Temperature of thermal plasma jets: A time resolved approach

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Abstract. Boltzmann Plot method is routinely used for temperature measurement of thermal plasma jets emanating from plasma torches. Here, it is implicitly assumed that the plasma jet is ‘steady’ in time. However, most of the experimenters do not take into account the variations due to ripple in the high current DC power supplies used to run plasma torches. If a 3-phase transductor type of power supply is used, then the ripple frequency is 150 Hz and if 3-phase SCR based power supply is used, then the ripple frequency is 300 Hz. The electrical power fed to plasma torch varies at ripple frequency. In time scale, it is about 3.3 to 6.7 ms for one cycle of ripple and it is much larger than the arc root movement times which are within 0.2 ms. Fast photography of plasma jets shows that the luminosity of plasma jet also varies exactly like the ripple in the power supply voltage and thus with the power. Intensity of line radiations varies nonlinearly with the instantaneous power fed to the torch and the simple time average of line intensities taken for calculation of temperature is not appropriate. In this paper, these variations and their effect on temperature determination are discussed and a method to get appropriate data is suggested. With a small adaptation discussed here, this method can be used to get temperature profile of plasma jet within a short time.

1. Introduction
The temperature measurement by Boltzmann plot method is now a standardized technique routinely used in thermal plasma jets emanating form DC plasma torches operating at atmospheric pressure. Here LTE is assumed to hold. Argon is the most commonly used plasmagen gas. Therefore, the discussion that follows assumes that Argon is the plasmagen gas. However, the analysis is applicable to any plasmagen gas provided it has emission lines suitable for the analysis discussed here.

1.1. Emission spectroscopy of plasma jets
Emission spectrum of Argon-I in the blue region shows about 12 strong spectral lines for which the transition probabilities are available in the tables. Also, there are many strong spectral lines in red region which can be used for temperature determination of plasma by relative intensity methods. One can choose blue or red region as per the quantum efficiency of the detector. One can record the relative line intensities and use them to determine plasma temperature by either Boltzmann plot method using several spectral lines or by two line ratio method using only two suitable lines [2].
1.2. Abel Inversion
Spectral line intensity recorded by the detector is its space integrated intensity along line of sight or equivalently from a ‘chord’ in the circular cross section of plasma jet as shown in figure 1. One has to record the spectral line intensity along many ‘chords’ and use Abel inversion technique to get a radial profile of spectral line intensity at a cross section of the plasma jet [1]. When radial profile for many spectral lines are available at the same cross section, one can determine radial temperature profile at that cross section using Boltzmann Plot method or two line ratio method. One can get the temperature on the center axis of the jet without Abel inversion [1] if steep temperature gradients exist along the radial direction. In this case, the contribution to the spectral line intensity from the central zone is maximum and thus contribution from other radial zones can be neglected.

![Figure 1: Cross section of plasma jet where intensity measurements are made.](image)

Typical measurement system is shown in figure 2. Here, the monochromator scans the spectral range and the intensity data is recorded along one chord of a circular cross section of plasma jet. The plasma torch is then moved by about fraction of a millimeter along x axis as shown in figure 2. The measurement procedure is repeated to get spectrum at a different chord at the same cross section. Plasma diameters of about 10 mm (typical to plasma spray torches) are covered in 7, 9 or 11 chords separated by equal distances. Once data for these many number of chords at a cross section is available, one can invert it by Abel’s formula to get radial profile of spectral line intensities. Radial temperature profile at this cross section is then determined by Boltzmann plot method or two line ratio method. Here, cylindrical symmetry of plasma jet is assumed. Whole procedure is repeated for another cross section by moving the torch along z axis as shown in figure 2. Thus a 3-D temperature profile of plasma jet is determined.

1.3. Unsteady plasma jets due to ripple in power supply
This method is very much time consuming due to low scanning rate of most of the electromechanically driven monochromators. Also, it assumes that the plasma of the jet coming out of the plasma torch is steady in time. Even if the jet is not steady in time scales of 3.3 ms, the measurement times are very much greater than 3.3 ms and a simple time averaged intensity is recorded due to inherently slow scanning monochromator. However, this simple time average of spectral line intensity is not a true measure of intensity of the spectral line as the spectral line intensity varies nonlinearly with the torch power as can be seen from figure 3. Hence it is inappropriate to use it for calculation of temperature by Boltzmann plot method or two line ratio method. We had observed that the intensity of the plasma jet in the spray torches does fluctuate with the power supply voltage at the rate of ripple frequency [4]. The power supplies used for the DC plasma torches are usually the SCR controlled or of transductor type. The rectified voltage shows a large amount of ripple. The transductor type of power supply shows the voltage ripple at a frequency of 150 Hz. The power fed to the
plasma torch also varies at the same frequency. Extent of fluctuations can be in excess of 60% of the average value especially at low power levels of < 10 kW [3,4]. The plasma jet is thus not in steady state within this time scale i.e. 6.67 ms (or 3.3 ms for SCR based, 6 pulse, 3 phase rectifiers) and the temperature of the plasma jet also varies greatly during this time. This variation is estimated [4] to be about 4300 K to 6500 K on the centerline in typical plasma jet as shown in figure 3.

1.4. Time at which the intensity should be recorded
If one looks at figure 3 carefully, the temperature drops to about 4000 K at a time 2 ms away from the peak. At this temperature, the spectral line intensities are low and the spectroscopic measurements reach their lower limit of validity. Due to this, the simple time average is not

Figure 3: Typical variation of a spectral line intensity with a transductor based power supply voltage (-ve ) and corresponding variation of temperature at the central axis of plasma jet at its nozzle. Plasma torch was used in a non transferred mode at 4.18 kW power. Plasmagen gas was Argon with flow rate of 20 SLM.
appropriate for determination of plasma temperature. When time averaged line intensity data cannot be a true representative of the spectral line intensity, we have to find a time duration within which the line intensity remains relatively steady. When we look at the variation of intensity of a spectral line with power supply voltage (or time), it is clear that the line intensity is relatively steady at the peak. Therefore, intensity measurements made at the peak will represent the real situation in a better manner, refer to figure 6. Temperature determined using this data will provide the peak temperature at the instant when power fed to the torch is at the peak during one cycle of the ripple.

1.5. Proof of unsteadiness of jet by high speed photography

The fact that the plasma jet intensity follows power supply ripple, is supported by imaging the jet by a high speed CCD camera. Figure 4 shows experimental setup to image the plasma jet by a high speed CCD camera. In addition to this, light signal from the jet recorded by a photo multiplier tube (PMT), torch current signal and torch voltage signal are recorded simultaneously by a 4 channel digital storage oscilloscope. It is clearly seen from the PMT signal that the jet luminosity varies exactly as the instantaneous power fed to the torch within a cycle of the ripple.

![Figure 4: System for recording jet images with a high speed high speed CCD camera within a cycle of ripple in the power supply. Photo Multiplier Signal ( -ve voltage signal) also shows similar behavior. Jet images at 3 powers P1, P2, & P3 show similar change in their lengths and diameters.](image)

To summarize: 1. Plasma jet is not steady in time due to ripple in the DC power supply. 2. Variations in luminosity of the plasma jet exactly follow the ripple. 3. It is inappropriate to take time averaged intensities of spectral lines for calculation of plasma temperature. 4. It is time consuming to get a 3-D profile of temperature of the plasma by conventional method.

2. Proposal for a different method

A more appropriate method is suggested here. In this, the spectral line intensity is measured only at the peak power, and a full image of the jet is recorded by a fast CCD camera with a spectral filter. This will provide chord integrated spectral line intensity data for a number of chords at many cross sections in the jet in a single photograph for one wavelength at a time. Different filters can be chosen for different wavelengths. This method will reduce the measurement time, and simplify the experimental procedure. Sequence of steps is as follows: 1. Choose isolated spectral lines from the spectrum of Argon (or other plasmagen gas used) 2. Get narrow band spectral filters to pass only these spectral lines (one at a time) and calibrate them for transmission. 3. Record full image of the jet with a high speed CCD camera through the filters one by one. Schematic of proposed experimental system is shown in Figure 5. Here, the high speed CCD camera will record image during the peak of the optical
signal. The peak of the optical signal follows the peak electrical power with a small time delay. This delay is due to finite velocity of the gas forming the plume. Time duration of the peak when the intensity drops by 10% of the peak value is about 0.3 ms. The camera should be exposed for half of this time i.e. 0.15 ms. Exposure time even up to a fraction of a micro second is available in modern fast CCD or CMOS cameras e.g. model No. 1200hs from M/s. PCO, Germany. 12 or 14 bit dynamic range of the CCD in the camera is preferable. These cameras are usually operated from a PC. Bandwidth of the optical filter is to be chosen to cover a spectral line along with its broadening. In atmospheric pressure thermal plasma jets, most Ar-I spectral lines are broadened to about 0.2 to 0.5 nm in the temperature range of 5000K to 15000K. Therefore, the spectral filter with bandwidth of 0.5 nm is expected to provide correct spectral line intensity. One should choose spectral lines well separated from nearby lines so as to accommodate only one line within the bandwidth of the optical filter. The optical filters should be calibrated for transmission. Usually, transmission coefficient of filters for different wavelengths is not the same. Therefore, their calibration using a standard source is to be done before using them in this experiment. Intensity data recorded using these filters then should be corrected for transmission coefficient of individual filters.

Figure 5: Proposed experimental system for quick recording of full image of the jet through a narrow band filter

Synchronize the camera with the power supply and record the image only at the maximum of the power, as shown in figure 6.
4. Get pixel by pixel record of amount of light collected during the exposure time. A sample picture is shown in figure 7.

5. Data of light collected on each pixel on CCD will serve as the ‘chord integrated intensity’ for each spectral line chosen by the spectral filter. Use the Abel inversion technique to get radial profile of intensity of the spectral line at the chosen cross section of the image. 6. Repeat this procedure for different spectral lines and use this data for determining radial temperature profile by Boltzmann plot method or by two line ratio method at this cross section. 7. Repeat whole procedure given in point number 5 and 6 for another cross section. Least count for choosing a different cross section is width of one pixel on CCD. Thus, if pixel size is 50 x 50 microns and length of image on CCD is 5 mm, then 100 different cross sections can be chosen. 8. Now one has radial temperature profiles at many cross sections in the jet giving a full 3-D temperature profile. Developing good software, one can do
above tasks. This analysis thus will give full 3-D temperature profile of a plasma jet in a very short time. Time for full 3-D temperature is:

\[(\text{Time to record image with 10 different filters for 10 spectral lines} + \text{Image analysis} + \text{Running Abel and Boltzmann plot codes}).\]

Our estimate of time is about a minute.

3. Conclusion

Atmospheric pressure plasma jets emanating from plasma torches are not steady in time due to ripple in the rectifier based power supplies. It is inappropriate to take time averaged measurements of spectral line intensities for temperature determination using relative line intensity methods. This is attributed to the fact that the intensities of spectral lines vary nonlinearly with the power fed to the plasma torch. However, it is feasible to determine 3-D temperature profile of plasma jets in a relatively short time by making innovative use of narrow band spectral filters, fast CCD camera and synchronizing circuitry to record images at the peak power. The 3-D Temperature profile will be more realistic at the instant when the power fed to the torch is at the peak, during a cycle of ripple in the power supply.

4. References

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