Journal of Visualization, Vol. 4, No. 1(2001)19-28

Visualization and Diagnostics of Thermal Plasma Flows

Boulos, M. I.*

* Plasma Technology Research Center (CRTP), Department of Chemical Engineering, Université de Sherbrooke, Sherbrooke (Québec) J1K 2R1, Canada.

Received 20 December 2000.
Revised 10 January 2001.

***Abstract*:** Flow visualization is a key tool for the study of thermal plasma flows. Because of their high temperature and associated self emission, standard and high speed photography is commonly used for flow and temperature field visualization. Tracer techniques through the injection of a seed powder in the plasma flow have also been often used for the study of flow structure. Shadowgraphs and Schlieren techniques have been used particularly when cold flow regions are present in the close proximity of the plasma discharge. They also provide key information about the flow structure in the fringes of the discharge. Laser strobe techniques are commonly used for the characterization of particle trajectories under plasma conditions. A brief review is presented of available plasma and particulate diagnostic techniques with detailed measurements reported for a radio frequency (r.f.) induction plasma discharge using enthalpy probe techniques.

***Keywords*:** thermal plasma flows, induction plasma, d.c. plasma jet, photographic techniques, schlieren, laser strobe, enthalpy probe techniques.

1. Introduction

Thermal plasmas are characterized by their high temperatures and velocities. These are often combined with the presence of steep temperature and property gradients and the simultaneous presence of particulate matter entrained by the plasma flow. Plasma flow visualization and diagnostic under these conditions offer quite a challenge which has been at the center of systematic study for the past three decades. Numerous techniques have been developed and are used on a regular basis for the visualization of plasma flows and the measurement of the plasma and/or particulate parameters for the purpose of fundamental research, model validationdel and on-line process controls. In the following, a brief over-view is given of the thermal plasma generation techniques and their principal characteristics. This is followed by a review of standard flow visualization and diagnostics techniques commonly used in thermal plasma studies. A number of general review papers have been published in the field (Boulos et al., 1986; Fauchais et al., 1989; Fauchais et al., 1992; Landers, 1997; Moreau, 1998). Details about the individual techniques can be found in the vast literature on the subject.

2. Thermal Plasma Sources

A critical discussion of flow visualization and diagnostic techniques requires a clear identification of the different plasma sources that would be the subject of study using these techniques. These can be classified for the purpose of the present review as direct current (d.c.), or inductively coupled, radio frequency (r.f.) discharges. The basic energy coupling mechanism and plasma flow configuration for each of these types of thermal plasma generators are presented schematically in Fig. 1. These are discussed in the following.

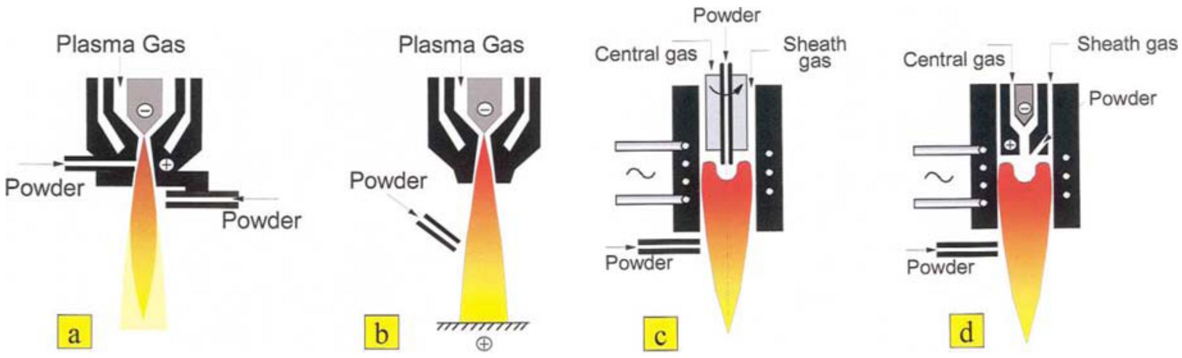


Fig. 1. Schematic of thermal plasma generation devices (a) d.c. plasma torch, (b) d.c. transferred arc, (c) r.f. induction plasma torch, and (d) d.c./r.f. hybrid plasma torch.

2.1 D.C. Plasma Jets

As shown in Fig. 1(a), standard d.c. plasma torches commonly used in plasma-spraying applications operate with a central Thoriated Tungsten cathode and a water-cooled annular copper anode. The plasma gas is injected into the gap between the two electrodes and serves to keep the arc root in a continuous motion over the surface of the anode. Typical torch currents are in the range of a few hundred Amps up to 1,000 A or more. The torch voltage depends largely on the nature of the plasma gas. It can vary between 25 to 30 V for pure argon operation, and increase up to 80 or 100 V when operating with molecular gases (Ar/H_2, N_2, O_2). As the gases pass around the arc through the anode nozzle constriction, they are heated and partially ionized emerging from the anode nozzle as a high velocity plasma jet with a mean temperature of the order of 12,000 K and centerline plasma velocities that can be as high as 1,000 m/s. Higher velocities can also be reached when discharging the plasma jet at low pressures 6.6 - 13.4 kPa (50 to 100 Torr). The anode nozzle discharge diameter is typically of the order of 5 to 8 mm giving rise to steep property gradients in the fringes of the plasma jet. These can reach as high as a (10^3 K/mm) or hundreds ((m/s)/mm). The fringes of the plasma jet are also characterized by a rather complex turbulence structure that results from the interaction of the plasma jet with the cold ambient gas (air) surrounding it. When used for materials processing and thermal spraying applications, powders ($5 < d_p < 100$ μm) are injected into the plasma jet either internally into the anode nozzle, or externally as shown on either side of Fig. 1(a). Typical material residence time in the plasma is less than one (1) ms.

2.2 D.C. Transferred Arc Plasmas

As shown in Fig. 1(b), transferred arcs differ from the standard d.c. plasma torches by the fact that they operate with an external anode that can be at a distance of a few centimeters up to 30 or 40 cm from the cathode. Typical arc currents are of the order of a few hundred Amps up to 1,000 A or more. Arc voltages can vary between 20 to 30 V up to a few hundred volts depending on the arc length and the nature of the plasma gas. The plasma gas is injected in this case into the annular region between the cathode and an auxiliary nozzle that is usually kept at a floating potential. Typical conditions in the arc column are temperatures in the range of 12,000 K to 20,000 K though temperatures up to 30,000 K have been reported near the cathode tip. Gas velocities are of the order of a few tens of m/s. Transferred arcs are often used for metal melting with the molten metal pool acting as anode in which the material in powder or chuck form is feed.

2.3 R.F. Inductively Coupled Plasma Discharges

In this case (Fig. 1(c)), the plasma is generated through the inductive coupling of the energy into the plasma. The induction coil is typically formed of a three (3) to eight (8) turns, water-cooled, copper coil, surrounding a gas or water-cooled quartz or ceramic wall plasma confinement tube. Induction plasma discharges have been operated at power levels ranging from a few kW to 400 or 500 kW with plasma confinement tube diameters ranging from 18 mm up to 150 mm respectively. Induction plasma discharges with a water-cooled, segmented-metal, plasma-confinement tubes have also been operated at power levels up to 800 or 1,000 kW. The operating frequency varies with the power range and the diameter of the plasma confinement tube. These are typically in the MHz range (3 - 40 MHz) for operation at power levels up to 200 kW. Operation at higher power levels is usually associated with a decrease of frequency to the 300 to 400 kHz range. Induction plasma torches have been operated at atmospheric pressure and soft vacuum conditions 13.4 - 40.1 kPa (100 - 300 Torr) with a wide range of gases including Ar, Ar/H_2, Ar/He, N_2, O_2 and Air. Typical temperatures prevailing in the discharge and at the exit of the torch nozzle are of the order of 8,000 - 10,000 K, and plasma velocities in the range of 40 to 50 m/s up to 2,000 or 3,000 m/s. The latter are achieved through the use of a supersonic Laval nozzle attachment with a chamber pressure downstream of the torch of the order of 6.7 kPa (50 Torr). Property gradients are less important in this type of device in the core of the plasma flow. Steep temperature and velocity gradients (10^3 K/mm and 10 to 50 (m/s)/mm) are still observed in the fringes of the discharge. When used for materials processing, the material to be treated is typically injected in powder form ($5 < d_p < 500$ μm) either axially into the center of the discharge, or radically into the plasma jet at the exit of the plasma torch. Typical materials residence time in the plasma is of the order of 10 to 20 ms depending on the discharge conditions.

2.4 Hybrid d.c./r.f. Plasmas Torches

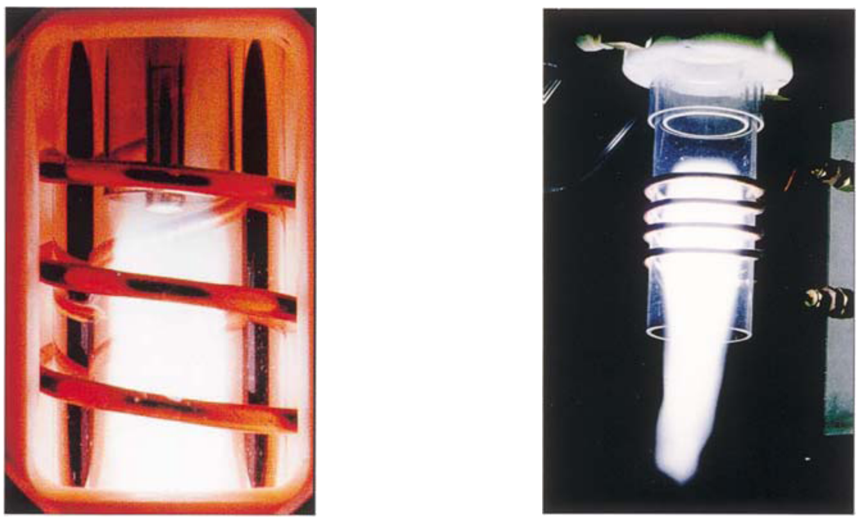
These are hybrid combinations of both d.c. and r.f. plasma generating devices (Fig. 1(d)) with approximately 5 to 10% of the total plasma power supplied to the discharge by a central d.c. plasma torch. The balance of the power is coupled inductively into the emerging d.c. plasma jet. While the technique is presently of limited use, it has its merits in allowing for the better control of the energy density distribution in the discharge and for the increase of the centerline plasma velocities compared to a standard r.f. induction plasma discharge. Operation of this type of discharge has been reported at powers up to a few hundred kW for plasma synthesis and materials processing applications.

3. Thermal Plasma Visualization Techniques

The standard range of flow visualization techniques commonly used in fluid dynamic studies is often called upon in most of thermal plasma flow investigations. Standard and high-speed photography, particle tracer techniques, Schlieren and laser strobe techniques are typical examples.

3.1 Photographic Techniques

Standard photographic techniques have commonly been used for flow and temperature field visualization in thermal plasma research. These rely on the relatively intense self-emission of the plasma in order to create an image of the discharge that would define its boundaries and, in the case of high-speed photography, its stability. Figure 2 shows typical examples of photographs of induction plasma discharges taken with a still camera with a relatively short exposure time. Figure 2(a) represents a pure argon discharge at atmospheric pressure confined by a 70 mm i.d., air-cooled, quartz tube. Because of the sensitivity of the photographic film to the total intensity of the light it receives, it is difficult to interpret the picture in terms of temperature of the discharge. Due to the axisymmetry of the flow configuration, the central region of the discharge integrates a longer optical path than the fringe regions. The outer contours of the discharge zone can be associated with a temperature isotherm in the range of 7,000 to 8,000 K based on spectroscopic and mathematical modelling studies (Boulos, 1997, 1985). The picture given in Fig. 2(b) corresponds to a similar inductively coupled plasma discharge except for the water-cooling of the quartz plasma confinement tube and the operation of the plasma at lower pressures, 40 kPa (300 Torr), with a mixture of argon and hydrogen as the plasma sheath gas. The latter is responsible for the red tone of the color of the picture due to the nature of the spectrum of the hydrogen emission.



(a) (b)

Fig. 2. Still photographs of induction plasma discharges: (a) atmospheric pressure Argon plasma at a power level of 10 kW in a 70 mm i.d. air-cooled quartz tube; (b) low pressure Argon/Hydrogen plasma, 7 kW in a 50 mm i.d. water-cooled quartz tube.

Corresponding pictures of d.c. plasma jets are shown in Fig. 3. These are taken for an open discharge at atmospheric pressure of a pure argon discharge at different arc currents varying between 200 and 500 Amps. The arc voltage was constant at about 24 Volts. The corresponding power of the discharge varied accordingly between 4.8 to 12.0 kW with about 60% of this power available as enthalpy in the plasma jet. The internal diameter of the discharge nozzle was 7.0 mm. It may be noted that the increase of the power in the plasma jet results in a considerable increase of the length of its core region. Here again, while the precise interpretation of the intensity of the picture of the discharge in terms of temperature would be rather difficult, the strong brightness observed at the exit region of the jet corresponds to its higher temperature (10,000 to 12,000 K) compared to that of r.f. inductively coupled discharges (8,000 to 10,000 K). It should also be pointed out that the ragged edge of the jet observed in these pictures reflects its highly turbulent nature.

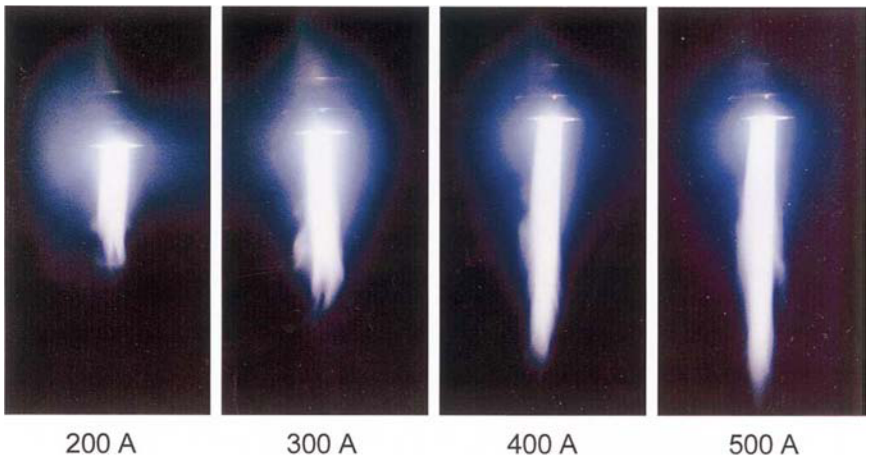


Fig. 3. Photographs of d.c. plasma jets of pure Argon at atmospheric pressure with varying arc currents (200 - 500 A). Nozzle internal diameter = 7.0 mm. Arc voltage = 24 V.

Special care should be exercised, in the interpretation of still photographic pictures in terms of turbulence or stability of a discharge. Such interpretation should obviously be closely tied to the exposure time of the picture. The effect is clearly demonstrated by the series of pictures shown in Fig. 4. These were taken at different exposure time varying between 1/1,000 and 1/60 s (left to right) with correspondingly varying camera apertures. The plasma jet in this case was that generated by an inductively coupled r.f. discharge operated at low pressure, 33 kPa (250 Torr), and a power level of 60 kW using a mixture of argon and hydrogen as the plasma sheath gas. The exit nozzle diameter of the plasma torch used in this case was 64 mm. The corresponding length of the plasma jet shown in the pictures is about 600 to 700 mm. It may be noted that while the jet shown in the picture at the extreme right hand side of Fig. 4 could be interpreted as being symmetrical and stable (laminar), the same conclusion could not be made of the picture shown on the extreme left hand side of the same figure which reveals an interesting swirling flow component which can be traced back to the gas injection mode into the plasma torch cavity.

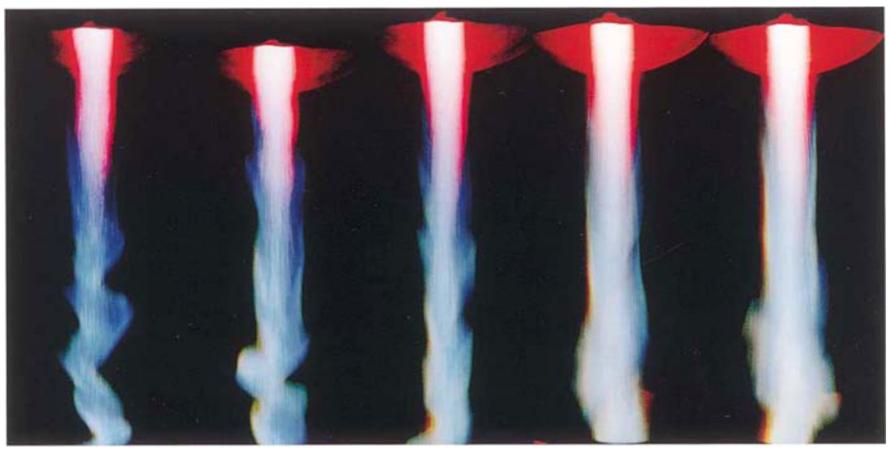


Fig. 4. Photographs of an inductively coupled r.f. plasma jet discharged in a low pressure chamber, 33 kPa (250 Torr), Argon/Hydrogen plasma, Plate power = 60 kW, discharge nozzle diameter = 64 mm. Photographs taken with different exposure time varying between 1/1,000 s (left) to 1/60 s (right).

Standard photographic techniques have also been of particular use in the study of the structure of supersonic plasma jets. The pictures shown in Fig. 5, represent a compilation of four photographs of plasma jets generated by inductively coupled r.f. discharges operated in a supersonic flow mode with exit flow nozzles designed for operation at Mach numbers of 1.5 and 3. These were all operated essentially at the same power level of about 20 to 25 kW with a discharge chamber pressure of 7.9 to 9.3 kPa (60 to 70 Torr). Figure 5(a) shows a supersonic argon plasma jet at a Mach number of 1.5. The photograph clearly reveals the details of the shock structure of the jet. Figures 5(b) and 5(c) show the corresponding jet structure when operated under essentially the same conditions using Ar/H_2 or air as the plasma gas at a Mach number of 1.5. Figure 5(d) shows the corresponding jet structure at a Mach number of 3 using air as the plasma gas.

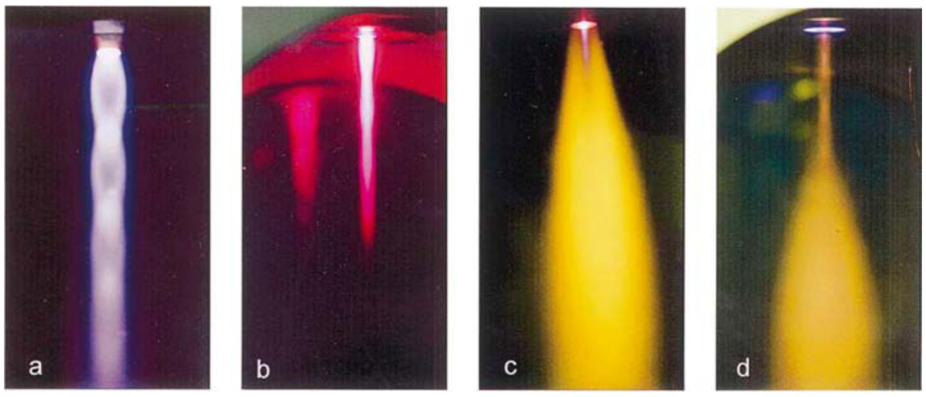
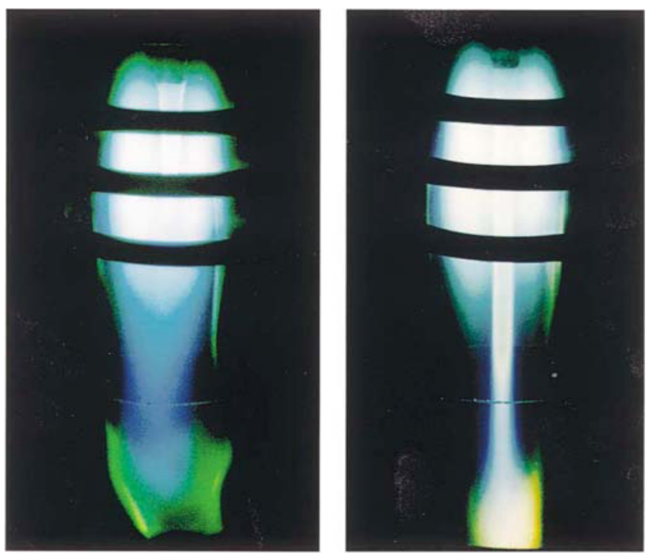


Fig. 5. Photographs of supersonic induction plasma jets (a) pure argon at $M = 1.5$, (b) Ar/H_2 at $M = 1.5$, (c) air at $M = 1.5$ and (d) air at $M = 3.0$.

Plasma flow visualization using standard photographic techniques can be further enhanced by flow seeding with either a tracer gas or a finely divided powder. In the latter case the individual powder particles injected into the discharge are heated through their contact with the plasma, melted and vaporized. The generated vapor could then be used as a tracer through its own spectral emission. The photograph given in Fig. 6 shows a low power (7 kW), r.f. inductively coupled discharge operated at atmospheric pressure with pure argon as the plasma gas. The quartz plasma confinement tube used in this case had a 50 mm i.d. In the central top section of each of these two pictures, a water-cooled powder-feeding probe is introduced. This served for the injection into the plasma of a very fine (5 to 10 μm) Zirconia powder with argon as carrier gas. As the powder came in contact with the plasma, the individual particles melted and vaporized. The excited emission of the Zirconium spectral lines could then be used to trace down the flow path of the gas centrally injected into the



(a) (b)

Fig. 6. Photographs of r.f. plasmas in the presence of zirconia powder as tracer, with different central gas injection flow rates (a) 1 - 2 slpm and (b) 4 - 5 slpm.

discharge through the injection probe. The photograph shown in Fig. 6(a) for a low tracer gas flow rate (1 - 2 slpm) shows the injected gas only partially penetrating the discharge. The reversal of the flow in this case was attributed to a well-documented flow recirculation pattern that is due to electromagnetic pumping effects characteristic of inductively coupled discharges (Boulos, 1997; Boulos, 1985; Mostaghimi and Boulos, 1989). The photograph given in Fig. 6(b) which corresponds to an operation with higher injection gas flow rate (4 - 5 slpm), reveals in this case the ability of the injected gas to fully penetrate the discharge with very little mixing between the centrally injected gas stream and the surrounding plasma.

3.2 Shadowgraph and Schlieren Techniques

Shadowgraph and Schlieren techniques have also been frequently used for flow visualization under plasma conditions. The photograph given in Fig. 7 is for a wire-arc spraying system in which an electrical arc is struck between two wires. A high-speed airflow is injected into the arc region in order to disperse the molten metal from the wire tip and project the formed molten metal droplets towards the substrate to be coated. Details of the shock wave structure formed around the nozzle used for air injection can be clearly observed in the photograph.

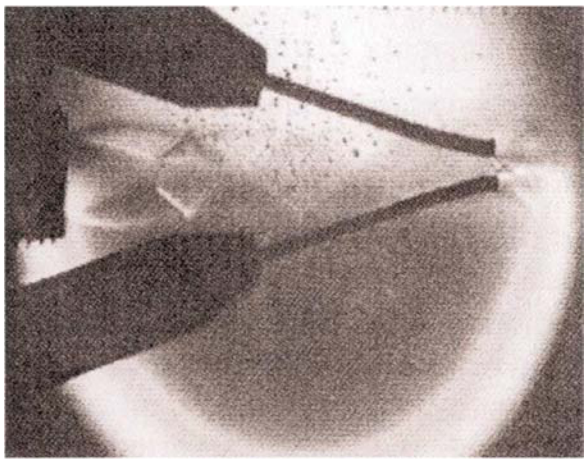


Fig. 7. Schlieren photograph of a twin wire arc system showing the supersonic structure of the flow of the atomizing air jet.

3.3 Laser Strobe Techniques

Laser strobe techniques have been frequently used for the visualization of relatively short transient phenomena under plasma conditions. An example of laser strobe photography applied to the wire-arc spraying process is shown in Fig. 8. The two high-speed photographs shown in this figure provide critical information about the mechanism of metal droplet formation through the interaction of the atomizing air blast with the molten metal on the wire tip.

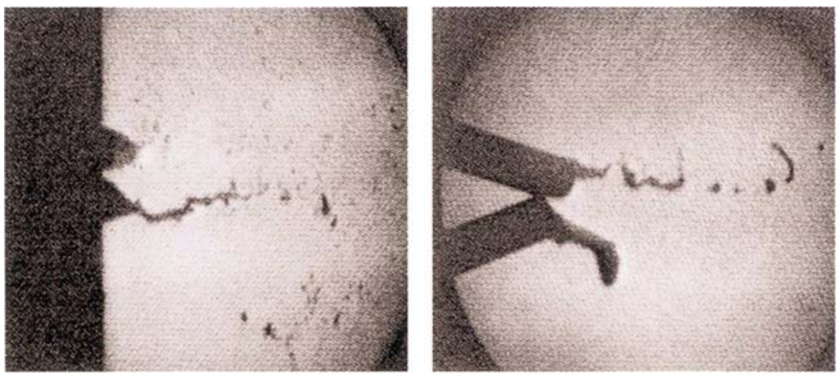


Fig. 8. Laser strobe photographs showing metal droplet formation in twin wire-arc spraying process.

4. Plasma and Particulate Diagnostic Techniques

A broad spectrum of diagnostic techniques has been successfully developed and used for the characterization of different plasma generating devices for a wide range of applications. These vary depending whether the measurement target is the plasma itself or the particulate matter being processed in-flight.

4.1 Plasma Diagnostic Techniques

These can be classified as follows according to the basic sensing technique used.

(a) Optical methods

These are by far the most commonly used diagnostic techniques.

- Emission/Absorption spectroscopy using absolute intensity line techniques, Boltzman plots, Stark broadening, and two-point light emission correlation analysis.
- Laser techniques including Laser Induced Fluorescence (LIF), Thomson and Rayleigh Scattering and Coherent Antistokes Raman Spectroscopy (CARS).

(b) Probe techniques

Probe techniques have been available for many years for plasma diagnostics. The most important of these are the Langmuir and enthalpy probes. The latter can be used for the simultaneous measurement of the local specific enthalpy, velocity and composition of the plasma. Their main advantage is the simplicity of the technique, and its possible use for the simultaneous measurement of multiple plasma parameters with a generally acceptable spatial resolution. Its main limitation is that it is an intrusive technique, with the probe inevitably causing a local perturbation of the flow. Enthalpy probe techniques can not be used either for time-resolved measurements.

(c) Acoustic and electrical signal analysis techniques

Increasing attention has been given over the past ten years to the relatively important information that can be obtained about the dynamics of the discharge through a simple spectrum analysis of the acoustic noise emitted and/or the arc voltage fluctuations associated with d.c. discharges (torches and transferred arcs).

4.2 Particulate Diagnostic Techniques

These are mainly optical techniques aiming at the measurement of the in-flight particle velocity, surface temperature, diameter and number flux density. The most common of these techniques are:

(a) Laser Doppler anemometry (or velocimetry)

These are based on the observation of laser light scattered by the particles as they cross the measuring volume defined by the point of intersection of two laser beams. The techniques give information about the particle velocity. When combined with phase-shift analysis at two different observation angles, the technique can be used to obtain information about the particle diameter as well.

(b) Laser strobe technique

When combined with high-speed photography and image analysis, laser strobe techniques can be used for particle trajectory and particle velocity measurement.

(c) Two-wave length pyrometry

Assuming gray body radiation, this technique can provide information about the in-flight surface temperature of the particles. When combined with time-of-flight measurement through the use of a well-defined observation window, this technique can be used for the simultaneous measurement of the particle velocity and surface temperature.

5. Examples of Enthalpy Probe Measurements

In the following, typical results are presented for enthalpy probe measurements in a r.f. inductively coupled plasma discharges. Details of the experimental techniques and measurement setup used can be found in the publication by Rahmane et al. (1995, 1994, 1996). The technique is based on measurement of the thermal energy associated with a specific mass of sampled plasma gas. This is calculated as the difference between the heat load on the sampling probe in the presence and absence of plasma gas sampling.

Figure 9 shows typical enthalpy probe measurements system set up around a r.f induction plasma discharge. The plasma torch used in this case is a Tekna model PL50 torch with a 50-mm i.d. ceramic plasma confinement tube and a 43 mm i.d. torch exit nozzle. The torch was mounted in this case on the top of a 200 mm i.d. water-cooled chamber maintained at on absolute pressure of 33.4 kPa (250 Torr). The operating conditions are: Sheath gas composed of an Ar/H_2 mixture (71 slpm Ar + 4 slpm H_2); central gas, 33 slpm (Ar). Nitrogen, axialy injected in the center of the discharge at a flow rate of 8 slpm, is used as a tracer gas in order to allow for the study the associated mass transfer phenomena under these conditions. The plate power of the r.f. power supply was 20 kW (about 13 kW coupled into the discharge), and the oscillator frequency was 4 MHz.

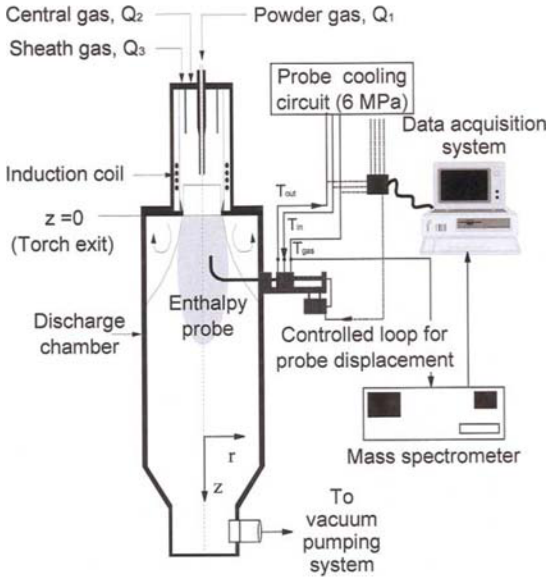


Fig. 9. Experimental set up used for the enthalpy probe diagnostics of an induction plasma flow (after Rahmane et al., 1995).

The results are compared with the predictions of a two-dimensional turbulent flow mathematical model, which are shown in Fig. 10 as temperature, flow and concentration isocontours for an atmospheric pressure case under similar operating conditions. The measurements and the corresponding model predictions are presented in terms of radial profiles of the plasma temperature (Fig. 11(a)), velocity (Fig. 11(b)) and composition (Fig. 11(c)) (expressed in mole fraction of N_2), at different axial locations in the torch and downstream chamber (z = –22, +23, +77 and +122 mm). The (z = 0) level coincides in these cases with the torch nozzle exit plane. In each of these figures the left hand side corresponds to measurements and computations for a low pressure discharge (33.2 kPa (250 Torr)), while the right hand side corresponds to a near atmospheric pressure discharge (82.4 kPa (620 Torr)). The observed agreement between the model predictions and the experimental data is quite satisfactory for the temperature and concentration profiles. The measured velocity profiles are, however, less consistent with the model predictions due to experimental difficulties resulting from the three-directional nature of the flow in the discharge region.

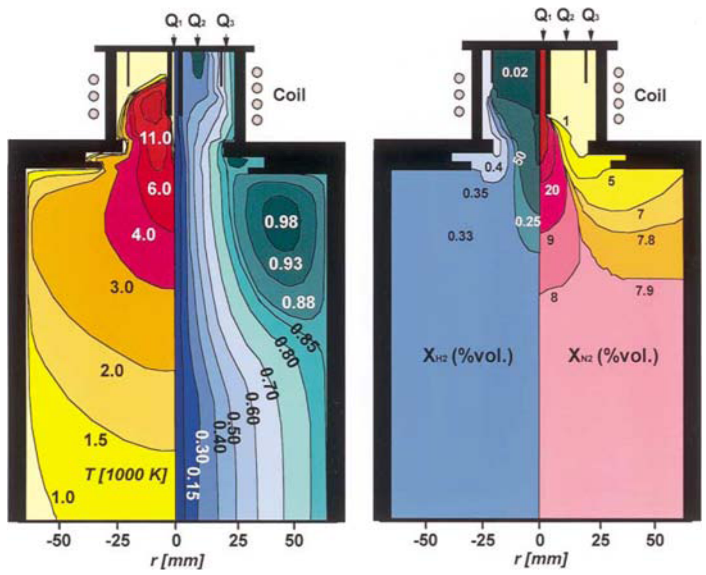


Fig. 10. Modeling predictions of the temperature, flow and concentration isocontours in an atmospheric pressure r. f. induction plasma discharge (after Rahmane et al., 1994).

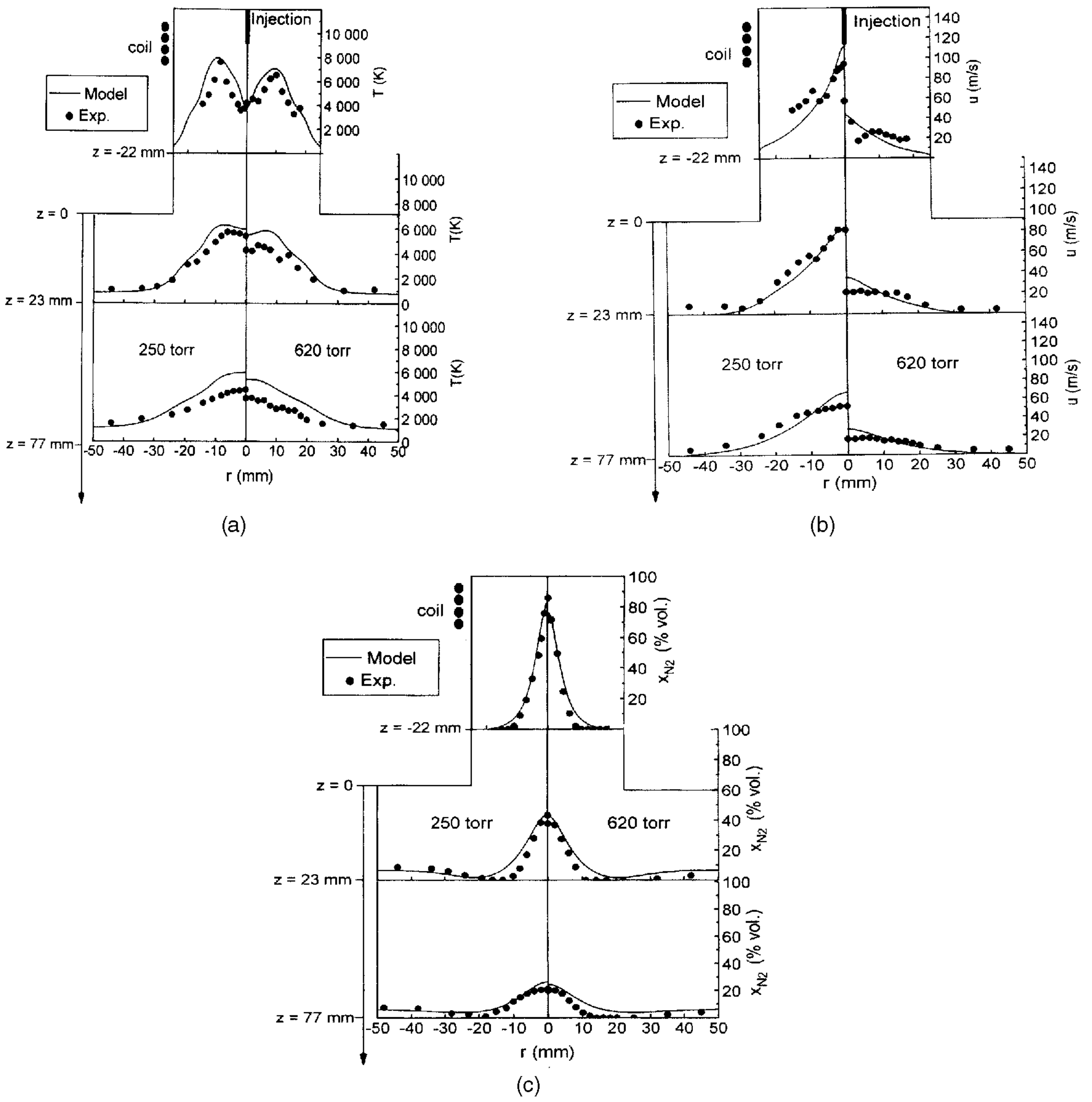


Fig. 11. Typical radial profiles of the (a) plasma temperature, (b) velocity and (c) concentration at different axial locations in the presence of axial injection of nitrogen in the center of the discharge (after Rahmane et al., 1996).

6. Summary and Conclusions

Flow visualization and diagnostics of plasma and in-flight particle parameters are of paramount importance for fundamental studies and on-line control of thermal plasma processes. A number of key flow visualization and diagnostic techniques have been developed and/or adapted to the high temperatures and high velocities normally prevailing in such sources. These are generally based on optical, probes, acoustic or electrical signal analysis techniques. With the exception of probes, comma, all of the techniques used are non-intrusive and consequently do not disturb the plasma source. They are, however, generally limited to the measurement of either the plasma parameters in the absence of the particulate or the in-flight particulate parameters alone. Very few techniques can be used for the measurement of the plasma parameters in the presence of the particulate matter. Further work is needed for the development and integration of simple and robust plasma and particulate flow visualization and diagnostic techniques for comprehension on-line process control.

References

Boulos, M., The Inductively Coupled r.f. Plasma, J. Pure and Applied Chemistry, 57 (1985), 1321-1352.
Boulos, M., The Inductively Coupled Radio Frequency Plasma, J. High Temperature Materials Processing, 1 (1997), 17-39.
Boulos, M., Fauchais, P. and Pfender, E. Diagnostic Techniques in Thermal Plasma Processing, DOE report, no. DOE/ER-0270, (1986), 1-2.
Fauchais, P., Coudert, J. F. and Vardelle, M., In Plasma Diagnostics, (1989), 349-446, Academic Press, N.Y.
Fauchais, P., Coudert, J. F., Vardelle, M., Vardelle, A. and Denoirjean, A., Diagnostics of Thermal Spraying Plasma Jets, J. Thermal Spray Technology, 1 (1992), 117-128.
Landers, K., Diagnostics and On-line Control of a Plasma Spray Process, High Temp. Materials Processes, 1 (1997), 315-326.
Moreau, C., Towards a Better Control of Thermal Spray Process, Proceedings ITSC-98 (Nice France), (1998), 1681-1693.
Mostaghimi, J. and Boulos, M., Two-dimensional Electromagnetic Field Effects in r.f. Inductively Coupled Plasmas, J. Plasma Chemistry Plasma Processing, 9 (1989), 23-42.
Rahmane, M., Soucy, G. and Boulos, M. I., Analysis of Enthalpy Probe Technique for Thermal Plasma Diagnostics, Rev. Sci. Instrum., 66 (1995), 3424-3431.
Rahmane, M., Soucy, G. and Boulos, M. I., Diffusion Phenomena of a Cold Gas in Thermal Plasma Stream, Plasma Chem. Plasma Proces., 16 (1996), 169S-189S.
Rahmane, M., Soucy, G. and Boulos, M. I., Mass Transfer in Induction Plasma Reactors, Int. J. Heat Mass Transfer, 37 (1994), 2035-2046.

Author Profile

Maher I. Boulos: He is a professor and director of the Plasma Technology Research Centre at the University of Sherbrooke. He received his B.Sc Chemical Engineering, Cairo University, Egypt (1963). M.Sc and Ph.D. (1968,1972) in Chemical Engineering, the University of Waterloo, Canada. He has published numerrous papers in scientific journals and conference proceedings, chapters in textbooks, and contributed to a number of patents in the field of thermal plasma conditions, mathematical modelling and diagnostics of plasma and particulate systems. His principal areas of interest are in Plasma-particle interactions, in D.C. and induction plasma systems and plasma processing of materials.
Email: boulos@courrier.usherb.ca