Study of jet fluctuations in DC plasma torch using high speed camera

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Abstract

The power supplies used for the plasma torches are usually SCR controlled and have a large ripple factor. This is due to the fact that the currents in the torch are of the order of hundreds of amperes which prohibit effective filtering of the ripple. The voltage and current vary as per the ripple in the power supply and causes plasma jet to fluctuate. To record these fluctuations, the jet coming out from a D.C. plasma torch operating at atmospheric pressure was imaged using high speed camera at the rate of 3000 frame per second. Light emitted from a well defined zone in the plume was collected using an optical fibre and a Photo Multiplier Tube. Current, voltage and PMT signals were recorded simultaneously using a digital storage oscilloscope (DSO). The fast camera recorded the images for 25 ms and the starting pulse from the camera was used to trigger the DSO for recording voltage, current and optical signals. Each image of the plume recorded by the fast camera was correlated with the magnitude of the instantaneous voltage, current and optical signal. It was observed that the luminosity and length of the plume varies as per the product of instantaneous voltage and current i.e. electrical power fed to plasma torch. The experimental runs were taken with different gas flow rates and electrical powers. The images were analyzed using image processing software and constant intensity contours of images were determined. Further analysis of the images can provide a great deal of information about dynamics of the jet.

1. Introduction

Atmospheric pressure thermal plasma jets generated in direct current (dc) arc plasma torches are used in a number of applications like plasma processing, surface modifications, spray coatings, material synthesis, and waste treatment [1]. In plasma spray applications, the stability and the structure of the plasma jet are important characteristics for efficient heating of the particles injected in the plasma jet. The plasma jet is not steady in time due to many reasons listed below. Therefore, analysis must account for such variations in a real situation.

The plasma jet fluctuations in a dc plasma torch arise from ripple in the DC power supply, random arc root movement, combine effect of gas dynamic & electromagnetic forces and cold gas entrainment. Power supply ripple causes a major repetitive variation in plasma jet. This variation is recorded by a fast camera and a Photo Multiplier Tube (PMT). The ripple in the SCR based DC
power supply is due to the fact that currents in the plasma torch are of the order of hundreds of amperes which prohibit effective filtering of the ripple [2]. Typical magnitude of the ripple is of the order of 5 to 10% of rated open circuit voltage (OCV) of the power supply. The OCV is usually much higher than the operating voltage. The ripple is very large compared to the dc value of voltage and current when the plasma torch is operated at low voltages and currents. In this paper, we have shown correlation of jet fluctuation with ripple of the supply. For this purpose, we simultaneously recorded:

1. Sequence of images taken by a high speed CCD camera.
2. The torch current,
3. Torch voltage,
4. Light signal from a small region in the jet (By a PMT),

using a 4 channel digital storage oscilloscope. These data show that the fluctuations in an argon plasma jet are mainly caused by the ripple in the power supply. It was confirmed that when instantaneous power was minimum, luminosity and visible length of the jet was minimum with a small time delay. PMT signal also shows a similar behavior. Luminous length of the jet was maximum when instantaneous power was maximum again with a small time delay during a cycle of the ripple.

2. Experimental set up:
The experimental set-up, shown in figure 1, consists of a dc plasma torch, a high speed CCD camera, a PMT, a digital storage oscilloscope and a PC. Software for the high speed camera, image processing software and digital signal processing software were used for the analysis. Torch parameters and power supply details are given in the table 1 and table 2 respectively. The current signal was taken directly across a shunt at the anode side. Torch voltage signal was derived using a voltage divider circuit. The power supply used for operating plasma torch was a 6 pulse, SCR based, 3 phase rectifier with current feedback control. The ripple frequency for this power supply was 300 Hz. It was observed that at low currents the ripple in voltage and current signal was near to 100 %.

![Figure 1: Schematic of experimental setup](image-url)
Image recording was done by a high speed (~ 3000 Frames per Second) CCD camera. We wanted to study the changes in visible length of jet in one cycle of ripple i.e. in 3.3 ms. Therefore, about 10 frames in 3.3 ms were thought to be appropriate to record these changes faithfully. The camera has a facility to provide a minimum exposure time of 1 µs. Luminosity of the plasma jet was high and we could get a clear image of the plasma jet at 1 µs exposure time. Inter frame time depends on the size of the image on the CCD plate. The image area on CCD plate (300 x 145 pixels) was chosen so that it covered entire plasma jet and still maintained the desired inter frame time of about 0.3 ms.

The arc current was varied from 100 to 200 A. Arc voltage was recorded by a DPM for average reading and by DSO for instantaneous value. Images were recorded by the fast camera for 25 ms so as to cover about 8 ripple cycles. Current, voltage and PMT signal were recorded simultaneously by triggering the oscilloscope with a trigger pulse from the camera. Trigger Signals from camera, PMT O/P, torch voltage & current as seen on the oscilloscope are shown in the figure 2. Sequences of jet images in one cycle of the ripple are shown in figure 3a and 3b for 20 and 30 lpm gas flow rates respectively. Torch current was kept constant at 100A. The corresponding average DC powers were 2.2 kW and 2.65 kW for two gas flow rates of 20 LPM and 40 LPM, respectively. The increase in the electrical power input to the torch for higher gas flow rate is attributed to higher arc voltage required to sustain the arc. The maximum jet length in one cycle of ripple was approximately 20 mm at 20 LPM gas flow rate and at 2.2 kW of power.

Images recorded by the fast camera on CCD were processed by image processing software. The Black and White fast camera CCD has a dynamic range of 10 Bits. The software was used to establish intensity patterns in the images. Constant intensity contours were drawn for each image. As expected, the core region of the plume shows high intensity and the intensity drops at larger radial zones and also at downstream locations. The processed images with false coloring are shown in figure 4.
Figure 2. Signals of trigger from camera, PMT O/P, torch voltage and current at torch power 2.2 kW and gas flow rate of 20 lpm

Figure 3a: Image sequence of plasma jet at torch power 2.2 kW and flow rate 20 lpm in one ripple cycle of about 3 ms
Figure 3b: Image sequence of plasma jet at torch power 2.65kW and flow rate 40 lpm in one ripple cycle about 3 ms

Figure 4: Intensity contours of plasma jet images at torch power 2.2kW and flow rate 20 lpm
3. Results and discussion:

It was found that the luminosity and the length of the jet follow torch power within one cycle of the ripple as shown in figures 3a and 3b. It also matches well with PMT signal. It was observed that luminous length of the jet increases with increased average torch power. At torch powers of 2.2 kW, 3 kW and 4.6 kW at gas flow rate of 20 lpm, the maximum jet lengths are shown in figure 5. The variation of visible length with torch power is as shown in table 3. When power was maximum in one ripple cycle, maximum luminosity of the jet was observed after a small time delay of about 0.3 ms to 0.9 ms as seen clearly in figure 6. The heat produced by the electrical arc in the torch is transferred to the gas and the gas temperature rises. The effect of higher gas temperature is reflected in the luminous length of the jet after some time. We may term this as the ‘thermal inertia’ of the gas and the above mentioned time delays can be attributed to the ‘thermal inertia’ of the plasma forming gas.

![Figure 5: Variation of jet length (Max. in one ripple cycle) for different torch input powers](image)

**Table 3.** Variation of visible jet length (Max. in one ripple cycle) with power

| Current [A] | Voltage [Volts] | Power [KW] | Flow rate [LPM] | Visible jet length [mm] |
|------------|----------------|-----------|-----------------|------------------------|
| 100        | 22             | 2.2 kW    | 20              | 20                     |
| 150        | 22             | 3.3 kW    | 20              | 28                     |
| 200        | 23             | 4.6 kW    | 20              | 32                     |

The gas dynamic force tries to push the arc root down stream, while the electrical forces try to minimize the length of the arc and thus arc voltage. Exact length of the arc is then dependant on the dynamic balance between these forces. Thus, the arc length and arc voltage fluctuate to produce variations in the arc voltage in the frequency range of 4 to 6 kHz riding over the low frequency changes (300 Hz) due to the ripple in the power supply. At higher gas flow rates, the gas dynamic force becomes higher and the amplitude as well as the frequency of variation in the arc voltage is more. To infer about the high frequency components in the voltage signal one can get FFT of the voltage signal and analyse the FFT in the frequency domain. Alternatively, one can get FFT of the optical signal from PMT which follows the voltage (strictly speaking power) signal and analyse it in frequency domain. For this purpose, FFT of optical signals from PMT at two different torch currents (100 and 200 A) and at two different gas flow rates (20 and 40 lpm) were analysed. Figure 7 shows FFT amplitude spectra for above currents and flow rates. It clearly shows more high frequency components at higher gas flow rates for both the currents.
Figure 6: Correlation of image with torch power. About 0.9 ms delay was observed between occurrence maximum power and that of maximum jet length. Similar delay of 0.3 ms was observed for occurrence of minimum power and that of minimum jet length.

Figure 7: FFT of PMT signal output signal at different flow rates and currents
4. Conclusion
In this paper, plasma jet variation in time is correlated with ripple of the power supply. It was observed that the luminous length of the jet increases with increasing torch power during a ripple cycle. The pattern of images taken is similar for two gas flow rates 20 and 40 lpm of Argon. Intensity contours for the images have been drawn which show the jet intensity in various parts of the jet. There is a small but definite time delay between occurrence of the maximum visible jet length and maximum instantaneous power. This delay is due to the ‘thermal inertia’ of the gas. More study in this regard may reveal dynamics of heat transfer from arc to the gas.

References
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