Diagnostics and modelling of a high-power r.f. plasma flow

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Abstract

The objective of this paper is to study the characteristics of a high power radio frequency (r.f.) induction plasma reactor (100 kW, 250 kHz). In the experimental study, emission spectroscopy and enthalpy probe techniques are used to measure the plasma temperature and velocity distributions of the plasma jet. The comparison of temperature measurements obtained by emission spectroscopic method and enthalpy probe is used to verify the validity of the local thermodynamic equilibrium conditions. In the mathematical modelling part of the study, a two-dimensional turbulent model is used for the simulation of the coupled temperature, velocity, concentration and electromagnetic fields inside the plasma torch and the reactor. The effect of turbulence in the plasma flow is investigated by means of a k-ε model. Results of modelling are presented and validated by the experimental data.

1. Introduction

Among the different techniques commonly employed for plasma generation, considerable attention has been given to inductively coupled, radio-frequency (r.f.) plasmas [1]. Because of the absence of electrodes in direct contact with the plasma, induction plasma can be generated in inert, reducing or oxidising gases. Over the past twenty years, a wide range of application for induction plasma has been emerged in the area such as spheroidisation, plasma spraying and plasma chemical synthesis.

Industrial applications demand a thorough understanding of the characteristics of plasma inside the torch, thus the measurement of temperature, velocity, enthalpy, and concentration in high-temperature gases has played an important role in developing this understanding. Of particular importance is knowledge of temperature and concentration distributions in a thermal plasma. For temperature measurement, the traditional approach to this question is to relate the measured intensity of emission lines to the gas or kinetic temperature of the atoms through the assumption of local thermodynamic equilibrium (LTE). In the current literature, numerous investigations have already been devoted to the study of the deviations from LTE conditions in direct current (DC) arc [2-5]. The results are, however, much fewer for high power r.f plasma [6]. In these investigations, emission spectroscopy may be useful for determining electron temperature even if the plasma is in PLTE, but does not yield information on gas kinetic temperatures. Thus, the application of enthalpy probes to the measurement of local gas temperature and velocity represents a robust, complementary alternative method. The enthalpy probe is generally considered to be a reliable diagnostic tool in the range from 2000 to 12 000 K [9] and has been used in high-temperature flow field research since the 1960s. More recently, the enthalpy probe has been used to a variety of thermal plasma investigation and processing problems [7-9].

While diagnostic techniques are powerful they require expensive and delicate, complicated equipment. The high cost of full scale tests has led to the adoption of numerical modelling. With the development of realistic mathematical modelling, the high cost of full scale design and experimentation will be substantially reduced.

The objective of the present study is the investigation on the temperature and velocity fields inside a high power r.f. plasma reactor (100 kW) under reduced pressure plasma conditions by numerical modelling and experimental measurements. Deviations from equilibrium are investigated by comparison of temperature measured by emission spectroscopy and that measured by enthalpy probe technique. The mathematical modelling is validated by the comparison with experimental values.

2. Experimental set-up

A sketch of the experimental set-up is shown in Fig. 1. It consists of a r.f. plasma torch system, an emission spectroscopy system, an enthalpy probe apparatus and a computer control system.

The plasma, generated by the radio-frequency power supply with a nominal oscillator frequency of 250 kHz and a maximum plate power of 100 kW, is confined in a Tekna model PL-70 water-cooled ceramic tube and is discharged into a water-cooled plasma reactor chamber, 2 m long and of 600 mm diameter. The quartz window in the reactor wall allows easy access for the spectroscopic measurement to the region near the torch exit. A sealed scanning system allows a two-dimensional measurements (r and z directions) of plasma parameters by enthalpy probe.

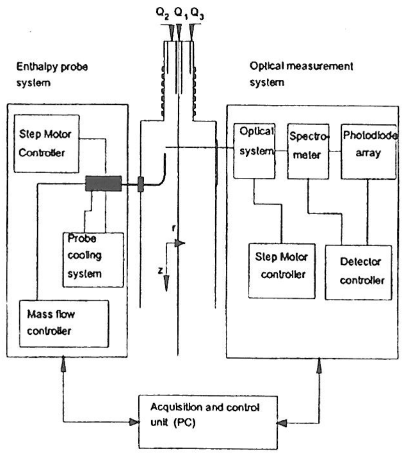

Fig. 1 Schematic of the experimental set-up

The emission spectroscopy measurement was carried out by means of a 1 m monochromator fitted with a grating having 1200 grooves/mm and with a linear dispersion of 0.78 nm/mm. The output signal was received by a photodiode array in the monochromator output plane. The absolute intensity of the radiation was obtained by calibration against a standard tungsten filament lamp. The photodiode signals were stored and processed by computer. Abel inversion technique was used to get the local values of the emitted intensity [4-6].

The enthalpy probe system included a water-cooled stainless steel probe, a closed loop for the cooling water recirculation system, a gas sampling line equipped with an appropriate mass flow controller, and a data acquisition and control unit, it is fabricated from three concentric stainless steel tubes [9].

3. Diagnostic techniques

The temperature from the emission spectroscopy was determined by the absolute intensity ε_v of a non-absorbed line. The thermodynamic equilibrium laws allow the composition of the Ar-H_2 plasma to be determined as a function of temperature so a value of T can be found for a given ε_v. The measurements were made on the argon line of 727.29 nm [4-6].

The enthalpy probe techniques allow the measurement of temperature and velocity of plasma at the same time of the emission spectroscopic measurement. The value of the local specific enthalpy (h_i) of the plasma flow can be derived from an energy balance applied to the cooling water flow through the probe and the gas sample extracted from the plasma. Detailed description of enthalpy techniques can be found in the references [7-9].

4. The mathematical modelling

Gas flows in plasma reactors take place as a combination of the laminar and turbulent regions. Under existing high temperature conditions, a laminar model might provide a reasonable predication of flow, temperature and concentration fields, in the low temperature region, however, the contribution of turbulence is very important and can not be neglected. In the present study, a k-ε model is used to represent the turbulent viscosity, the differential kinetic energy of turbulence and the turbulence dissipation rate equations. The theoretical foundations of this model have been presented by Chen *et al* [10] and Rahmane *et al* [11]. The assumption involved in this model are: (1) two-dimensional axisysmmetrtric temperature and flow fields; (2) two-dimensional electric and magnetic fields with negligible displacement currents; (3) turbulent flow and heat transfer with negligible viscous dissipation; (4) local thermodynamic equilibrium condition and optically thin plasma.

5. Modelling results and its experimentation validations

The operating arrangements are shown in Fig. 1. The central gas Q_1 is not used in the present study. The plasma gas Q_2 is pure Ar with constant flow rate of 45 slpm and with swirl velocity 10 m/s at the entrance boundary. The sheath gas Q_3 is argon-hydrogen mixture (120 slpm, 10% H_2, vol.). The power used in the experiment is 50 kW and the pressure is 350 torr. A set of non uniform grid points, 65x96, is used in the present calculation.

Fig. 2 illustrates the isotherms and the streamlines for the 350 torr chamber pressure and 50 kW power conditions. The maximum temperature is around 10 000 K and two recirculation zones are observed in the reactor. The first, in the coil region, is due to the electromagnetic pumping inside torch. And the second, in the reactor, is due to the sudden expansion of plasma jet. The influence of power on the axial temperature and velocity profiles is shown in Figs. 3 and 4. As the power is increased from 50 kW to 100 kW, maximum temperature is increased slightly and the highest temperature zone is expanded and pushed further towards the wall of plasma confinement tube. Higher axial velocity is also observed with the increase of power. The influence of chamber pressure is investigated for the two different conditions, 350 and 600 torr, at the power level of 100 kW. The influence of chamber pressure is due to two principal effects. The first is the change of inlet velocity which is inversely proportional to pressure. The second is the change in the thermophysical and transport properties of the gas. These will modify the transport phenomena and the energy dissipation in the induction plasma. Figs. 3 and 4 show also when pressure increased from 350 to 600 torr, the maximum temperature is almost unchanged and the maximum axial velocity decreased. With the increase of the pressure, the higher temperature zone shift further upstream, because the arc becomes shorter in the higher pressure environment.

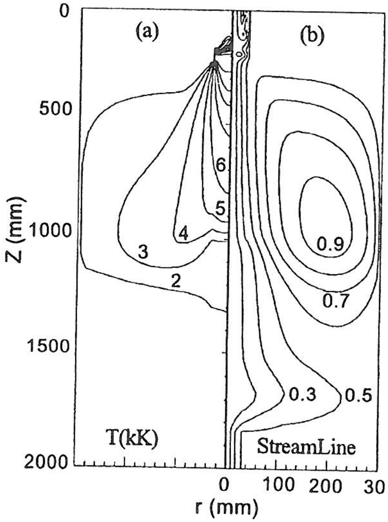

Fig. 2 Isotherms (a) and the streamlines (b) for the r.f. plasma reactor at the conditions of 350 torr and 50 kW

The comparison between the modelling results and the experimental data is shown in Figs. 5 and 6. Due to

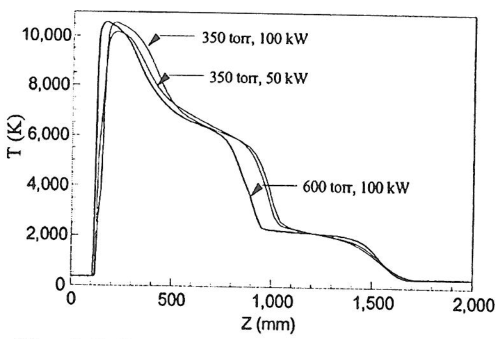

Fig. 3 Influence of pressure and power on the axial temperature profiles.

limitations in the experimental conditions and opportunity, only one set of experiments is carried out at the position of 106 mm downstream from the torch exit for both the spectroscopic and enthalpy measurements.

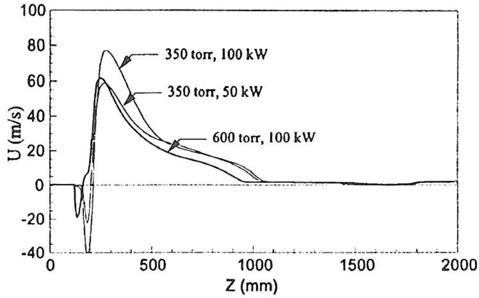

Fig. 4 Influence of pressure and power on the axial velocity profiles.

Fig. 5 illustrates the comparison between the axial velocity obtained from the modelling and that from the enthalpy probe measurement. Good overall agreement is observed except in the region near the axis of the plasma jet, where enthalpy probe measurement shows that axial velocity maximum is not in the centre. The lower velocity zone in the centre is due to the strong intensity of swirl of velocity component in the central plasma. The difference between the prediction and that of probe measurement can be explained by the uncertainty of the value of inlet swirl velocity used in the modelling. Fig. 6 shows the comparison of the corresponding radial temperature profiles computed and measured. Again good agreement is observed between the radial temperature profile obtained from the modelling and that from the spectroscopy measurement. However, discrepancy is found between temperature calculated from the modelling and that measured by enthalpy probe. The deviation from LTE conditions may be invoked to explain the difference between results of the

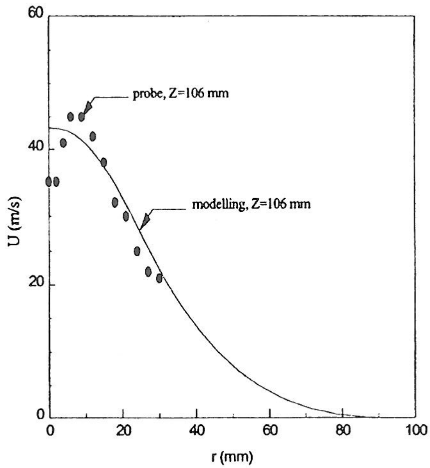

Fig. 5 Comparison of axial velocity profiles between the modelling and the enthalpy probe measurement.
(Z=106 mm, 50 kW, 350 torr)

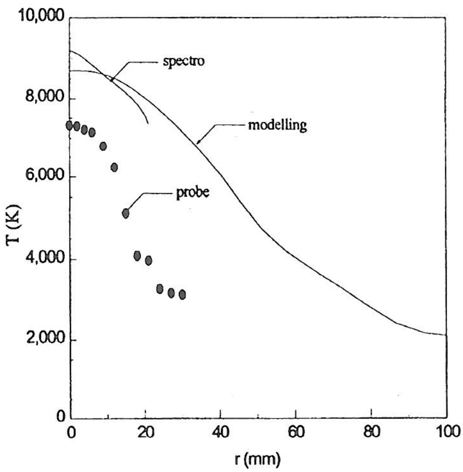

Fig. 6 Comparison of axial temperature profiles between the modelling and the experimental values.
(Z=106 mm, 50 kW, 350 torr)

modelling, spectroscopic and the enthalpy probe measurement. Both the model and the emission spectroscopy technique used here are based on the LTE conditions, however at the position 106 mm from torch exit, the LTE condition may not be valid because the electron density at that region is very low. Therefore the values of temperature determined by the modelling and the spectroscopic measurement shows systematically higher that measured by the enthalpy probe, which is independent on the LTE conditions.

6. Conclusions

In the present study, a turbulent model is developed for a higher power r.f. plasma torch. The influence of chamber pressure and the power is investigated. Both the spectroscopic measurement and enthalpy probe measurement are carried out . Good agreement between the temperature obtained from the modelling and that from the spectroscopic measurement, however, difference is observed between the temperature obtained from the modelling and that from the enthalpy probe measurement. The reason may be due to the deviation from LTE conditions in the plasma flow. Further investigation will be devoted to the detailed study of the validation of the LTE conditions and the development of a two-temperatrue model.

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References

[1] Boulos. M. I., Pure Appl. Chem., **57**, p1321 (1985)
[2] Hsu K.C., Pfender E., J.Appl. Phys. **54**, p3818 (1983)
[3] Mostaghimi J., Proulx P. and Boulos M.I., J.Appl. Phys. **61**, p1753
[4] Sabsabi M., Gravelle D.V. and Vaquire S. and Boulos M.I, J.Phys.D: Appl. Phys., **25**, p425 (1992)
[5] Sabsabi M., M.Cao, Gravelle D.V. and Vaquire S., J.Phys.D: Appl. Phys., 27, p2388 (1994)
[6] Gravelle D.V., Beaulieu M. and Boulos M.I., J.Phys.D: Appl. Phys. **54**, p3818 (1989)
[7] Pfender E., Finck J.R. and Sporees, Plasma Chem. and Plasma Process., **11**, p529 (1991)
[8] Fincke J.R. Snyder S.C. and Swank W.D., Rev. Sci. Instrum. **64**, p711 (1993)
[9] Rahmane M., Soucy G. and Boulos M.I., in press, Rev. Sci. Instrum (June 1995).
[10] Chen K amd Boulos M.I, J.Phys. D:Appl. Phys., **27**, p946 (1994)
[11] Rahmane M., Soucy G. and Boulos M.I., Int. J. Heat Mass Transfer, **37**, p2035 (1994)