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Electrothermal efficiency, temperature and thermal conductivity of plasma jet in a DC plasma spray torch

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Abstract. A study was made to evaluate the electrothermal efficiency of a DC arc plasma torch and temperature and thermal conductivity of plasma jet in the torch. The torch was operated at power levels from 4 to 20 kW in non-transferred arc mode. The effect of nitrogen in combination with argon as plasma gas on the above properties was investigated. Calculations were made from experimental data. The electrothermal efficiency increased significantly with increase in nitrogen content. The plasma jet temperature and thermal conductivity exhibited a decrease with increase in nitrogen content. The experiment was done at different total gas flow rates. The results are explained on the basis of dissociation energy of nitrogen molecules and plasma jet energy loss to the cathode, anode and the walls of the torch.

Keywords. Plasma spray torch; electrothermal efficiency; temperature and thermal conductivity.

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1. Introduction

Different types of DC plasma torches operating at power levels between 2 to 6000 kW [1] are used for plasma processing of materials. Plasma spray torches are used for coating of materials to enhance wear, thermal and corrosion resistance properties of surfaces of machinery components working in hostile environments. For spray coating of materials, argon is commonly used as plasma forming gas.

The material to be coated will be fed into the plasma jet in the form of powder particles; the particles get melted and projected to impinge on the substrate to form a coating. The thermoelectric efficiency and thermal conductivity are important properties in plasma spray process. Efficiency depends on several parameters such as torch design, plasma gas flow rate, nature of plasma gas, torch input power etc. For a given torch, a diatomic gas like nitrogen is mixed with argon to enhance efficiency of the torch. Nitrogen being a reactive gas, only a small percentage is added to the argon gas.

In the present investigation, the effect of nitrogen content on efficiency, temperature and thermal conductivity of the plasma jet have been studied. The torch was operated at power levels from 4 kW to 20 kW. At each power level and at each total gas flow rate, argon : nitrogen flow rate ratio was changed and the properties studied.

A significant increase in efficiency with increase in nitrogen content was observed. However, the temperature and thermal conductivity of the plasma jet were found to decrease with increase in nitrogen content. The increase in electrothermal efficiency, η, was up to 15%.

While several studies have been made on η [2–7], both theoretical and experimental investigation of the effect of nitrogen over a considerable range of nitrogen content on η, the temperature and thermal conductivity of the plasma jet appear to be very rare in literature. Hence the present investigation was undertaken. Situations with small nitrogen content are commonly encountered in plasma processing applications. The results are explained on the basis of dissociation energy of nitrogen molecules.

2. Basic equations

2.1 *Electrothermal efficiency*

In a DC plasma torch an electric arc is initiated between the tip of the cathode and the water cooled anode (figure 1). The plasma forming gas is introduced either axially or with an additional swirl component to improve arc stability. The plasma is initiated when electrons released from the cathode are accelerated towards the anode. They collide with, excite and ionize the atoms or molecules in the gas. The additional electrons resulting from ionization cause further ionization producing arc plasma. The collisions transfer the kinetic energy of the electrons to other species and raise the temperature of the gas. The arc plasma emanate through the anode as a jet [8].

The electrothermal efficiency of a plasma torch is defined as the percentage of the electric power input to torch, contained in the plasma jet [2].

Efficiency of low power arc heated plasma jets were reported by Jhan [3] who found that η ranged between 40 and 60% for a torch operating with argon and argon + nitrogen mixtures as plasma forming gases. Brossa and Pfender [9] measured the η of a DC plasma torch using an enthalpy probe and reported nearly same values for different arc currents and gas flow rates of argon gas. Pfender and Eckert [10] studied the energy balance in the plasma torch. Houben and Azaat [11] developed energy balance equations based on the conservation of energy and momentum. Kim and Hong [4] measured the electrothermal efficiency of APS (atmospheric plasma spraying) and LPPS (low pressure plasma spraying) systems and showed that η was higher for the LPPS system. Sreekumar *et al* [5] measured

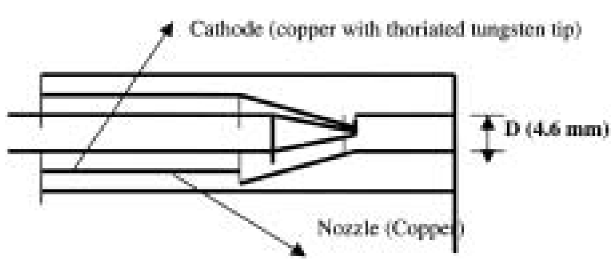

Figure 1. Schematic of a DC plasma spray torch.

electrothermal efficiency using standard calorimetric method; η was in the range of 59–72%. Recently Wood *et al* [6] studied η, *I–V* characteristics, energy balance and electrode phenomena in a low-power MPD (magnetoplasmadynamic) device. Bokhari and Boulos [12] did a two-level factorial analysis with arc current, electrode spacing and gas flow rate as parameters for three different nozzles (nozzles with different lengths and diameters). Theoretically, Ramasamy *et al* [13] measured electrothermal efficiency in a DC plasma spray torch operating with argon at atmospheric pressure with power in the range of 6–20 kW using energy balance equation.

In the present work, efficiency was calculated using the formula

$$\text{Efficiency } (\eta) = \left(\frac{p - Q_{\text{loss}}}{P}\right) \times 100, \tag{1}$$

where P is the input power to the torch and Q_{loss} is the power dissipated through cooling water.

$$Q_{\text{loss}} = 4.18 \times c_{\text{p}} \times v(t_2 - t_1), \tag{2}$$

where 4.18 is the conversion factor for converting cal/s into watts, c_{p} is the specific heat of water (1 cal/cm^3), v is the amount of cooling water supplied (cm^3/s) and t_1 and t_2 are the inlet and outlet water temperatures.

2.2 *Temperature and thermal conductivity of the plasma jet*

The temperature of the plasma jet at the exit of the nozzle was calculated and relationship between efficiency and temperature is assumed to be given by the following polynomial fit:

$$E\eta = m\int_{T}^{T_0} a + bx + cx^2 + dx^3, \tag{3}$$

where E is the input power (kW), m is the mass of the plasma forming gas (argon, argon + nitrogen mixture) (lpm) and a, b, c, d are the coefficients of polynomial fit equation.

Using temperature and specific heat capacity values (from thermal properties of gas tables) third degree polynomial was plotted. T and T_0 values were changed to match the left-hand side of eq. (3). From the values of temperature, the thermal conductivity was estimated from thermal properties tables for pure argon and for pure nitrogen and for the mixture.

3. Methodology and experiment

The torch was operated with input power in the range 6 to 20 kW. The total gas flow rate was fixed at 20, 25 and 30 lpm. Nitrogen was mixed and its content was varied from 1 lpm to 5 lpm such that the ratio of argon : nitrogen volume was changed as *c*-1:1, *c*-2:2, *c*-3:3, *c*-4:4, and *c*-5:5, where *c* is the total gas flow rate. Water flow rates were measured using rotometers and inlet and outlet temperatures were measured using RTD sensors. From Q_{loss} and input power, η was determined.

3.1 *Temperature and thermal conductivity*

From $E\eta$ and third degree polynomial fit equation values, temperature of the plasma jet was determined. Right-hand side of eq. (3), third degree polynomial is equated to the left-hand side term, $E\eta$, at every temperature range. When the equation is balanced, the corresponding temperature is taken as the plasma jet temperature. From the value of T, using the thermal properties tables, the thermal conductivity for pure argon and also for pure nitrogen are taken. For the mixture components, thermal conductivity is determined as follows: for 25 lpm total flow rate and 24 : 1 argon : nitrogen

$$k_{\text{argon mixture}} = k_{\text{argon}} \times 24/25$$

and for nitrogen component

$$k_{\text{nitrogen mixture}} = k_{\text{nitrogen}} \times 1/25$$

for mixture 24 : 1 argon : nitrogen

$$k_{\text{mixture}} = k_{\text{argon mixture}} + k_{\text{nitrogen mixture}}.$$

3.2 *The plasma spray torch*

The cathode was made of copper with thoriated conical shaped tungsten at the tip. The anode was made of copper in the form of a nozzle with diameter 4.6 mm and length 4.5 mm. The electrode gap between the cathode and the anode was 12 mm. The electrodes are water cooled by reservoir and cooling tower.

4. Results and discussion

4.1 *Effect of power*

The electrothermal efficiency as a function of input power and nitrogen content at selected total gas flow rates are illustrated in figures 2–8.

For pure argon as plasma forming gas (figure 2), η decreases with increase in power. For 30 lpm at 4 kW power level, η was 70 indicating that the torch has very high efficiency. At lower flow rates, η is lower. Keeping all other parameters constant, with increase in input power η decreases for all the flow rates [3,9,14]. The decrease is 15% for 30 lpm for an increase of input power from 4 to 10 kW.

Actually η depends on thermal loss from the hot plasma by convection, conduction and radiation. It has been shown that radiation losses are negligible [13] in plasma torches operating at low power levels. The losses due to conduction and convection (heat transfer to electrodes and walls) increase with increase in plasma temperature. With increase in power the arc temperature should increase, since the heat dissipation is proportional to I^2. An increase in temperature in turn increases the heat energy transport to the walls and electrodes which is taken away by the coolant water. Q_{loss} is plotted against input power

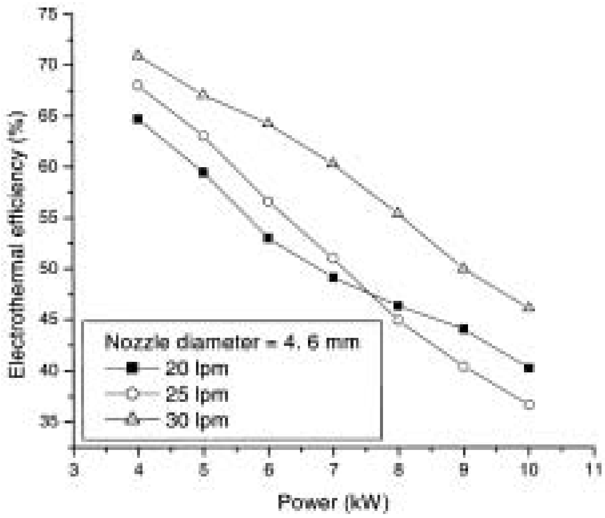

Figure 2. Variation of electrothermal efficiency with increase in input power at various argon gas flow rates.

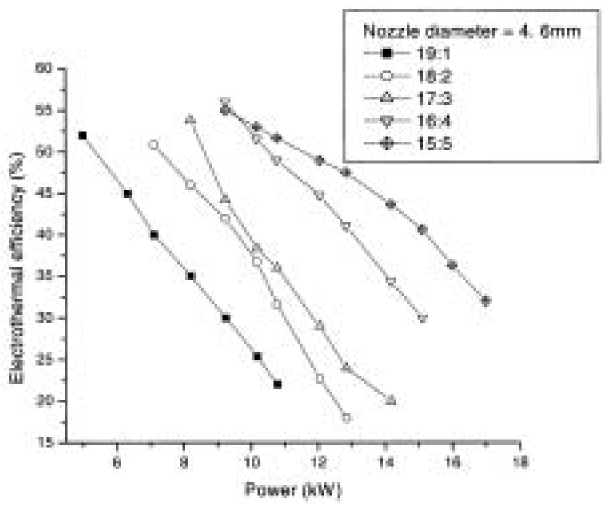

Figure 3. Variation of electrothermal efficiency with increase in input power at various nitrogen mixture gas flow rates.

in figure 9. It is seen that with increase in power, Q_{loss} is increased. Hence the efficiency should decrease with increase in power.

For pure argon at 30 lpm, the decrease in η for the input power in the range from 4 to 10 kW is 15% (figure 2), while the same for 18 : 2 argon : nitrogen content is 17% (figure 3). The nature of variation is the same for different total flow rates and with different nitrogen contents as shown in figures 4 and 5. Also it is seen that higher the nitrogen content, higher is the η.

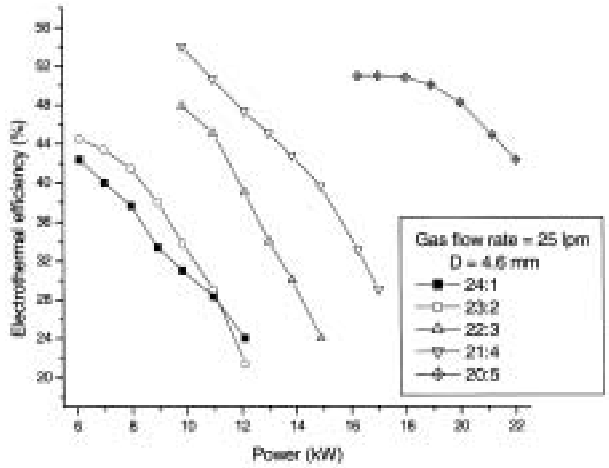

Figure 4. Variation of electrothermal efficiency with increase in input power at a nitrogen mixture gas flow rate of 25 lpm.

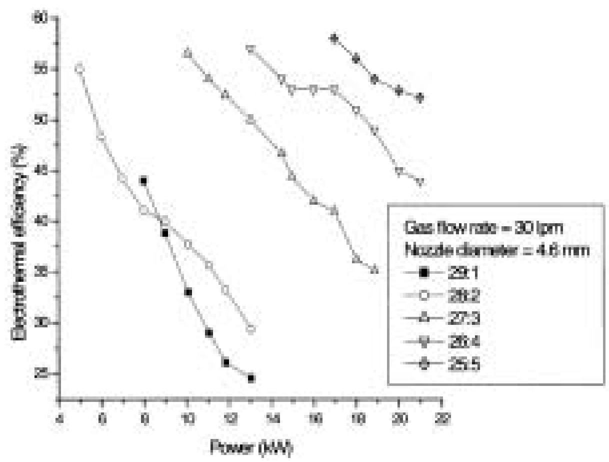

Figure 5. Variation of electrothermal efficiency with increase in input power at a nitrogen mixture gas flow rate of 30 lpm.

At a given input power, when nitrogen is mixed with argon, the plasma jet temperature is lower [13] and hence heat loss is lower. Therefore, higher efficiency is expected and the same has been observed. For example, at 10 kW input power and with argon : nitrogen as 19 : 1, η is 25 and for 15 : 5 argon : nitrogen, η is 53 as shown in figure 3.

With nitrogen content and with increasing power level, the number of atoms available for heat transport from plasma to the electrodes and to the walls is higher than with pure argon since nitrogen molecules dissociate to become atoms. However, since the temperature is lower, the rate of decrease of η for pure argon and that of argon+nitrogen mixture are approximately the same. For example, for 30 lpm η decreases from 70 to 40 for increase in power from 4 to 10 kW and η decreases from 53 to 40 for an increase in power level

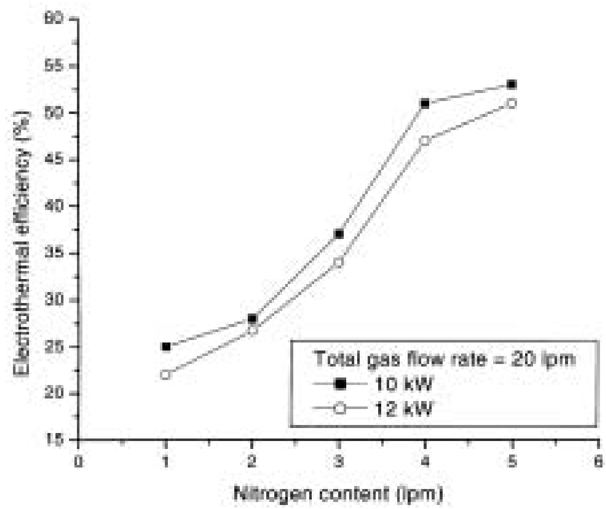

Figure 6. Variation of electrothermal efficiency with increase in nitrogen content at two input power levels. Total gas flow rate is 20 lpm.

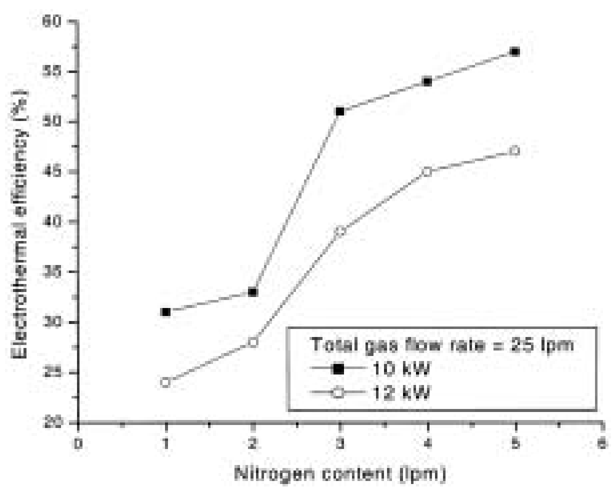

Figure 7. Variation of electrothermal efficiency with increase in nitrogen content at two input power levels. Total gas flow rate is 25 lpm.

from 5 to 11 kW for a total gas flow rate of 20 lpm and argon : nitrogen ratio 19 : 1 (see figure 2).

4.2 *Effect of nitrogen*

Effect of nitrogen on η is interesting (figures 6–8). The general observation is that as nitrogen content increases, initially η increases relatively rapidly and then slowly afterwards. At a higher power level at any nitrogen content, η is lower.

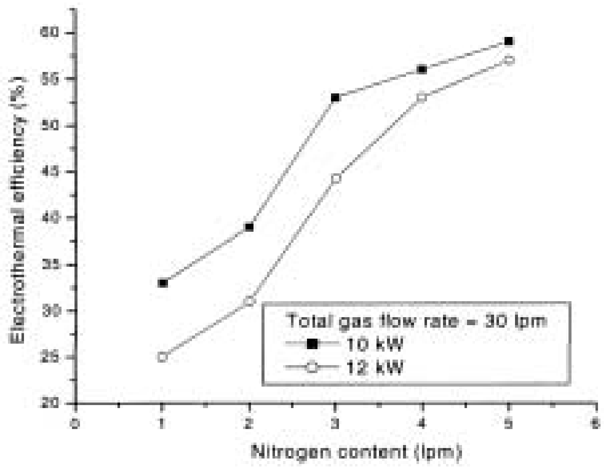

Figure 8. Variation of electrothermal efficiency with increase in nitrogen content at two input power levels. Total gas flow rate is 30 lpm.

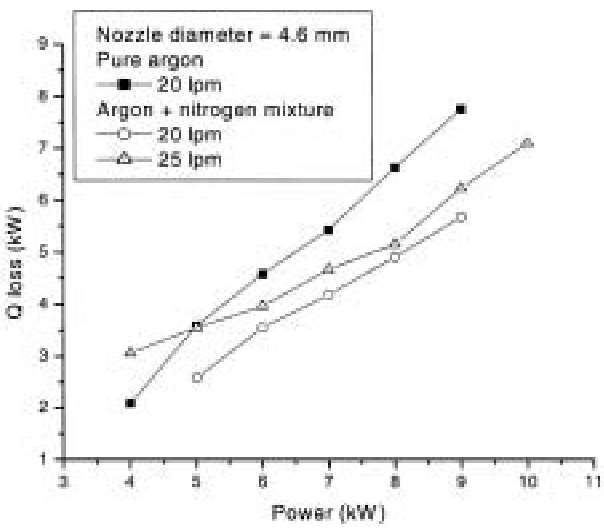

Figure 9. Dependence of *Q* loss in input power.

With addition of nitrogen, not only a part of the energy is utilized to dissociate nitrogen molecules, but also to heat more number of atoms. Therefore, the temperature of plasma is expected to be smaller than with pure argon resulting in reduced losses. For the same input power if the loss is reduced, η will increase [3,9,14–16]. However the gain in η due to dissociation is countered by the increase in number density of atoms. Therefore, the rate of increase with increase in nitrogen content slows down at higher percentage of nitrogen content.

In figure 4 it is seen that the experimental curve for 20 : 5 argon : nitrogen deviates from the rest. It is because as the input power increases the dissociation rate of nitrogen

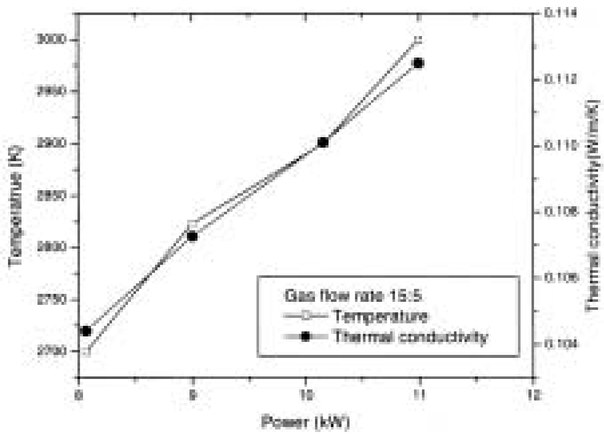

Figure 10. Variation of temperature and thermal conductivity with increase in input power at a total gas flow rate of 20 lpm.

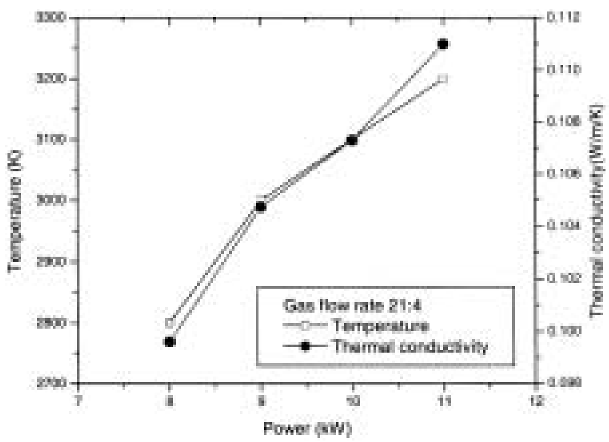

Figure 11. Variation of temperature and thermal conductivity with increase in input power at a total gas flow rate of 25 lpm.

molecules increases resulting in lowering of jet temperature which in turn contributes to an increase in η. For the same nitrogen content for further increase in power, dissociation is faster and the large fraction of atomic nitrogen similar to that of argon atoms helps to increase the jet temperature which lowers η. Therefore, the variation curve for 20 : 5 argon : nitrogen is much different from the others. It may also be seen that there is a small similarity of 20 : 5 curve of figure 4 with 15 : 5 curve of figure 3 where also the nitrogen content is high.

4.3 *Temperature and thermal conductivity*

Increase of temperature and thermal conductivity with increase in power are illustrated in figures 10–12. When there is increase in input power from 8 to 11 kW, the temperature

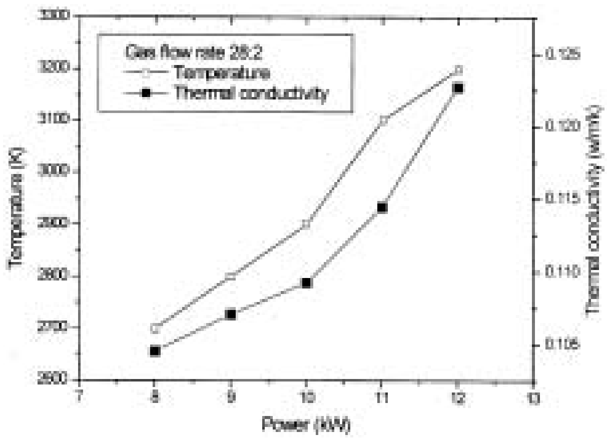

Figure 12. Variation of temperature and thermal conductivity with increase in input power at a total gas flow rate of 30 lpm.

increase is almost linear indicating good proportionality between the two (figures 10 and 11). In addition, thermal conductivity variation almost overlaps (or it would be parallel if one chooses a different scale for plotting) with the temperature curve exhibiting both linearity with input power and correlation with temperature variation. It appears that increase in charge carriers is closely correlated to temperature. However, there is deviation from linearity for both temperature and thermal conductivity for 28 : 2 argon : nitrogen (figure 12). The result is interesting since an increase in temperature takes place, in spite of energy utilization for dissociation of nitrogen molecules and heat loss to the walls and electrodes.

5. Conclusion

Work was done to study the effect of nitrogen content along with argon as plasma gas on electrothermal efficiency of a plasma spray torch and the temperature and thermal conductivity of the plasma jet. A systematic study revealed that increase in nitrogen content increased the efficiency considerably. It was interesting that the temperature of the jet has linear relationship with input power, better than one could account for. Also, thermal conductivity of the jet was found to increase with input power and has good correlation with temperature.

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