Parametric study of the electrical to thermal power conversion in an inductively coupled RF plasma torch

J R PAI, N VENKATARAMANI and V K ROHATGI

Plasma Physics Division, Bhabha Atomic Research Centre, Trombay, Bombay 400 085, India

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Abstract. An inductively coupled (IC) radio-frequency (RF) stabilized argon plasma was generated in a quartz tube using a 7 MHz RF generator. The electrical and thermal powers were measured and the efficiency of energy conversion was computed. The results indicate that for a constant power input, there is an optimum argon flow rate for which maximum energy conversion efficiency occurs.

Keywords. IC plasma torch; efficiency; argon; plasma temperature; skin depth; RF plasma.

1. Introduction

The earliest work on radio frequency (RF) coupled plasma, was carried out by Babat (1947). Later Reed (1961) stabilised the atmospheric pressure RF plasma, which has been studied extensively by many authors (Eckert 1974; Yoshida *et al* 1983; Boulos 1985). But due to the fragility of the apparatus and other related technical problems, commercial exploitation of the RF plasma has been very poor. However, in recent years, the subject has drawn the attention of chemists and extractive metallurgists (Mostaghimi *et al* 1984; Boulos 1985).

2. Theory

The high frequency plasma generator is an electrodeless device (figure 1) and has a low plasma velocity (a few metres per second). The plasma is stabilized by a combination of parameters: frequency, tube/coil diameter, gas flow rate and input power. The stability of the torch at a given input power can be improved by tangential feed (Gross *et al* 1968, p. 260). The basic mechanism of plasma flow in a radio frequency induction torch involves electromagnetic heating, swirling, diffusion, chemical reaction/ionization/recombination, radiation and other processes. The exact flow path is complex and modelling is extremely difficult.

In order to establish even a simplified model, it is necessary to postulate the governing equations and the boundary conditions. A number of simplifying

Figure 1. Schematic of the RF torch.

assumptions should be made invoking local thermodynamic equilibrium (LTE), steady-state laminar flows, one-dimensional electric and magnetic fields and two-dimensional flow and temperature profiles. Since the properties, specifically the electrical conductivity, are strongly temperature-dependent, one necessarily has to adopt a numerical procedure for the solution (Zhao & Zhu 1986; Mostaghimi *et al* 1984). This will be specific for each problem.

The alternative approach to the fluid dynamic model is to adapt the theory of induction-heating of solids to RF plasmas (Freeman & Chase 1968). It is based on induced currents and conceptually visualizes a skin depth which is primarily decided by the frequency, the electrical conductivity and the relative permeability (nearly equal to 1). Unlike in solids, the conductivity is highly nonuniform. Certain gross simplifications result in simple relations, which at best can be qualitative.

The system can be considered as a conducting cylindrical plasmoid inside an induction coil. The power per unit length of the plasmoid $P(\text{W/m})$ is given by (Freeman & Chase 1968)

$$P_{(L-1)} = \int_{r=0}^{r=a} 2\pi r E^2 \sigma \, dr,$$

where $E(\text{V/m})$ is the electric field intensity, $\sigma(\text{ohm}^{-1}\text{m}^{-1})$ electrical conductivity at a

point $r(m)$ which is the plasma radius. This expression for a conventional induction heating of a solid leads to

$$P = (8\pi H_0^2 a F) / (\sigma \delta), \quad (\delta = 1/(\pi \mu \sigma f)^{1/2}),$$

where H_0 (A/m) is the intensity of the magnetic field of the solenoid, δ (m) is the skin depth, μ (H/m) is the magnetic permeability, f (Hz) is the frequency and F is the geometric factor which is a function of a/δ .

It has also been established that the specific power has an optimum value when a/δ is about 2 for solids. For plasma this value is closer to 4 (Mitin & Pryodkin 1966) and is the basis for selecting the optimum geometric dimensions and frequency. For $a/\delta < 4$, the plasma is transparent to an electromagnetic field and for $a/\delta > 4$, the effective heat-release volume decreases. Thus the efficiency falls in both the cases.

Of the total energy input into the RF plasma, a part is lost by radiation (Q_R). A considerable amount is conducted away by heat transfer to the walls of the device (Q_W). Only a part of the input power remains with the plasma (Q_g). The present study is undertaken to determine the loss mechanism for various input conditions. This will help in achieving optimum operating conditions.

The total power input into the plasma (Q_e) is thus equal to ($Q_R + Q_W + Q_g$) and the torch efficiency is given by

$$\eta_T = Q_e / Q_p,$$

where Q_p is the electrical power input.

The useful conversion efficiency η_g is given by

$$\eta_g = Q_g / Q_p = \eta_T \bar{Q}_g,$$

where $\bar{Q}_g = (Q_g / Q_e)$ is the fraction of the input power to the plasma which comes out as useful enthalpy of the gas,

$$(\bar{Q}_g + \bar{Q}_R + \bar{Q}_W = 1).$$

3. Experiment

The experimental system consists of an induction plasma torch and diagnostic instruments for measurement of the various parameters (figure 1).

3.1 Description of plasma torch

A 40 kW (nominal rating) RF oscillator is used for plasma heating. The RF oscillator tube is a Philips make TAW 15/35 G having an operating plate voltage of 15 kV. In view of the limited life of the oscillator, the tube has been derated and is currently operated at reduced power levels. The power to the oscillator is varied by varying the plate d.c. voltage; this is accomplished by changing the variac position at the input transformer of the d.c. voltage supply. The RF oscillator is a Colpitt type with frequency fixed at about 7 MHz. The RF plasma torch consists of a quartz tube of 2 mm wall thickness and 50 mm ID. The bottom side of the quartz tube is connected to a brass holder which has a tangential inlet port for gas flow, the gas used is argon for the present set of experiments (figure 1). It is well known that the vortex formed by the tangential flow of gas helps in stabilizing the plasma column (Gross *et al* 1968, p. 260).

The top side of the quartz tube is connected to a flange, followed by a 100 mm long spacer section with square cross-section and lined with ceramic. The flange and the spacer section are water cooled.

3.2 Description of measuring system

3.2a Input power measurement: The electrical power into the RF plasma is measured by noting the no-load and full-load plate current (I_0 , I_p) values and plate voltage (V_p) (Simpson 1960, p. 203). The current is measured in the ground lead of the power supply. The plate d.c. voltage is measured between ground and the output of the power supply. The product $V_p I_p$ gives the power dissipated in the oscillator tube, tank circuit, load and radiation heating losses in adjacent walls. The accuracy of the input power ($Q_p = V_p I_p$) measurement is better than 10%.

3.2b Thermal output measurement of the plasma: The total thermal heat content of the plasma in the set-up is measured by measuring the loss of heat from the plasma due to conduction and radiation and estimating separately the enthalpy of the outgoing gas. The conventional calorimetric method is used to measure conduction heat loss.

The coolant water flow rates to the flange and spacer sections are measured by a flowmeter and the temperature is measured with mercury-in-glass thermometers with least counts of 0.1°C. These thermometers have proved to be more reliable than electronic devices due to RF pick-up. The quartz tube temperature is measured by a thermocouple using analog d.c. meters at three points longitudinally for estimating the convective heat loss. The accuracy of the heat loss measurement is better than 5%.

The measurement of heat loss due to radiation is carried out using a half hemi-cylindrical aluminium water-cooled bolometer. The measured heat flux is corrected for the area coverage and absorptivity of the bolometer surface. The overall accuracy in radiation heat loss is expected to be about 25%.

The outgoing gas temperature at the spacer outlet is measured using a platinum wire probe coupled with an optical pyrometer and/or a tungsten-rhenium (W-Re) thermocouple with a d.c. meter. An analog d.c. ammeter is used to avoid RF interference from RF sources. By properly locating the thermocouple leads near the junction along the isothermal regions, errors due to conduction of heat through leads are eliminated. Radiation effects are included as shown below to estimate the true gas temperature.

For a low wall temperature, the gas temperature T_g and measured thermocouple temperature T are related by (Merch 1971)

$$T_g/T = 1 + (\sigma_s \varepsilon / \alpha) T^3,$$

where σ_s is Stefan's constant, ε the emissivity of the thermocouple and α the heat transfer coefficient from plasma to thermocouple. α is determined from the relationship (Merch 1971)

$$\alpha = \lambda_A \text{Nu} / 1.4d,$$

where λ_A is the thermal conductivity of argon, Nu the Nusselt number and d the wire diameter. The Reynolds number of the hot gas flow is determined from

$$\text{Re} = (Gd)/(A\mu),$$

where G is the argon mass flow rate, A the area of cross-section of the spacer and μ the

viscosity of gas at the temperature T_g . For typical operating conditions, Nusselt number is given by (Merch 1971)

$$\text{Nu} = 0.24 + 0.56 \text{Re}^{0.45}, \quad \text{Re} \leq 44.$$

By an iterative procedure T_g is evaluated. The estimated accuracy in T_g is around 10%. The measured gas temperatures after applying the correction are 1500–3000 K depending on the operating conditions. The enthalpy of the gas can be calculated knowing T_g and mass flow rate of gas.

3.2c Initiation of RF plasma: The inert gas used is argon which is monatomic. By introducing an auxiliary rod type ms wire into the quartz tube from the top of the quartz tube, RF is inductively coupled to the wire which in turn gets heated up and emits electrons. The argon gas surrounding the wire gets heated and due to collisions with the electrons is ionized and because of the vortex formed by the tangential flow of gas a thin cold boundary layer is constantly formed near the quartz wall

Figure 2. RF plasma generator, top flange removed. Quartz tube dia = 50 mm.

Table 1. Operating conditions of the IC plasma torch.

Frequency	: 7 MHz (nominal)
Quartz tube	: dia 50 mm (ID); 55 mm (OD)
Coil	: dia 60 mm (ID); 76 mm (OD)
Pitch of the coil	: 10 mm
Number of turns	: 4
Total length	: 60 mm
$V_p I_p$	: 3.25, 4.5, 6.6, 8.4 and 10 kW
Gas flow rate (argon)	: 40, 50, 60, 70, 80, 90, 100 l/min

constricting the centre, which gets heated up by the RF current. Thus a stable intense argon plasma comes out from the torch (figure 2).

4. Results and analysis of results

The plasma torch was operated for varying conditions of input power and gas flow rates. The operating frequency and the tube/coil diameters were kept constant. Table 1 summarises the experimental conditions. For each operating condition, complete heat balance measurements were taken, viz. the input power (Q_p), the heat flux to wall (Q_w), heat loss by radiation (Q_R) and the enthalpy of the gas at the spacer outlet (Q_g).

Figures 3–7 show the values of $\bar{Q}_g$, $\bar{Q}_w$, $\bar{Q}_R$, η_T and η_g plotted as a function of gas flow rate at five different input power levels. The following general trends can be observed. Q_w is larger at small flow rates and at large flow rates, with about a 10% dip at intermediate flow rates. At large flow rates the convective heat transfer is large leading to high heat flux to the wall. As the flow rate reduces, the heat flux also reduces. However with the reduction of the flow rate and the RF power input remaining the same, the heating of the gas is more intense leading to higher core temperatures, steeper temperature gradients in the boundary layer and increased heat flux. Radiative loss occurs primarily from a central hot core at a high temperature.

Figure 3. Percentage variation of $\bar{Q}_R$, $\bar{Q}_w$, $\bar{Q}_g$ and η_T with argon gas flow for $Q_p = 3.2$ kW.

Figure 4. Percentage variation of $\bar{Q}_R$, $\bar{Q}_w$, $\bar{Q}_g$ and η_T with argon gas flow for $Q_p = 4.5 \text{ kW}$.

Figure 5. Percentage variation of $\bar{Q}_R$, $\bar{Q}_w$, $\bar{Q}_g$ and η_T with argon gas flow for $Q_p = 6.6 \text{ kW}$.

Figure 6. Percentage variation of $\bar{Q}_R$, $\bar{Q}_w$, $\bar{Q}_g$ and η_T with argon gas flow for $Q_p = 8.4 \text{ kW}$.

Figure 7. Percentage variation of $\bar{Q}_R$, $\bar{Q}_W$, $\bar{Q}_g$ and η_T with argon gas flow for $Q_p = 10 \text{ kW}$.

The additional gas flow rate cools the core but at the same time increases the radiating volume. Thus the radiative loss may not follow a consistent pattern, which is also reflected in the experimental results. The enthalpy retained in the gas will follow (in an inverse way) $\bar{Q}_W$ and $\bar{Q}_R$. Thus at intermediate flow rates $\bar{Q}_g$ is higher than at low or high flow rates. This behaviour is consistently observed in all the figures 3–7. $\bar{Q}_g$ max is observed between 50–80 litres per minute depending on input power with the higher flow rate corresponding to higher input power.

The variation of absolute values of $\bar{Q}_g$ and η_g with input power are shown in figures 8–9 respectively. For a given flow rate there is an optimum input power for which $\bar{Q}_g$ is the highest and which corresponds to good coupling, low losses and efficient retention of heat.

With the present experimental data it is possible to deduce approximately the operating conditions of the plasma. Analogous to displacement thickness and enthalpy thickness (Schlichting 1968), one can assume the RF torch to consist of an effective central core. If $G(\text{kg/s})$ is the mass flow rate,

$$G = \int_0^a \rho u 2\pi r \, dr.$$

Let the velocity profile and temperature profile across the tube be defined by (Boulos 1976)

$$u/u_c = 1 - (r/a)^m \quad \text{and} \quad T/T_c = 1 - (r/a)^m,$$

$$T_c \gg T_w,$$

$$T_w/T_c \sim 0,$$

$\rho(\text{kg/m}^3)$ is the density of plasma at the centre line, $u_c(\text{m/s})$ the velocity of plasma at the centre line, a the radius of the quartz tube and T_w the quartz wall temperature. Then

$$G = \rho_c u_c \pi a^2.$$

The enthalpy flow rate can be integrated to yield

$$G_H(\text{in watts}) = \rho_c u_c (\bar{C}_p T_c) \pi a^2 [m/(m+2)],$$

Figure 8. Variation of Q_g with Q_p , argon gas flow rate – 40, 60, 80 and 100 litres per minute (LPM).

Figure 9. Percentage variation of η_g with Q_p . Argon gas flow rate – 40, 60, 80 and 100 litres per minute (LPM).

where $\bar{C}_p$ (J/kg·K) is the mean specific heat of the argon plasma in the temperature range considered. If the hot plasma is assumed to be flowing through a cylinder at temperature T_c , velocity u_c and density ρ_c then,

$$a_c = a[m/(m+2)]^{1/2},$$

and the specific enthalpy at the centre line

$$H_c = [(m+2)/m][G_H/G].$$

Consider typical optimum operating conditions

$$Q_p = 8.438 \text{ kW}; \quad G = 2.38 \times 10^{-3} \text{ kg/s (80 litres per minute);}$$

$$Q_w = 0.783 \text{ kW}; \quad Q_R = 1.007 \text{ kW};$$

$$Q_g = 3.016 \text{ kW}; \quad Q_e = 4.806 \text{ kW}.$$

Using the value of $m=2$ which has been observed under the experimental conditions (Boulos 1976), this yields an H_c of $4.044 \times 10^6 \text{ J/kg}$ or a centre line temperature of approximately 8000 K. (The specific heat is nearly constant $520 \text{ J/kg} \cdot \text{K}$ upto 8000 K which justifies taking $\bar{C}_p$.) The centre line velocity is about 18 m/s. The skin depth can be calculated with a σ_c of $1.64 \times 10^3 \text{ ohm}^{-1}/\text{m}$ (Mitin & Pryodkin 1966)

$$\delta = \frac{1}{(\pi \sigma \mu f)^{1/2}} = 4.7 \text{ mm}.$$

With a_c calculated as 17.7 mm

$$a_c/\delta = 3.8 \quad \text{and} \quad a/\delta = 5.3.$$

This value is about twice the value corresponding to optimum conditions in the case of metals. Similar results for plasmas have been obtained (Mitin & Pryodkin 1966).

Radiation from the plasma can be estimated as radiation from a cylindrical volume of radius a_c and length equal to coil height (60 mm) at a temperature $T_c(8000 \text{ K})$,

$$Q_R(8000) = 0.18 \times 10^8 \text{ w/m}^3 \text{ (Emmons 1967).}$$

The total radiation thus works out to be 1060 watts which compares favourably with the figure 1007 obtained experimentally.

Thus plasma parameters like temperature and velocity correspond to about 8000 K and 18 m/s which are comparable to the results obtained with similar units.

5. Conclusion

The radiofrequency-induced plasma torch has been operated at varying power inputs and gas flow conditions. For a given input power there is an optimum gas flow rate for which maximum enthalpy is obtained in the gas. The plasma at the centre core region has a temperature of 8000 K but cools rapidly to give about 2500–3000 K at the outlet of the spacer.

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