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TEMPERATURE PROFILES IN ARGON ARCS BY OPTICAL EMISSION SPECTROSCOPY

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A fully-automated emission spectroscopic set-up has been employed to measure temperature profiles in free-burning argon arcs (1 atm, 13 mm electrode gap) by absolute line intensity of argon I lines at 6965, 7147 and 7635 Å, under the assumption of LTE. The following salient results were obtained: (a) the peak temperature, 4 mm below the cathode tip, varied from 10100 to 11050 K when arc current was varied from 75 to 300 A; (b) at 100, 150, 250 and 300 A, peak temperatures of 10865, 11113, 11293 and 11750 K were calculated, respectively, at increasing distances of 1 to 4 mm below the cathode; and (c) isotherms obtained from simultaneous/consecutive measurements of 6965, 7635 and 7147 Å lines at 200 A, yielded peak temperatures of 11658, 11157 and 11368 K, respectively, thereby suggesting that the self-absorption of the 7635 Å line has only a small effect on the extracted temperature profiles.

Key words: Temperature profiles, Emission spectroscopy, Argon arcs.

Introduction

Thermal plasmas, such as argon welding arcs, can be well understood by analyzing their electrical and thermodynamic properties. Of all these properties, plasma temperatures are the most important because their computation also leads to an understanding of other properties as well. A knowledge of temperature profiles in argon welding arcs, for example, helps in developing a better understanding of the heat transfer process and may well mean an improvement of the welding process itself.

Since arc temperatures may be as high as 12000 K, temperature probes are generally not employed in thermal plasmas. Of all the optical diagnostic techniques (active or passive) employed for temperature analysis, passive optical emission spectroscopy is still the most popular.

This paper employs emission spectroscopy to investigate the temperature variations, in free-burning argon arcs, as a function of arc current.

In emission spectroscopy, the most popular technique employed for obtaining radial temperature profiles involves the computation of radial line-emission-coefficient profiles by using the absolute line intensity method, under the assumption of LTE, Abel inversion procedure is taken for obtaining the line emission coefficients and temperature profiles.

Line emission coefficients [1,2] are related to temperature by the following expression:

$$\varepsilon_L = \frac{1}{4\pi} h\nu A_t^s n_s = \frac{1}{4\pi} h\nu A_t^s . n_o \frac{g_s}{Z_o} \exp(-E_s/kT) \quad \text{.........(1)}$$

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where A_t^s is the probability of transition (sec^{-1}) from level s to t, n_s the number density of level s, nO is the atomic number density (m^{-3}), g_s is the degeneracy, Z_o is the partition function of atoms, E_s is the upper energy level (joules) and T is the temperature (°K). Equation (1) can be solved in conjunction with the following three equations:

(i) Saha Equation:

$$S_T = \frac{n_e n_i}{n_o} = 2 \frac{Z_i}{Z_o} \left[\frac{2\pi m_e kT}{h^2}\right]^{3/2} . \exp\left[-\frac{\chi_o - \Delta\chi}{kT}\right] \quad \text{...........(2)}$$

where n_e is the electron number density (m^{-3}), n_i is the ion number density (m^{-3}), Z_i is the partition function of ions, m_e is the electron mass (kg), χ_o is the ionization potential (joules), and Δx is the lowering of ionization potential (joules).

(ii) Equation of State:

$$P = (n_e + n_i + n_o)\, kT \quad \text{...(3)}$$

where P is the pressure (pascal).and

(iii) *Charge equilibrium for a singly ionized plasma:*

$$n_e = n_i \quad \text{...(4)}$$

The lowering of ionization potential $\Delta\chi$ in Eq. (2) for Ar is given by:

$$\Delta\chi = (4.6464 \times 10^{-30}) \sqrt{\frac{n_e}{T}}$$

The partition function Z_o for Ar atoms is given by:

$$Z_o(T) = \sum_i g_i . \exp\left(-\frac{E_i}{kT}\right)$$

where i represents the energy level. The partition function for Ar atoms is approximately 1 for temperatures up to 10,000°K. The partition function Z_I for Ar ions is given by the following relation:

$$Z_I(T) = 1 + 61 \exp\left(\frac{-2{,}060}{T}\right) + 2 \exp\left(\frac{-156{,}560}{T}\right) = 8 \exp\left(\frac{-190{,}550}{T}\right) \quad \text{.......(7)}$$

For temperatures less than 15,000°K, only the first two terms are sufficient.

Equations 1-7 were used to create a data bank of emission coefficients vs temperatures. These data have been utilized for all work employing absolute line intensity method to calculate temperature profiles in this experiment.

Experimental

Apparatus. A fully automated emission spectroscopic set-up (Fig. 1), particularly suitable for steady state discharges, has been employed for this experiment. The side-on intensity of a spectral line, its neighbouring continuum and the intensity distribution of a spectral band (emanating from molecular spectra or atomic line shape) of approximately 110 Å are recorded simultaneously. A radial scan of the discharge, monitoring above data at 50 spatial points, is completed in 4 sec, a raster scan of the arc, comprising 10 such radial scans, can be completed in 40 sec. The entire data acquisition process, including XY electro-optical scanning of the discharge, scanning of the spectrograph's spectral range, wavelength selection on the monochromator and the photo-detectors' exposure time settings, is pre-programmable. Plasma sources can be scanned both radially and axially, regardless of the orientation of their axis of symmetry; additionally, the plasma can be scanned with a minimum step size of 7.3 μm and a repeatability of 0.01%. The set-up is usable for a wide variety of plasma studies.

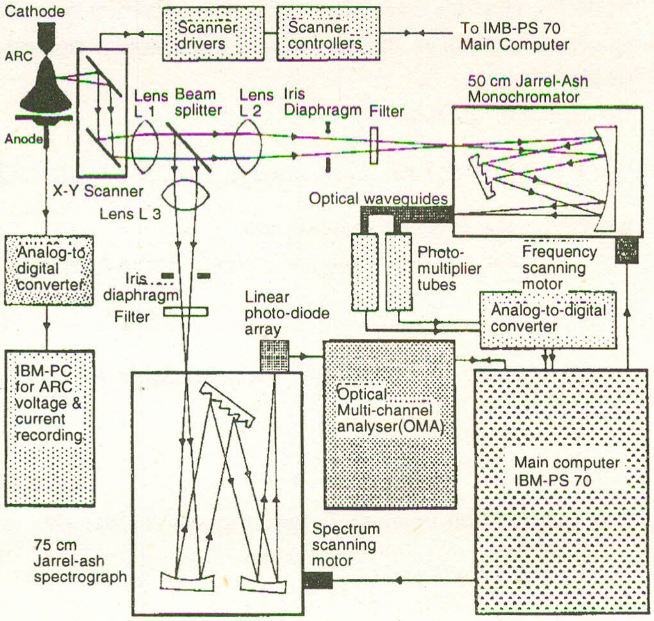

Fig. 1. Emission spectroscopic set up.

Fast data acquisition improves the accuracy of measurements by reducing the error caused by temperature fluctuations due to erosion of cathode tip and displacements of electrode attachments. Simultaneous measurement of line and corresponding continuum intensities is helpful in reducing errors caused by measurement of line and neighbouring continuum at two different times. The ability to simultaneously record a spectral line, its neighbouring continuum and a spectral band of 110Å either of a molecular spectra or of an atomic line shape, significantly enhances the researcher's ability to study multi-component plasmas and deviations from LTE.

Results and Discussion

For this investigations, argon arcs at 1 atmosphere and 13 mm electrode gap were studied. The cathode material was 1% thoriated tungsten and pointed to 60° angle while the anode material was a flat copper plate. A radial step size of 0.182913 mm and an axial step size of 0.995866 mm were used during optical scanning of the plasma. The optical data was integrated for a 15 ms exposure time and photo-diode detector temperature was kept at 0°C. The spectrograph and monochromator entrance slit widths were set at 10 and 60 μm respectively. The two PMTs, for line and continuum, were operated at 0.977 and 0.935 KV respectively.

Temperature vs arc current. In the first part of this study, temperature in the arc, 4 mm below the cathode tip, was measured as a function of arc current. Radial scans were performed in the range of 75 to 300 A with a current step of 25 A. In order to measure the arc temperature, radial scans comprising 100 spatial points with a step size of 0.182913 mm were used. The 7635 Å Ar I line and its neighbouring continuum were monitored on the monochromator and radial temperature profiles were obtained using the 'absolute line

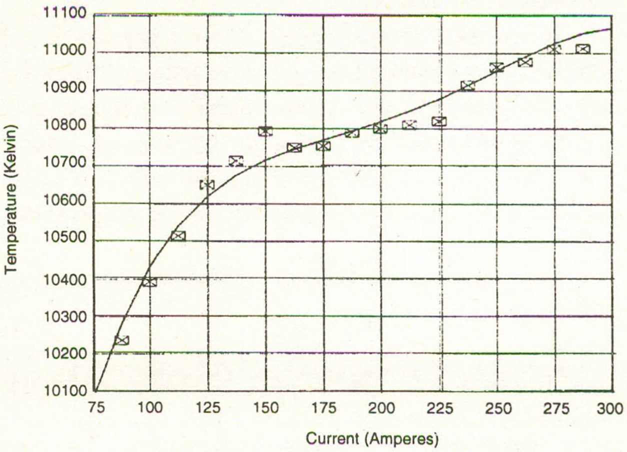

Fig. 2. Temperature vs current (1 atm. Ar arc with 13 mm electrode gap).

intensity method described above; the resulting peak temperatures are plotted in Fig. 2. The graphed data is curve fitted with a fifth order polynomial to yield the following expression:

$$T = a.I^4 + b.I^3 + c.I^2 + d.I + e$$

where T is the peak temperature (K), I the current (A), and the coefficients have the following values:

$a = 1.79 \times 10^{-6}$, $b = 1.539 \times 10^{-3}$, $c = -0.4828$, $d = 67.83$, $e = -7117.3$.

The curve fitted temperature profile is also shown in Fig. 2. The result shows that the arc temperature, at this axial location, varies from 10,100 to 11,050 °K when current varies from 75 to 300 A.

Glickstein [3] carried out a similar study of a GTA welding arc with 2 mm electrode gap spacing; the electrodes were made of 2% thoriated tungsten and pointed to 28° angle. He measured peak temperatures 1 mm below the cathode for current range between 50 to 200 A. In his experimental arrangement, he used manually driven mirrors for scanning of the arc and a photographic plate as the detector. He observed a temperature variation from 8,500 to 11,500 °K with current variation from 50 to 200 A. The only other measurement referred by Glickstein in this current range for an argon arc are those of Simonik [4] who employed carbon electrodes instead of tungsten. Simonik found a temperature variation of 9,400 to 10,300 °K over the current range of 50 to 200 A. In general, comparison of this paper's findings with the rest of the literature is difficult because the electrode material and electrode shape in welding arcs influence the arc configuration and its temperature distribution.

Isothermal maps at various arc currents. In the second part of this study, raster scans of the 7635 and 6965 Å Ar I lines were performed at various arc currents. Each raster scan comprised 16 radial scans and was completed in 2.13 min; each radial scan comprised 100 spatial points along the arc radius. The 7635 Å line was monitored on the monochromator while the 6965 Å line on the spectrograph. Raster scans were executed at 100, 150, 250 and 300 A. In all the above cases, the 'absolute line intensity' method was used to obtain the radial temperature profiles. These profiles were, in turn, used to compute the desired isotherms. Fig. 3 shows the resulting isotherm map for the 7635 Å line at 100 A arc current; the peak temperature (10,865 °K) in the arc occurs 1 mm below the cathode tip. Figure 4 shows the isotherm map for the 7635 Å line at 150 A arc current; the peak temperature (11,113 K) in the arc occurs 1 mm below the cathode tip. Fig. 5 shows the isotherm map for the 7635 Å line at 250 A arc current; the peak temperature (11,293 °K) occurs 2 mm below the cathode. Lastly, Fig. 6 shows the isotherm map for the 6965 A line at 300 Å arc current; the peak temperature (11,750 °K) in the arc occurs 4 mm below the cathode tip.

Gick [5] used an electrostatic probe to measure the temperature profile in a 100 A TIG arc with 8 mm electrode gap spacing; the cathode was 1.5 mm in diameter and pointed at the tip, while the anode was a flat mild steel plate. His isotherm plots at 100 A show a peak temperature of 11,000 °K about 1.5 mm below the cathode. Seeger *et al.* [6] measured temperature profiles in a similar TIG arc with 12 mm elec-

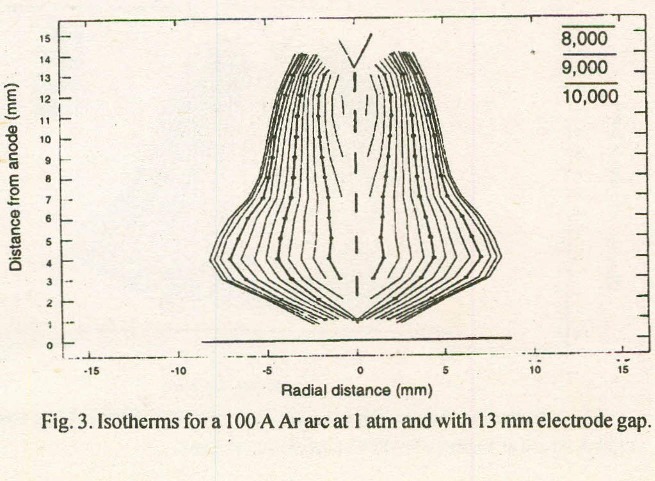

Fig. 3. Isotherms for a 100 A Ar arc at 1 atm and with 13 mm electrode gap.

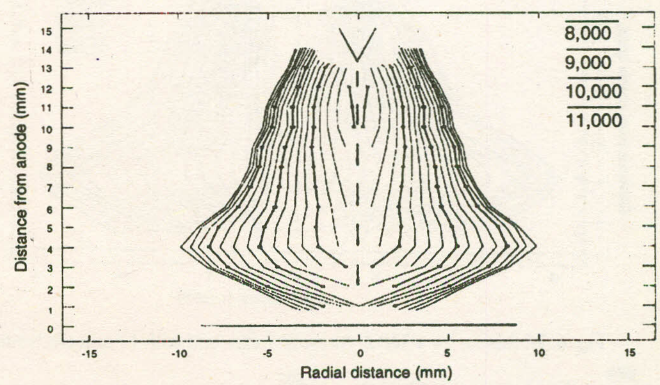

Fig. 4. Isotherms for a 150 A Ar arc at 1 atm and with 13 mm electrode gap.

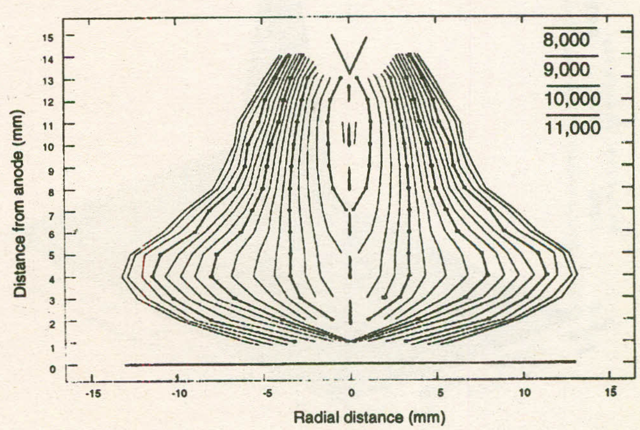

Fig. 5. Isotherms for a 250 A Ar arc at 1 atm and with 13 mm electrode gap.

trode gap spacing; the experimental arrangement included a manual scanning system and a single monochromator. They noted a peak temperature of 12,500 °K, about 1 mm below the cathode. In comparison with above findings the results in the existing investigation are expected to be accurate due to the simultaneous measurement of spectral lines and their neighbouring continuum and also due to faster data acquisition.

This experiment demonstrates that the plasma increases in radius, particularly close to the anode, with increase in arc current; additionally, the location of peak temperatures along the axis shifts away from the cathode. These observations are supported by Glickstein [3] and Olsen [7].

Comparison of temperatures from various Ar I lines. Because a spectral line, its neighbouring continuum and a complete band of approximately 110 Å can be recorded simultaneously, the employed emission spectroscopic set-up is also suitable for a comparison of temperature profiles obtained from lines which have been simultaneously measured. For example, temperature profiles derived from a self-absorbing line (measured with the monochromator) may be compared with those derived from an absorption-free line (measured with the OMA).

This part of the experiment investigated the possibility of using the Ar I 7635 Å and 7147 Å lines for diagnostic studies. Both these lines have the following favourable characteristics: (1) they are strong lines (2) there are no other lines in their vicinity, so the neighbouring continuum is well defined and (3) they are located in a convenient part (near-IR) of the electromagnetic spectrum. Several researchers have, however, pointed out that at least the 7635 Å line is self-absorbing [8-11]. On the other hand, the 6965 Å line does not suffer from self-absorption [11] and is often used for diagnostic studies. A comparison of the temperature profiles derived from lines 6965 and 7635Å, can give a good indication of the error in temperature due to self-absorption of the 7635 Å line. For such a comparison to be correct, it is, however, necessary to measure both lines simultaneously; therefore, a raster scan of 7635 Å line and its neighbouring continuum was done with monochromator and a raster scan of Ar I 6965 Å line was simultaneously done with the spectrograph. Immediately afterwards the Ar I 7147 Å line was recorded with the spectrograph. A radial scan (4 mm above

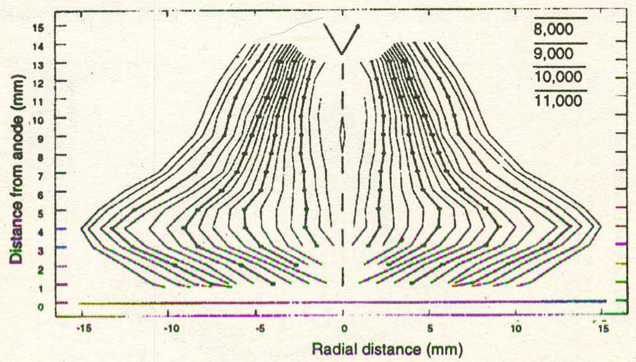

Fig. 6. Isotherms for a 300 A Ar arc at 1 atm. and with 13 mm electrode gap.

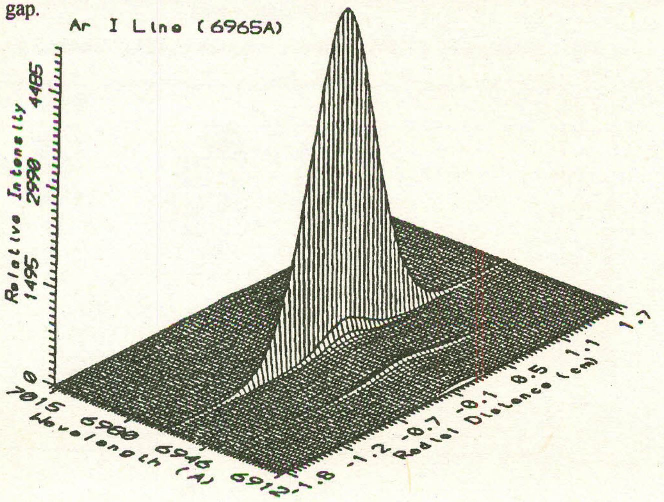

Fig. 7. Radial scan of 6965 Å line recorded 4 mm above the anode (Ar arc at 1 atm, 200 A and 13 mm electrode gap).

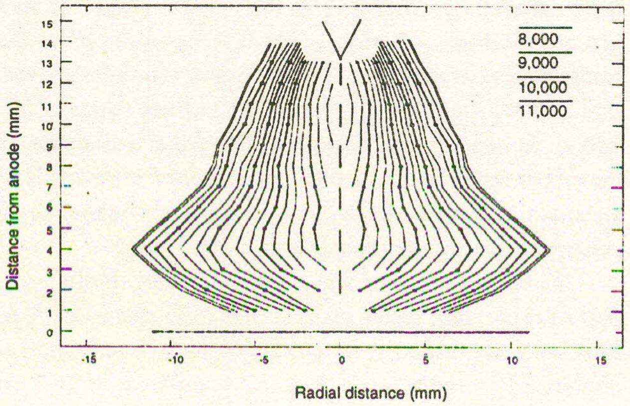

Fig. 8. Isotherms obtained from the absolute intensity of 6965 Å Ar I line (200 A Ar arc at 1 atm and with 13 mm electrode gap).

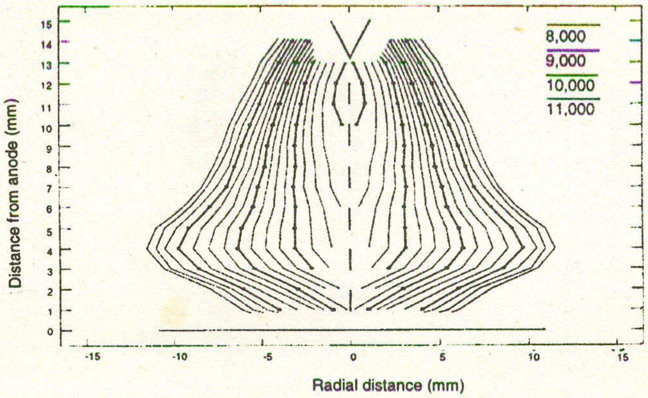

Fig. 9. Isotherms obtained from the absolute intensity of 7635 Å Ar I line (200 Å Ar arc at 1 atm and with 13 mm electrode gap).

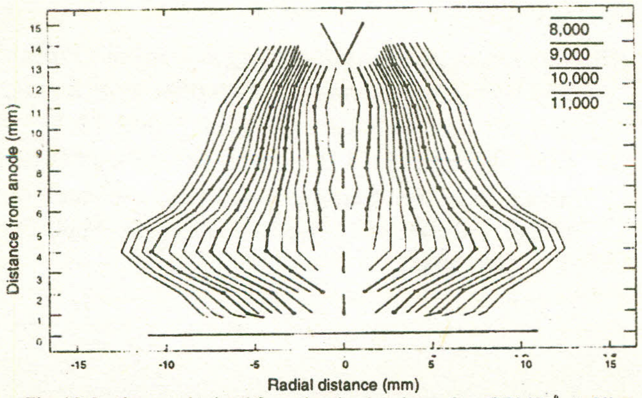

Fig. 10. Isotherms obtained from the absolute intensity of 7147 Å Ar I line (200 A Ar arc at 1 atm and with 13 mm electrode gap).

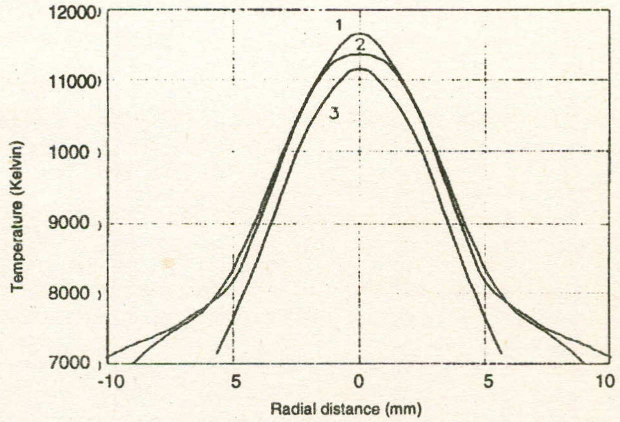

Fig. 11. Peak temperature profiles from Ar I lines: (1) 6965 Å (2) 7147 Å and (3) 7635 Å. Arc parameters are: 1 atm, 200 A and 13 mm electrode gap.

the anode) of the arc at 200 A, monitoring the 6965 Å Ar I line, is shown in Fig. 7. The arc current in this study was 200 A. Each raster scan comprised 16 radial scans; each radial scan and comprised 100 radical points. Isotherm plots, derived by 'absolute line intensity' method, for 6965, 7635 and 7147 Å lines are shown in Figs. 8-10, respectively; the three lines yielded peak temperatures of 11,658, 11,157 and 11,368 °K, respectively. These peak temperature profiles are shown in Fig. 11. The 7635 and 7147 Å lines are seen to yield about 500 and 300 °K lower temperature, respectively, than 6965 Å line.

Bober *et al.* [8] carried out spectroscopic measurements of the 7635 Å Ar I line in an argon plasma generated in a free burning arc; the resulting emission coefficients were corrected for self-absorption. They found that self-absorption had a strong effect on the measured transition probability but little effect on the temperature profile. Olsen [9,10] also pointed out that 7635 Å line has a definite absorption profile which is characteristic of several other strong atomic lines observed at longer wavelengths, but absorption has little effect on resulting temperature profiles. Haddad *et al.* [11] pointed out that 6965 Å line has a maximum absorption coefficient which is only 20% of that for 7635 Å line and therefore 6965 Å line is expected to yield accurate temperature profiles. The findings in existing investigation are in general agreement with the above studies.

Conclusion

Temperature profiles in free-burning argon arcs (1 atm, 13 mm electrode spacing, tungsten cathode tip, flat copper anode) were measured with a fully automated, fast and accurate emission spectroscopic set up. Absolute line intensities of Ar I lines 6965, 7147 and 7635 Å were recorded at arc currents of 100, 150, 200, 250 and 300 A to study: (a) the variation of arc temperatures with increase in arc current and (b) the effect of self-absorption on temperature profiles yielded by 7635 Å Ar I line. The following results were obtained from this study: (a) the peak temperature, at an axial location of 4 mm below the cathode tip, increases from 10,100 to 11,050 °K when current increases from 75 to 300 A (b) in a 100 A arc with 13 mm electrode gap spacing, a peak temperature of 10,865 °K occurs 1 mm below the cathode tip (c) in a 150 A arc, a peak temperature of 11,113 °K occurs 1 mm below the cathode tip (d) in a 250 A arc, a peak temperature of 11,293 °K occurs 2 mm below the cathode tip (e) in a 300 A arc, a peak temperature of 11,750 °K occurs 4 mm below the cathode tip (f) the plasma increases in radius with increase in arc current (g) the location of peak temperatures, in the axial direction, shifts away from the cathode (and towards the anode) with increase in arc current and (h) at 200 A, Ar I lines at 6965, 7635 and 7147 Å yield peak temperatures of 11,658°, 11,157° and 11,368 °K, respectively, thereby suggesting that the self-absorption of 7635 Å line has only a small effect on the extracted temperature profiles.

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