TEMPERATURE AND PRESSURE MEASUREMENTS IN A LOW-POWER INDUCTIVELY COUPLED PLASMA DISCHARGE

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ABSTRACT

Spatial radiation, excitation temperature, stagnation pressure, and axial velocity distributions are reported for argon inductively coupled plasma (ICP) discharges operated at power levels between 0.5 and 1 kW and a frequency of 27 MHz under various gas flow conditions. The influence of gas flow rates and linear velocities are examined.

1. INTRODUCTION

Although the inductively coupled plasma discharge (ICP) is growing rapidly as a spectrochemical analysis excitation source, diagnostic information about the temperatures and velocities in the discharge are relatively limited (1). The ability to predict particle trajectories, sample decomposition and excitation processes, and the resulting spectral radiation depends upon a detailed knowledge of these critical plasma characteristics.

Various diagnostic methods are available for the determination of temperatures, number densities, and gas velocities in RF-heated induction discharges, and many of the thermal and gas dynamic methods and results of plasma diagnostics have been reviewed by Eckert (2), Gol'dfarb (3), Goykhman and Gol'dfarb (4), and Czernichowski and Jurewicz (5). Recent measurements in spectrochemical ICP discharges are surveyed by Barnes (1).

The ICP discharge applied in spectrochemical analysis differs in configuration from those induction discharges employed for plasma chemistry and material processing in that one or two gas streams support the discharge, isolate it from the confinement tube walls, and position it within the induction coil, and with an additional argon flow, sample is carried into the discharge. The central carrier gas flow rates ranging from 0.4 to 2 L/min with sufficient linear velocity to form a channel along the the centerline of the discharge transports solution, liquid, or metal aerosols; gases, or chemically and thermally generated vapors into and through the annular discharge. Because the spectrochemical ICP discharge contains this strong central flow, spatial temperatures and velocity distributions differ substantially from those observed in induction discharges without this directed central flow.

In the present investigation a spectrochemical ICP discharge with a central argon flow but without solution aerosol is examined to establish temperature and velocity distributions for comparison to theoretical predictions from computer models.

2. EXPERIMENTAL

Only during the past five years have spatially resolved spectroscopic temperature measurements been performed for spectrochemical ICP discharges (1), and of the spectroscopic diagnostic techniques suitable for these plasmas three methods are best suited for excitation temperature determination in a pure argon ICP discharge. These include a) radiance of a single atomic line, b) spectral radiance of the argon continuum, and c) atomic line radiance ratio. Excitation temperatures have been determined using atomic and/or ionic line radiance ratio methods with iron, titanium, and zinc tracer elements introduced as aqueous solution aerosols. Gas temperatures and ionization temperatures, also determined spectroscopically, indicate departure from local thermodynamic equilibrium (LTE). The ICP discharge also appears to be thermalized by the injection of water. Since introduction of aqueous aerosols is undesirable during comparisons with theoretical models, the radiance of atomic lines of argon and the spectral radiance of the argon continuum were the selected temperature diagnostic methods. Argon atom wavelengths at 430.0 nm and 425.9 nm are measured as is the argon continuum at 533 nm. These techniques are less sensitive to measurement error than the radiance ratio methods, but they are not necessarily more accurate owing to the need for absolute transition probabilities, correction factors, and the assumption of local thermodynamic equilibrium.

Temperature profiles are determined at various axial positions; net lateral radiance profiles are reduced to radial emission coefficient profiles by means of the Abel inversion evaluated by the Nestor-Olsen method.

Of the three velocity measuring techniques available (i.e., particle tracking, impact tube, and laser Doppler anemometry) both particle tracking and Pitot tube measurements are used in the present investigation to define the spatial pressure and velocity distributions in the induction discharge. The velocity is calculated from the spatially resolved pressures using Carelton and Kadlec's (6) modified form of the Bernoulli equation. Initial measurements were made manometrically whereas recent determinations utilize an electronic pressure transducer with either analog or digital readout. High-speed photographic particle tracking provides trajectory visualization and quantitative velocity data in spatial zones adjacent to those defined by the Pitot-tube measurements. Alumina particles are fluidized and injected with the argon carrier gas stream.

3. RESULTS

Two independent sets of data are collected for the argon ICP discharge at 26.5 MHz. The quartz plasma torch consisted of three concentric tubes the outermost one of which was 18 mm internal diameter (7). The range of experimental operating parameters considered are listed in Table 1. Excitation temperatures derived from absolute radiance of Ar I 430.0 nm and 425.9 nm compare well with those obtained from the Ar continuum measured at 533 nm. Stagnation pressure distributions measured with water-cooled Pitot tubes 3.4 mm and 1.83 mm in diameter are recorded throughout the discharge with 2 mm axial resolution, and velocities are calculated for corresponding temperature and pressure data.

Radial and axial temperature and velocity results indicate an off-axis temperature maximum and centerline temperatures that strongly depend upon the central argon gas velocity and, therefore, upon the injection nozzle shape and volumetric gas flow. The central gas velocity distribution in the discharge is moderately confined in the induction coil region and expanding downstream from the induction coil. In many respects the central region of the discharge appears to respond independently of the discharge annulus and its outer edges for changes in the central zone flow. Similarily, variation in the outermost gas flow rates does not seriously affect the temperatures along the discharge centerline. All of the experimental observations are consistent with theoretical velocity and temperature values based upon semi-empirical computer models.

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REFERENCES

(1) R.M. Barnes, Crit. Rev. Anal. Chem., 1978, 7, 203.
(2) H.U. Eckert, High Temp. Sci., 1974, 6, 99.
(3) V.M. Gol'dfarb, "Thermal and Gasdynamic Methods for Diagnostics of Plasmas" and "High-Frequency Inductive Plasmatrons", in "Physics and Technology of Low-Temperature Plasmas", edited by S.V. Dresvin (Iowa State University Press, Ames Iowa 1977).
(4) V. Kh. Goykhman and V.M. Gol'dfarb, "The Radiofrequency Thermal Induction Discharge", in "Plasma Chemical Reactions and Processes", edited by L.S. Polak (NAUKA Publishing House, Moscow 1977); English translation by Th. Cheron and H.U. Eckert.
(5) A. Czernichowski and J. Jurewicz, Pr. Nauk. Inst. Chem. Nieorg. Metal. Pierwiastakow Rzadkich Politech. Worcław., 1975, 24, 3; English translation in ICP Inf. Newsl., 1976, 2, special issue 1, 1.
(6) F.E. Carleton and R.H. Kadlec, AIChE J., 1972, 18, 1065.
(7) R.M. Barnes and R.G. Schleicher, Anal. Chem., 1975, 47, 724.

TABLE 1 RANGE OF EXPERIMENTAL OPERATING CONDITIONS

Plasma Torch Configuration	18 mm id (7)
Central Injection Nozzle Orifice	0.9 to 2.1 mm
RF Input Power(7)	0.46-0.85 kW
Gas Flow Rates Argon	
Outer (Plasma)	10-18 L/min
Intermediate	0 L/min
Central	0-1.8 L/min