GAS AND PARTICLE VELOCITY MEASUREMENTS IN AN INDUCTION PLASMA

J. Lesinski*, R. Gagné and M.I. Boulos
Department of chemical engineering
University of Sherbrooke, Sherbrooke, Québec, Canada J1K 2R1

ABSTRACT

Laser doppler anemometry was used for the measurements of the plasma and particle velocity profiles in the coil region of an inductively coupled plasma. Results are reported for a 50 mm i.d. induction torch operated at atmospheric pressure with argon as the plasma gas. The oscillator frequency was 3 MHz and the power in the coil was varied between 4.6 and 10.5 kW. The gas velocity measurements were made using a fine carbon powder as a tracer ($d_p \simeq 1$ µm). Measurements were also made with larger silicon particles ($d_p = 33$ µm and $\sigma = 13$ µm) centrally injected in the plasma under different operating conditions.

INTRODUCTION

Over the last few years a special attention has been given to the development of elaborate mathematical models for the calculation of the velocity and temperature fields in an inductively coupled plasma (1-3). While the computed temperature fields were generally consistant with the available literature data, it was not possible, so far, to compare the computed gas and particle velocities against experimental data due to serious difficulties involved in such measurements.

With the rapid development of laser doppler anemometry, a new tool became available that proved to be quite useful for gas and particle velocity measurements even under plasma conditions (4-7). The objective of the present study was therefore to adapt this technique to measurements in an induction plasma and to obtain gas and particle velocity data in the discharge zone under different operating conditions. These are compared with the predictions of the available mathematical models.

EXPERIMENTAL SET-UP

The experimental set-up and details of the induction torch are shown on Figure 1 and 2 respectively. The torch was of a standard design made of a 50 mm i.d., 54 mm o.d. quartz tube. Concentric with this tube was a second smaller quartz tube 38 mm i.d., 42 mm o.d. The sheath gas, Q_3, was introduced in the annular space between these two tubes while the plasma gas Q_2 was introduced in the central tube as shown in Figure 2. The powder carrier gas Q_1, was introduced in the center of the torch using a water-cooled stainless steel probe 3.2 mm i.d., 12.7 mm o.d.

The LDA system was essentially the same as that used earlier for the velocity measurements in a d.c. plasma jet (7). It consisted of a Thermo Systems Inc. (TSI) counter type model 1995 with a 35 mW He/Ne laser. The unit was

* Dr Lesinski is with the Institute of Nuclear Research, 05-400 Swierk/Otwock, Poland.

used in the forward scatter made with a beam spacing of 50 mm. The focal length of the transmitting and receiving lenses were 247 mm. This gave rise to a measuring volume in the form of an ellipsoid of major and minor axis of 4.6 and 0.32 mm respectively. The interference fringe spacing was 3.2 μm. In order to reduce the background noise of the signal caused by plasma radiation, a narrow band-pass interference filter supplied by Omega Optics Inc. was placed immediately after the receiving lens. The filter was centered on a wave-length of 628.3 nm and had a half band width of 0.27 nm. The data acquisition and treatment system was the same as that described in (7). The statistical analysis was performed with a minimum of 1000 independant measurements for each point. Two principal difficulties were anticipated in this study:

a. Interference due to r.f. noise
b. The presence of recirculation patterns which would give rise to low and negative velocity components.

These, however, could be overcome rather easily by the use of frequency shifting which allowed easier separation and filtering of the r.f. noise as well as the determination of the direction of the flow.

RESULTS AND DISCUSSION

Two sets of measurements were made. The first aimed at the determination of the velocity of the plasma. The powder carrier gas and/or the central gas were, therefore, separately seeded with a fine carbon powder elutriated from a fluidized bed. Seeding the sheath gas resulted in the deposition of the fine powder on the walls of the quartz tube and thus reducing visibility. A number of other seeding techniques were tried unsuccessfully such as the addition of a small quantity of acetylene to the plasma gas in order to generate, in situ, a fine soot seed powder. This, however, influenced the coupling caracteristics of the torch and did not insure either a uniform distribution of the seed powder in the flow. In fact, non of the gas seeding techniques used were able to insure the uniformity of the seeding. Seeding was particularly difficult in the recirculation zone where unfortunately, plasma velocity measurements could not be made. This was due to the fact that the gas velocity in these regions was so low that the particle residence time was long enough for it to be completely evaporated. As will be shown later plasma velocity measurements were restricted to the central region of the flow ($-8<r<+8$ mm).

The second set of measurement was carried out with the objectives of measuring the velocity of a fine silicon powder ($\bar{d}_p$ = 33 μm, σ = 13 μm) introduced axialy in the plasma through the powder feeding probe. These measurements were far easier than those of the plasma velocity. However, due to the axial trajectory of the particles, the results obtained were again limited to the central region of the flow.

A summary of the operating conditions used for the plasma and particle velocity measurements is given in Table 1. The levels at which gas and particle velocity profiles were made are shown in Figure 2. The axial velocity profiles obtained for the plasma are shown in Figure 3. It is noted that, close to the point of injection ($0<z<35$ mm) the velocity profiles are rather similar to that for a free jet. Further downstream they become increasingly flat with the mean velocity dropping rather slowly. As expected, the centerline velocity in the torch increases with the increase in the powder gas flow rate, Figure 3-b, but much less so with the increase in the plasma power, Figure 3-c.

Similar velocity profiles were also obtained with the silicon particles under the same operating conditions. There are given in Figure 4. It is noticed that in this case the particle velocity was systematically lower than that of the plasma. The difference is best demonstrated in Figure 5 in which the axial velocity profiles of the plasma and the particles along the centerline of the torch are given. Included also for comparison are the axial velocity profiles for the gas in the torch at ambient conditions (i.e. without ignition). It is noticed that, in contrast to the plasma velocity profile, the cold gas axial velocity drops rapidly with distance along the axis of the torch.

CONCLUSIONS

Measurements were made of the plasma and particle velocity profiles in the coil region of an inductively coupled plasma under different operating conditions. Serious difficulties were encountered in the seeding of the recirculation regions of the flow in which measurements were unfortunately not possible. Work on this study is presently continuing with the objectives of collecting more data including radial and tangential velocity components under the same operating conditions. Computations are also being carried out of the flow and temperature fields in the torch under the same operating conditions for comparison with the experimental data.

ACKNOWLEDGMENT

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Table 1:- Operating conditions used for the LDA measurements in the induction plasma

Oscillator frequency	3 MHz		
Coil	4 turns		
Plasma gas	Argon		
Plasma gas flow rate Q_2	11.7 ℓ/min		
Sheath gas flow rate Q_3	63.0 ℓ/min		
	(a)	(b)	(c)
Powder carrier gas flow rate, Q_1 ℓ/min	4.8	7.4	7.4
Power, P kW	4.64	4.64	10.28

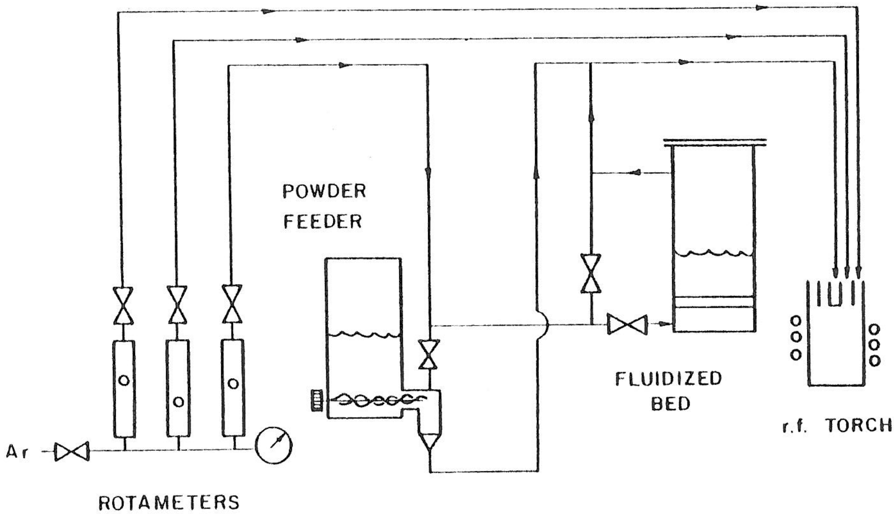

Figure 1:-Experimental setup

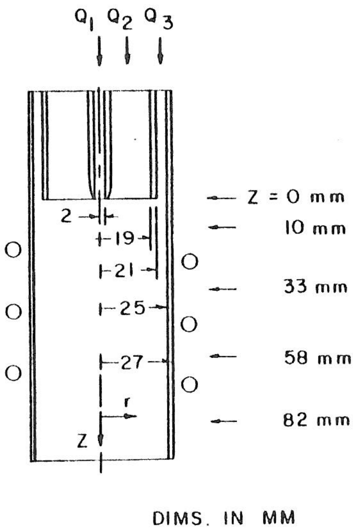

Figure 2:-Details of the induction torch

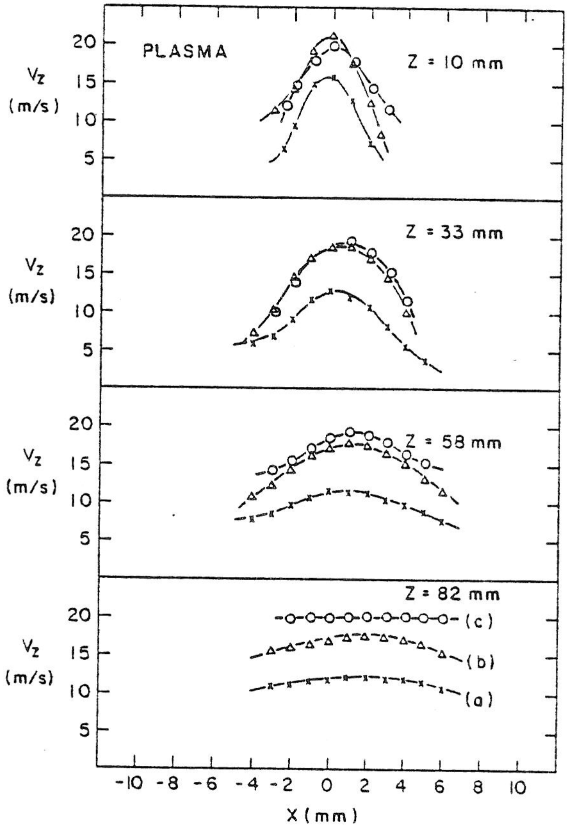

Fig.-3:-Plasma velocity profiles over the central region of the torch.

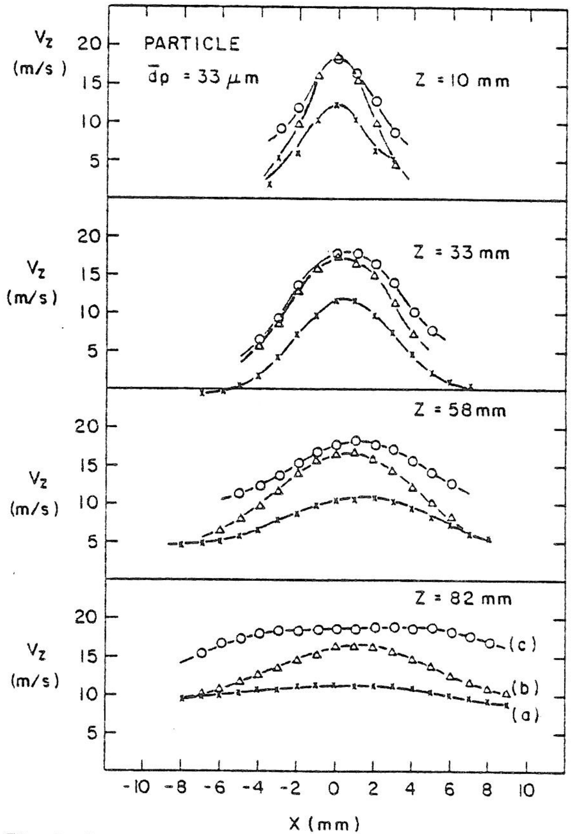

Fig.4:-Particle velocity profiles over the central region of the torch.

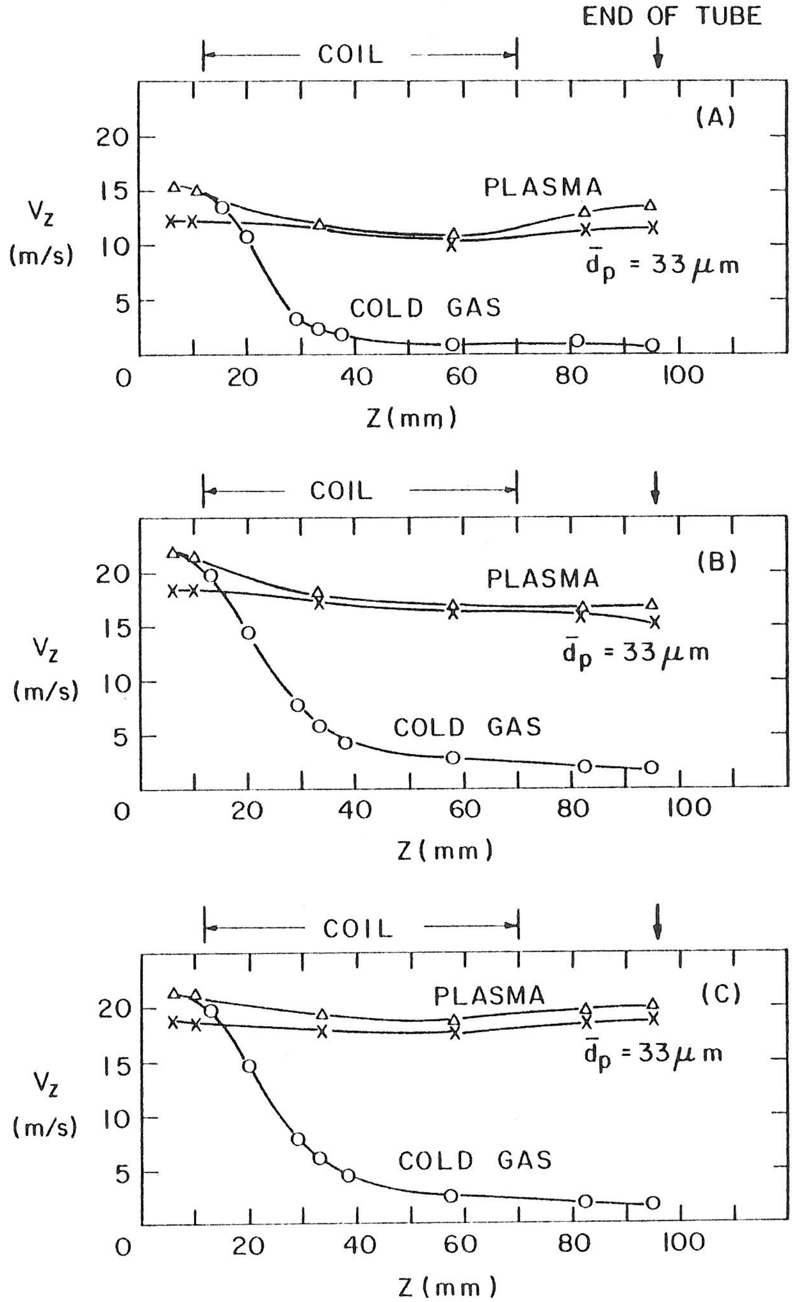

Figure 5:-Plasma and particle axial velocity profiles along the centerline of the torch