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Analytical Study of Electrothermal Efficiency of Plasma Jet in Plasma Spray Torch

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Abstract

We derive simplified analytical expression for electrothermal efficiency from energy balance equation, the electrothermal efficiency of an atmospheric plasma spray torch for Argon gas and Argon – Nitrogen gas mixture were determined by using energy balance equation at different input power levels and different gas flow rates. Using this analytical expression, we interpret the variation of temperature difference between the inlet and outlet of the torch with input power is linear. We concluded the increases the input power of the torch decrease the electrothermal efficiency of the torch. We obtained that more electrothermal efficiency and less temperature difference between the inlet and outlet of the torch when we use small percentage of Nitrogen mixed with argon gas as plasma forming gases than argon gas.

Keywords: Electrothermal efficiency, Plasma torch , Argon and Nitrogen gases.

Introduction

The different types of plasma torches operating at power levels 2 to 6000kW [1] are used for processing materials. Especially, the plasma spray torches are used for coating of the materials to enhance wear, thermal and corrosion properties of the coated materials. The material to be coated by plasma technique, will be fed in to the plasma jet in the form of powder particles, the particles get melted and projected to impinge on the substrate to form plasma coating.

The electrothermal efficiency and thermal conductivity are important properties in the plasma spray coating process. The electrothermal thermal efficiency is the capability of the torch to convert electric energy in to thermal energy. The efficiency depends on several parameters such as torch design, plasma gas flow rate, nature of the plasma gas, torch input power etc. The Atmospheric Plasma Spray (APS) torch uses the argon and mixture of Argon and Nitrogen gases as plasma forming gases.

In the present investigation, the effect of temperature difference between inlet and outlet of the torch on electrothermal efficiency and input power are studied, and prove the linearity between temperature difference between inlet and outlet of the torch and electrothermal efficiency by derived analytical expression from energy balance equation.

In the present study is carried out for different set of parameters of input power and gas flow rate for argon and argon- nitrogen as plasma forming gases to obtain the linear relation between input power and temperature difference between inlet and outlet temperature of the torch and hence thermal efficiency decrease with increase in the power input. The APS torch was operated at power levels at 2 to 35 kW and gas flow rate at 20 lpm, 30 lpm and 40 lpm for Argon gas and flow rate at 1lpm, 3 lpm and 5lpm for Nitrogen gas in the mixture.

Basic equations

Electrothermal efficiency (η):

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

Electrothermal efficiency of torch was calculated by using energy balance equation. The electrothermal efficiency of the non-transferred DC plasma torch was calculated by using the energy balance equation [3]. Efficiency is denoted by η. The equation of η is given below,

Electrothermal efficiency $$\eta = \left(\frac{IP - Q_{loss}}{\mathrm{IP}}\right) \qquad \ldots\ldots\ldots\ldots (1)$$

Where,

IP is the input power to the torch.

Q_{loss} is the summation losses from cathode anode of the torch i.e., power dissipated through cooling water and it is given as:

$$Q_{loss} = 4.18 \times C_p \times V\,(T_2 - T_1)$$

Where,

4.18 is the conversion factor for converting cal/s into watts,

C_p is the specific heat capacity of water (1cal/cm^3),

V is the amount of cooling water flow rate (cm^3/s),

T_1 and T_2 are inlet and outlet temperatures respectively.

3. Basic Technique: Theory

The Electrothermal efficiency η is given in the Eqn **(1) becomes**

Electrothermal efficiency $$\eta = \left(\frac{IP - (4.18 C_P V (T_2 - T_1)}{\mathrm{IP}}\right)$$

Let $\Delta T = T_2 - T_1$

$m = 4.18 C_P V$

Electrothermal efficiency $\eta = \left(\frac{IP - m\Delta T}{\mathrm{IP}} \right)$

$$\eta = \left(1 - \frac{m\Delta T}{\mathrm{IP}} \right)$$

$$\eta = \left(-\frac{m\Delta T}{\mathrm{IP}} + 1 \right)$$

$$\eta = \left(-m \frac{1}{(\mathrm{IP}/\Delta\mathrm{T})} + 1 \right) \quad \ldots\ldots\ldots \quad (2)$$

Equation (2) represents the straight line as

y = -mx +c

Where,

$y = \eta$,

$$x = \frac{1}{\left(IP/_{\Delta T} \right)}$$

Let η_f = IP/ΔT be Efficiency factor

Eqn **(2) becomes**

$$\eta = \left(-m \frac{1}{\eta_c} + 1 \right)$$

Therefore

The Efficiency factor is defined as ratio of input power of the torch to temperature difference between the inlet and outlet temperatures of the torch.

$$\eta_f = \left(\frac{IP}{\Delta T} \right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

From Eqn (3), it is clear that

IP = η_f ΔT

Therefore IP α ΔT ……………… (4)

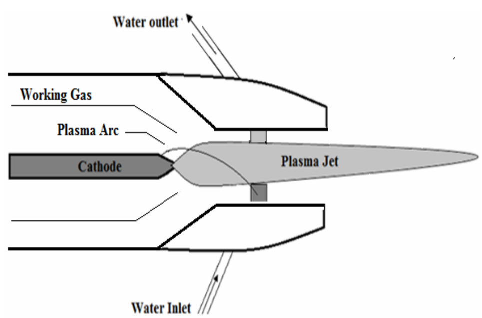
The Eqn (4) represents the variation of temperature difference between the inlet and outlet of the torch with is input power is linear.

Experimental setup:

Atmospheric Plasma Spray torch:

It consists of a conical cathode usually made up of copper with tungsten tip and a nozzle-anode made of copper. It has provision for plasma gas flow, water cooling and powder injection [4]. In dc plasma torch and electric arc is initiated between the tip of the cathode and the water-cooled anode.

The plasma forming gas is introduced either axially or with an additional swirl component. The latter improves arc stability in the vicinity of the cathode and rotates the anode root. The gas flow forces the anodic arc root to stride into the nozzle. The plasma is initiated when electron are accelerated from the cathode to anode. The electron collides and gets ionize the atoms or molecules in the gas. The additional electron fed by the ionization cause further ionization. The collision transfers the kinetic energy of the gas. The gas heated by the arc emanates as plasma jet from the torch orifice.



Results and Discussion

The electrothermal efficiency of the plasma jet in the torch for Argon and Argon-Nitrogen gas mixture at given gas flow rates were determined by using Eqn (1) and results were given in Table 1 and 2.

The variation of electrothermal efficiency with the reciprocal of efficiency factor **(η_f),** variation of electrothermal efficiency with temperature difference (ΔT) between the inlet and outlet of the torch and relation between input power and temperature difference (ΔT) were illustrated in Fig.1a,1b and 1c, and Fig 2a, 2b and 2c

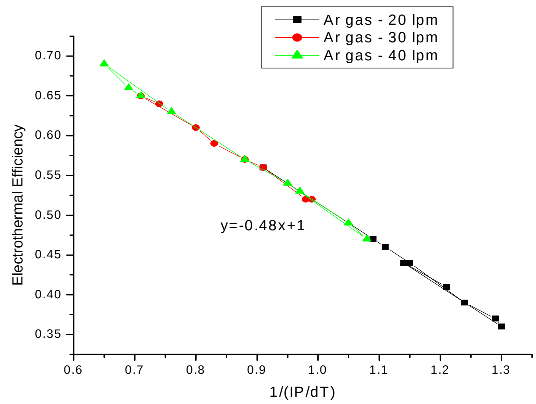


Fig.1a . The variation of η with $1/\eta_f$ for argon gas

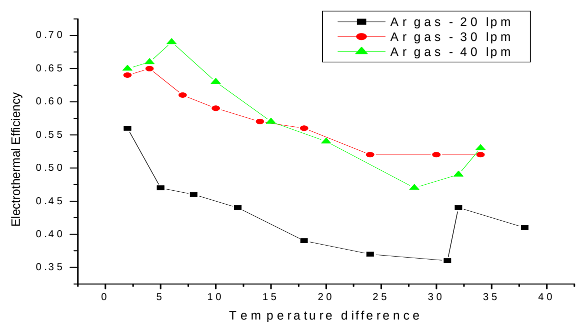


Fig.1b . The variation of η with ΔT for Argon gas

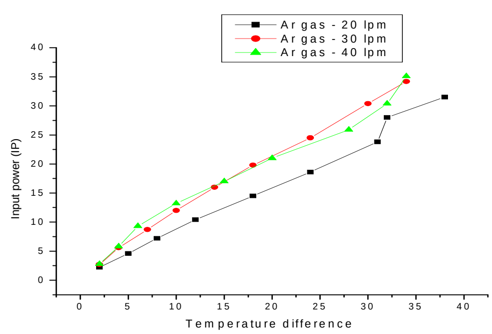


Fig.1c . The relation of IP with ΔT for Argon gas

Table:1 Electrothermal efficiency for Argon gas

S.No	Input power [IP] (KW)	Inlet Temp. T_1 ^oC	outlet Temp. T_2 ^oC	$\Delta T = T_2 - T_1$	Q_{loss}	$1/(IP/\Delta T)$	Electrothermal effieciency (η) %	Electrothermal effieciency (η)
Gas flow rate : 40 lpm								
1	2.8	22	24	2	0.98	0.71	65.17	0.65
2	5.8	22	26	4	1.95	0.69	66.37	0.66
3	9.3	22	28	6	2.93	0.65	68.54	0.69
4	13.2	22	32	10	4.88	0.76	63.06	0.63
5	17	22	37	15	7.32	0.88	56.97	0.57
6	21	22	42	20	9.75	0.95	53.56	0.54
7	25.9	22	50	28	13.65	1.08	47.28	0.47
8	30.4	22	54	32	15.61	1.05	48.67	0.49
9	35.1	22	56	34	16.58	0.97	52.76	0.53
Gas flow rate : 30 lpm								
1	2.7	22	24	2	0.98	0.74	63.88	0.64
2	5.6	22	26	4	1.95	0.71	65.17	0.65
3	8.7	22	29	7	3.41	0.80	60.76	0.61
4	12	22	32	10	4.88	0.83	59.36	0.59
5	16	22	36	14	6.83	0.88	57.33	0.57
6	19.8	22	40	18	8.78	0.91	55.67	0.56
7	24.5	22	46	24	11.70	0.98	52.23	0.52
8	30.4	22	52	30	14.63	0.99	51.88	0.52
9	34.2	22	56	34	16.58	0.99	51.52	0.52
Gas flow rate : 20 lpm								
1	2.2	22	24	2	0.98	0.91	55.67	0.56
2	4.6	22	27	5	2.44	1.09	46.99	0.47
3	7.2	22	30	8	3.90	1.11	45.81	0.46
4	10.4	22	34	12	5.85	1.15	43.73	0.44
5	14.5	22	40	18	8.78	1.24	39.46	0.39
6	18.6	22	46	24	11.70	1.29	37.08	0.37
7	23.8	22	53	31	15.12	1.30	36.48	0.36
8	28	22	54	32	15.61	1.14	44.27	0.44
9	31.5	22	60	38	18.53	1.21	41.17	0.41

Table :1 Electrothermal efficiency for Argon – Nitrogen mixture gases

S.No	Input power [IP] (KW)	Inlet Temp. T_1 °C	outlet Temp. T_2 °C	$\Delta T = T_2 - T_1$	Q_{loss}	$1/(IP/\Delta T)$	Electrothermal effieciency (η) %	Electrothermal effieciency (η)
Gas flow rate ($Ar:N_2$) : 30 lpm : 1lpm								
1	3	22	24	2	0.98	0.67	67.49	0.67
2	6.4	22	27	5	2.44	0.78	61.90	0.62
3	9.9	22	30	8	3.90	0.81	60.59	0.61
4	14	22	33	11	5.36	0.79	61.68	0.62
5	18.5	22	38	16	7.80	0.86	57.82	0.58
6	22.8	22	43	21	10.24	0.92	55.08	0.55
7	28.7	22	49	27	13.17	0.94	54.12	0.54
8	32.8	22	54	32	15.61	0.98	52.42	0.52
Gas flow rate ($Ar:N_2$) : 30 lpm : 3 lpm								
1	3.4	22	24	2	0.98	0.59	71.31	0.71
2	7	22	27	5	2.44	0.71	65.17	0.65
3	10.8	22	30	8	3.90	0.74	63.88	0.64
4	15.2	22	34	12	5.85	0.79	61.50	0.62
5	20	22	38	16	7.80	0.80	60.99	0.61
6	24.6	22	42	20	9.75	0.81	60.35	0.60
7	29.4	22	48	26	12.68	0.88	56.87	0.57
8	36	22	54	32	15.61	0.89	56.65	0.57
Gas flow rate ($Ar:N_2$) : 30 lpm : 5 lpm								
1	4.8	22	24	2	0.98	0.42	79.68	0.80
2	10.8	22	27	5	2.44	0.46	77.42	0.77
3	17.7	22	34	12	5.85	0.68	66.94	0.67
4	24	22	42	20	9.75	0.83	59.36	0.59
5	30	22	50	28	13.65	0.93	54.48	0.54
6	37.8	22	54	32	15.61	0.85	58.72	0.59

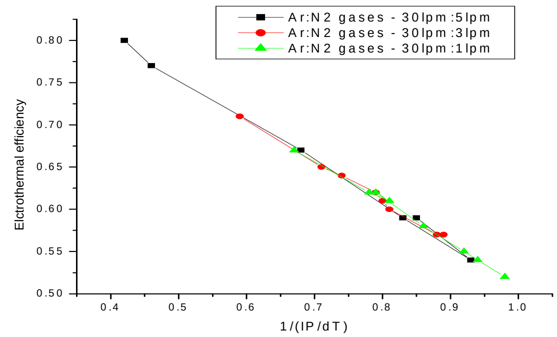


Fig.2a . The variation of η with 1/η_f for Argon –Nitrogen gas mixture

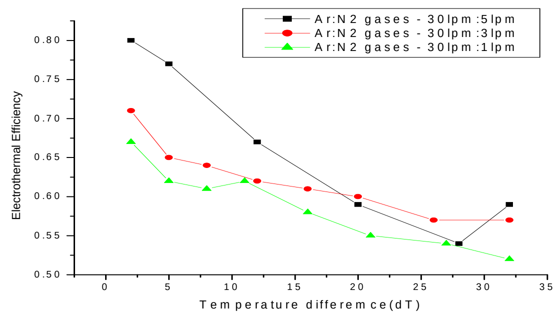


Fig.2b . The variation of η with ΔT for r Argon –Nitrogen gas mixture.

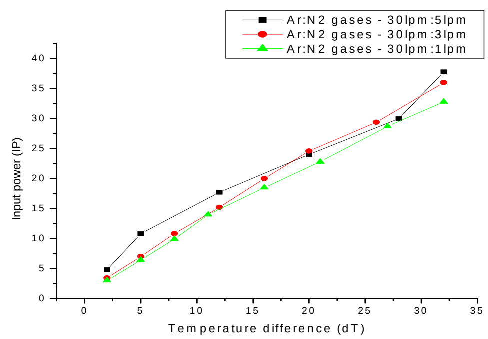


Fig.2c . The relation of IP with ΔT for Argon –Nitrogen gas mixture

We observed that there is inverse linearity between the electrothermal efficiency with the reciprocal of efficiency factor η_f i,e., the electrothermal efficiency decrease with increase in input power incorporated in the efficiency factor and also found the efficiency is increased with increase the gas flow rate. The same observations were made by John [5] observed that there is increase in the thermal efficiency as increase in the gas flow rates and decrease in the thermal efficiency as decrease in the increase in the power. We studied that temperature difference increase will reduce the efficiency of the torch since the losses due to conduction and convection (heat transfer to electrodes and walls) increase with increase in plasma temperature [8] . The similar result is obtained by Bokhari et, al [6], reported that the efficiency of the torch increases as convective and radiative losses decrease by decreasing the size of the anode

We obtained the electrothermal efficiency from 41% to 65% of plasma jet in the APS torch for Argon gas. We obtained the maximum efficiency of the torch operating with small percentage Nitrogen mixed with Argon gas. With addition of nitrogen [8], not only a part of the energy is utilized to dissociate nitrogen molecule, but also to heat more number of atoms. Therefore, the temperature of plasma is expected to be smaller than with pure argon resulting losses. For the same input power if the loss is reduced, the efficiency will increase [7, 8, 9-11] Fauchais et. al [12] obtained the efficiency range between 30 and 45% using argon gas as plasma forming gas while that for nitrogen gas it is above 85%.

When there is increase in input power from 3 to 38 kW, the temperature difference increase is almost linear indicating good proportionality between them, illustrated in Fig.1c and Fig.2c. The similar observations are made by G.Shanmugavelayutham et al [13], that the variation of temperature and thermal conductivity with increase power at gas flow rate of 30 lpm for argon-nitrogen gas mixture.

Conclusions

i) The electrothermal efficiency of an atmospheric plasma spray torch for Argon and Argon - Nitrogen mixture were determined by energy balance equation at input power level from 3 kW to 38 kW and 20 lpm, 25 lpm, 30 lpm and 40 lpm gas flow rates for Ar gases and (30 lpm: 1 lpm), (30 lpm : 3lpm)and (30lpm:5 lpm) flow rates for Ar : N_2 gases .

ii) We derive simplified analytical expression for electrothermal efficiency from energy balance equation, using this expression; we interpret the variation of input powers with temperature difference between the inlet and outlet of the torch is linear

iii) We concluded the increases the input power of the torch decrease the electrothermal efficiency of the torch.

iv) We obtained maximum electrothermal efficiency of the plasma jet in the APS torch when we are using small percentage of nitrogen mixed with argon gas.

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