution of 100 μm was chosen for the radial direction, whereas the axial one has a resolution of 200 μm, since the gradients in the axial planes are lower than in the radial ones. Since the arc window was chosen as 10-mm width and 5-mm high, this gives 2500 points to map the whole arc (25 horizontal planes with 100 points each), which led to a 2 ¼ hours for each run. The 10-mm radius refers to an *optical radius* beyond which optical measurements are doubtful because of lack of LTE. The programs employed in this stage are described in Vilarinho (2002). They were written in Array Basic® language using the Spectramax Software® for the spectrometer control and in Turbo C® for the stepper motor control. Each experimental point consists of an ASCII file that contains the wavelength interval and the intensity values with 1024 points.

After the experiment, data is gathered and analysed by Abel inversion of the integrated chordal intensity to recover the radial distribution of the emission coefficient (assuming axial symmetry and optically thin plasma). Temperature is then derived assuming that a Boltzmann distribution holds for the excited state population densities and using the Fowler-Milne method described. An ASCII file is generated at the end with the temperature values for each axial and radial position. This final file is read using the Statistica® software to plot the arc isotherms interpolating the raw data using the least square method.

It was proposed to investigate argon arcs at three different currents (50, 100 and 200 A). The arc length was 5 mm and the gas flow rate was 10 l/min. The electrode stick-out was kept at 5 mm.

2.2. Langmuir probes

Figure 3 shows the experimental rig utilised. The power supply, the electrodes, the cooling system and the welding parameters are the same employed for the spectroscopic rig. A DC motor rotated the probe-holder disk and by varying its input voltage, it was possible to change the probe speed through the arc up to 5.0 m/s.. The probe disk can hold 12 probes equally spaced (30º) at the same time, although it employed a maximum of 11, since a gap is necessary to identify each probe from the acquired spectrum. Copper probes with a diameter of 250 µm were employed . The apparatus for the probe alignment consisted of a telescope equipped with a vernier with a 10-µm resolution focused on the probes and provided both the probe height and straightness.

The probe current is collected by carbon brushes in contact with the probe-holder disk (Figure 3). The electric circuit for data acquisition, both in floating (or unbiased) and biased conditions, is shown in Figure 3. The floating regime is obtained disconnecting the DC power supply (battery) and making the resistor R_{DAQ} high enough in order to limit the drained current (~60 mA). Fanara & Richardson (2001) asserted that the minimum R_{DAQ} to obtain floating conditions is approximately 15 kΩ. In later measurements, a value of 67 kΩ was used.

To build the characteristic curve, in the biased case it is necessary to acquire both the current and probe voltage by reading the voltage drop across the known resistance R_{RL} = 4 Ω and disconnecting the R_{DAQ} ($R_{DAQ} = \infty$). The choice of the value for R_{RL} is a compromise between the need to effectively bias the probe (e.g. 'small value') and to avoid drawing a too high current from the arc ('high value'). The acquisition rate employed was 70 kHz for each of the three channels (bias voltage V_b, probe voltage V_p and readout voltage V_{RL}). It should be pointed out that a battery and a rheostat were used to bias the probe, since electronic DC power supplies have an intrinsic control to compensate the circuit fluctuations, which, in this case, spoil the experiment. The rheostat resistance varies from 0.25 to 10.8 Ω.

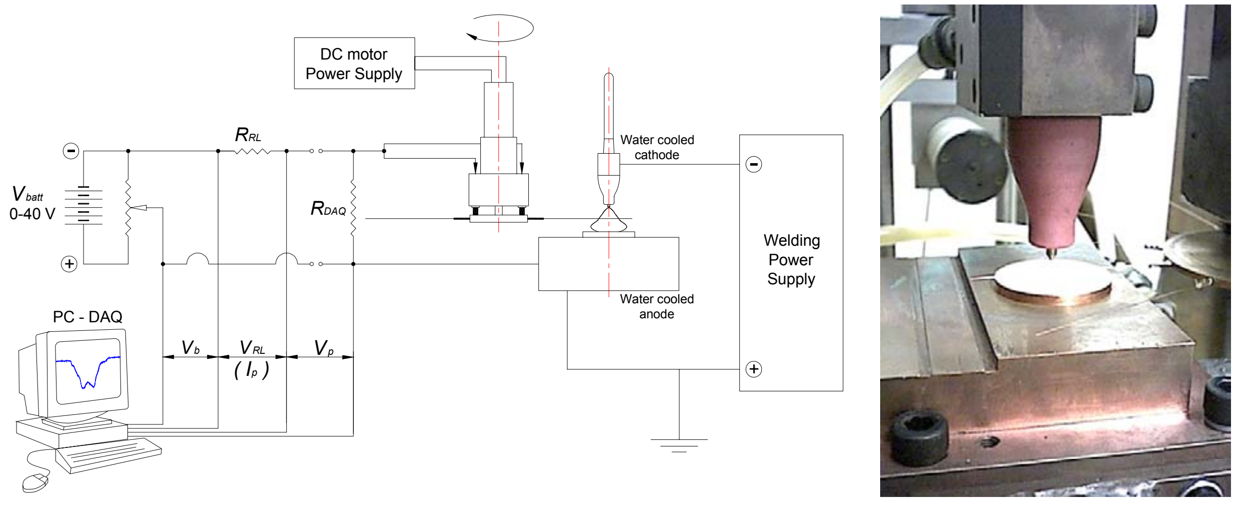

Figure 3. Left, electrical setup for the Langmuir probes. Right, torch nozzle with W tip, and copper anode.

3. Results and discussion

3.1. Optical emission spectroscopy

Following the procedure presented in the previous section, the arc map temperature was obtained for pure Ar at several arc currents. Figure 4 shows two different temperature maps at I=200 A, one for 696.54 nm (solid lines) and the other for 706.72 nm (dashed lines).. (The electrode is in the same scale as the arc). These agree well one with the other and with existing literature in both experimental and numerical works (for instance, Haddad & Farmer, 1985).

The obtained temperature map for pure argon at 100 A (Figure 5) agrees with previous published data (both experimental and numerical results). Agreement between temperature values from the 696.54 and the 706.72-nm lines was also obtained for different radial temperature profiles at different heights. This is a strong evidence of the LTE.

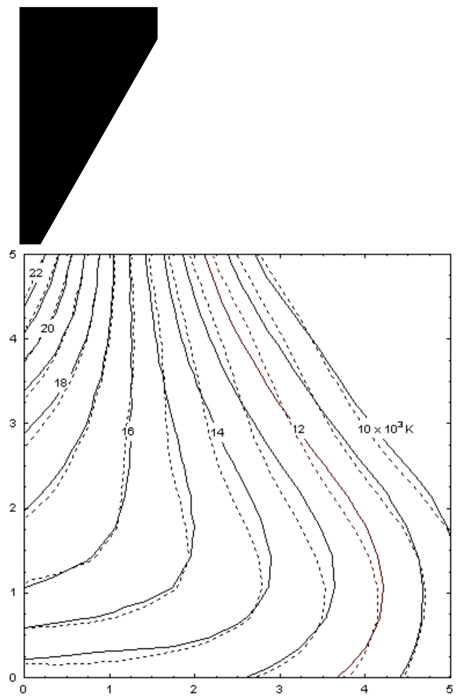

Figure 4. Comparison between temperatures obtained from 696.54-nm argon line (solid lines) and 706.72 nm (dashed lines) for pure Ar at 200 A.

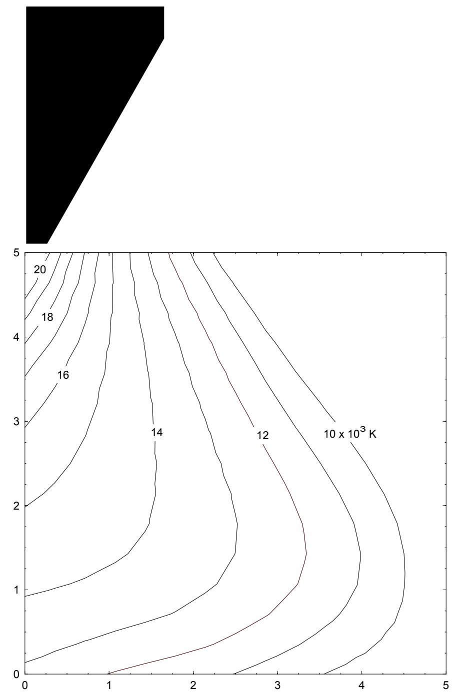

Figure 5. Temperature map for pure Ar at 100 A using 696.54-nm line.

The same procedure was performed using steel anodes in order to investigate differences in the anode region due to the formation of metal vapours. This was carried out for pure Ar at 50 A using the 696.54-nm line (Figure 6). One restriction of this measurement was the limited time of available before anode melting. Since it was not possible to scan the whole arc, an extrapolation from the cooper anode arc case to the mild steel one was assumed. As the maximum of the Fowler-Milne is reached at a high radial intensity profile, this value was taken from the cooper-anode arc case and used in the mild-steel one. This assumption was verified in Vilarinho (2002). Since the ratio tends to one, the assumption is correct, because it is expected that the anode material does not influence the arc structure beyond a certain height (Gleizes et al., 1997).

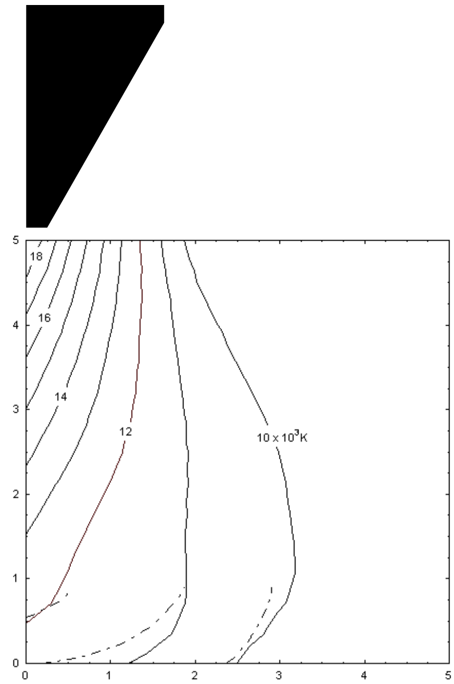

Figure 6. Comparison between cooper anode (solid lines) and mild steel anode (dashed-dotted lines) for Ar at 50 A using 696.54-nm line.

3.2. Langmuir probes

After the characteristic curves were obtained, Equation 2 (Gick et al., 1973) was employed to calculate the temperature maps using the ion saturation current. The maps are shown in Figure 7 for 50-A, Figure 8 for 100-A and Figure 9 for 200-A argon arcs.

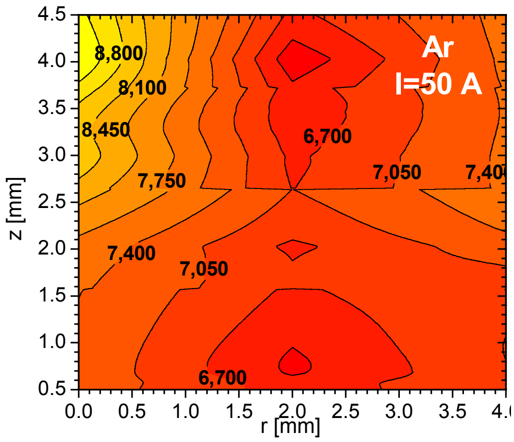

Figure 7. Temperature map for 50-A argon arc.

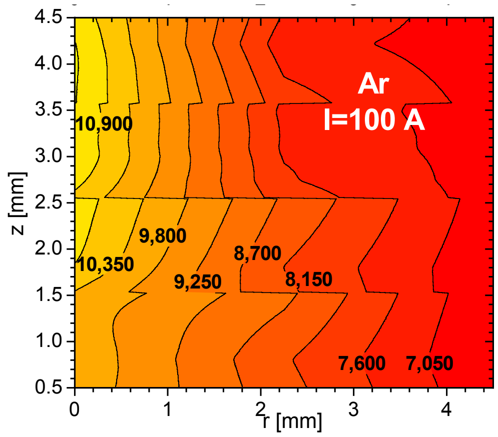

Figure 8. Temperature map for 100-A argon arc.

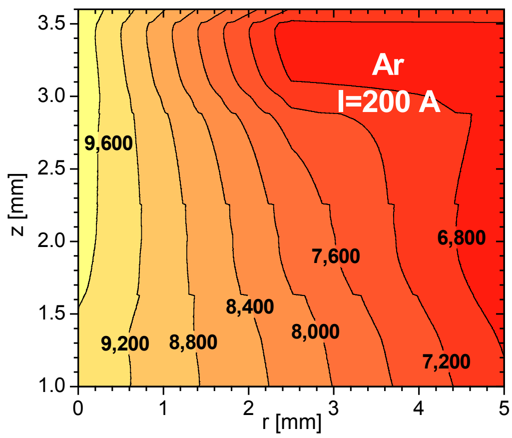

Figure 9. Temperature map for 200-A argon arc.

3.3. Comparison

It is possible to compare the different temperatures obtained using the techniques presented here. Figure 10 brings the comparison among the maximum arc temperatures at different currents and arc lengths (L_a). As can be seen, the temperatures measured by the spectroscopy were the higher than the probe temperatures ones.

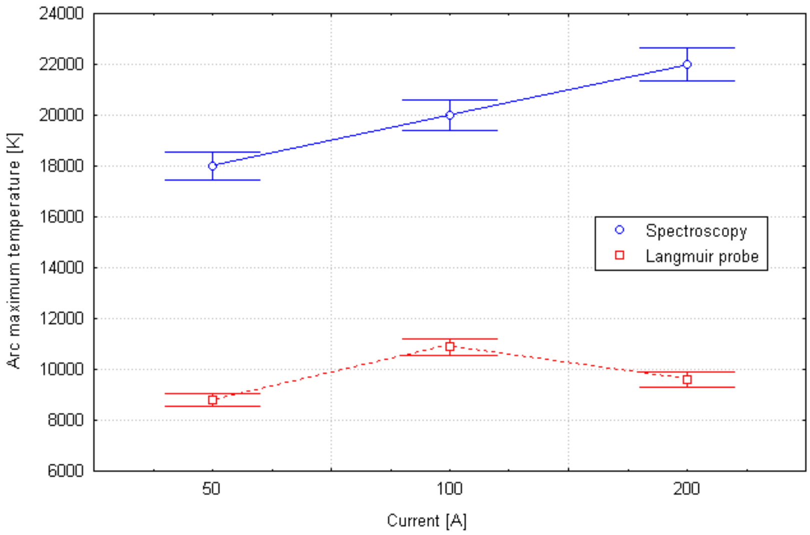

Figure 10. Comparison of the different maximum temperatures obtained for Ar arcs using the presented techniques.

The lower probe temperatures compared to the spectroscopic ones (~45-70%) can be explained by different mechanisms, all of them involving probe disturbance of the arc:

- Heat transfer between the probe surface and the plasma;
- Charge depletion by fluid convection;
- Charge depletion by ion-electron recombination;
- Ion energy loss;
- Temperature obtained is an ion temperature rather than an electron temperature.

A semi-analytical analysis of the current-temperature relationships, which is non monotonic in the temperature range of interests and a comparison with a normalized collisional recombination coefficient, make it possible to conclude that recombination seems the most important mechanisms for the 'low' temperatures obtained by probes (Fanara, 2003). The ions approaching the probes in ion saturation conditions are thus reduced in numbers during the travel (within the probe 'perturbing region') from the bulk of the plasma to the sheath outer surface, thus causing a lowering of the temperature.

Arguments towards the exclusion of the other mechanisms are based on the consideration of the low probe to arc flow velocity ratio (fluid convection), on ion-neutral cross sections (ion energy loss), and on the assumption that departure from LTE (if any) is weak (thus the temperature is an electron temperature) – Fanara (2003).

One further comparison can be traced using the numerical results presented by Zhang (2002). Zhang (2002) simulated the probe in a TIG arc at 200 A and pure argon. Her results present a wide region where probe perturbs the arc (~ 3 probe diameters). Also, Fanara & Vilarinho (2003) proposed an experimental technique based on spectroscopic and high-speed filming for the measurement of the probe boundary layer (or 'perturbing region' if free-stream conditions cannot be guaranteed).

4. Conclusions

It is possible to conclude that:

- The developed procedure for arc mapping temperature using the optical emission spectroscopy was capable to provide the temperature distribution for welding arcs over a wide range of currents;
- The arc maximum temperature is proportional to its current; the bigger the current the bigger the temperature;
- The obtained temperature maps agree with both experimental and numerical data for pure argon arcs obtained in literature;
- The maximum temperature values predicted by the Langmuir probe technique were lower than the ones predicted by the emission spectroscopy with the order of 45 % to 70%.
- More theoretical efforts are needed towards the understanding of high-pressure flowing plasma regimes, in order to overcome the many difficulties in the interpretation of the results obtained by the Langmuir probe technique;

A more detailed analysis of the radial and axial temperature distributions obtained from the Langmuir probe method is under way and will be the subject of a forthcoming paper.

5. Acknowledgement

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