

ELECTRON-TEMPERATURE AND ELECTRON-DENSITY PROFILES IN AN ATMOSPHERIC-PRESSURE ARGON PLASMA JET

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ABSTRACT

Line-shape analysis of the electron feature of Thomson-scattered laser light has been used to directly determine axial electron-temperature and electron-density profiles of an atmospheric-pressure argon plasma jet. Measured centerline values of the electron temperature are in excess of 20000 K at the torch exit, and remain essentially constant with increasing axial distance even though the plasma is recombining. The electron temperature profiles are compared with gas temperature profiles determined by both high resolution line-shape analysis of the ion feature of Thomson-scattered light and enthalpy probes, as well as temperatures profiles determined from emission spectroscopy. One concludes from this comparison that the plasma is far from local thermodynamic equilibrium.

INTRODUCTION

Direct measurement of heavy particle kinetic temperature, electron temperature, and electron density in plasmas is, to the authors' knowledge, only possible by line-shape analysis of Thomson-scattered laser light. If the degree of ionization of the plasma is low, Rayleigh scattering dominates and only heavy particle kinetic temperature can be measured. For electron densities greater than 10^{22} m^{-3} the scattered-light line shape consists of a central narrow ion feature and a broad symmetric electron feature. Analysis of this line shape yields heavy-particle temperature, electron temperature and electron density without having to assume that the plasma is in local thermodynamic equilibrium (LTE).

This paper presents axial electron-temperature and electron-density profiles of an atmospheric-pressure subsonic argon plasma jet discharged into ambient air, determined from line-shape analysis of the electron feature of Thomson-scattered laser light. Electron-temperature profiles are compared with temperature profiles determined from LTE emission spectroscopy and gas-temperature profiles determined from line-

shape analysis of the ion feature of Thomson-scattered light and enthalpy-probe measurements.

THEORY

Laser light is scattered by a plasma because of density fluctuations of the scattering centers in the plasma. In the case of Thomson scattering, density fluctuations of the free electrons in the plasma are due to thermal motion of the free electrons, plasma waves, and density fluctuations of ions. The latter density fluctuations result in the ion feature of the Thomson line shape, while the former case results in the electron feature of the Thomson line shape. Interpretation of the Thomson line shape requires only an assumption that the electrons and ions have Maxwellian velocity distributions. However, no assumption is made about the existence of LTE. Analysis of the electron-feature line shape yields electron temperature and electron density. Analysis of the ion feature gives the gas or kinetic temperature. The details of the line shape theory are discussed elsewhere [1].

EXPERIMENT

The argon plasma jet studied was generated by a Miller Model SG-100 plasma torch. The laser source was a Q-switched frequency-doubled pulsed neodymium-doped yttrium aluminum garnet (Nd:YAG) laser operating at a wavelength of 532 nm. The pulse duration was 10 ns and the pulse rate was 10 Hz. The scattered laser light was spectrally resolved using a 1.3-m monochromator equipped with a 600 groove mm^{-1} grating. Line shapes were detected using a thermoelectrically-cooled gated 576 x 384 pixel two-dimensional intensified charge-coupled device (ICCD) diode array detector. The gated intensifier was triggered by the firing of the laser. The incident laser beam was focused into the plasma using a 1.5 m focal length lens to reduce perturbation of the plasma by the laser beam. The torch was operated vertically, and the scattering angle was 90° to both the plasma flow axis and incident laser beam. Emission spectroscopy data consisting of neutral and singly-ionized argon lines were taken using the same optical and detector setup except that a 90° image rotator was placed in the optical path to orient the plasma jet image horizontally on the monochromator entrance slit. More details of the experimental setup can be found elsewhere [2]. A schematic of the scattering experiment is presented in Fig. 1.

RESULTS AND DISCUSSION

Typical electron features taken at the radial position $r = 0$ mm and axial position of $z = 2$ is presented in Fig. 2. The torch current and voltage was 900 A and 23 V, respectively, and the argon flow rate was 35.4 l min^{-1} . This line shape was accumulated over 50 laser pulses to improve the signal-to-noise ratio. The intense peak at 0 GHz is the unresolved ion feature. The smooth line is the nonlinear least squares fit of the line-shape theory to the data, excluding the ion feature. Electron temperature and electron density were determined from this fit

to be $26750 \text{ K} \pm 3\%$ and $1.40 \times 10^{23} \text{ m}^{-3} \pm 3\%$, respectively. The electron temperature is high due to laser heating, as will be discussed shortly. The symmetry of the line shape implies that the electron velocity distribution function is Maxwellian as assumed [3]. The effect of convolution of the instrument response function with the line shapes was minor, changing the fitted values of the electron temperature and density by $< 2\%$.

Significant laser heating of the electrons by linear inverse bremsstrahlung was observed. This made it necessary to measure electron temperature as a function of incident laser pulse energy. The unperturbed or actual electron temperature was then found by extrapolating the linear fit of the data to the 0 mJ pulse^{-1} laser energy [4,5]. A representative laser heating curve, taken at $r = 0 \text{ mm}$ and $z = 2 \text{ mm}$ with a torch current of 900 A is given in Fig. 3. Electron-density values were not observed to be significantly affected by the laser energy. Unless otherwise noted, all electron-temperature data reported have been corrected for laser-heating effects.

Plotted in Figs. 4 and 5 are the 900 A centerline axial electron-temperature and electron-density profiles, respectively. Also plotted in Fig. 4 are temperatures determined from emission spectroscopy, and gas temperatures determined from ion-feature line-shape analysis [6] and enthalpy-probe measurements [7]. Emission temperatures were calculated from absolute intensity measurements of the 696.5 nm and 738.4 nm neutral argon lines and the 480.6 nm singly-ionized argon line assuming LTE [8]. In Fig. 4, the solid circles are electron temperatures determined from Thomson scattering. The solid squares are gas temperatures determined from ion feature measurements of Thomson scattered light and enthalpy-probe measurements. The open circles, triangles, and squares are temperatures determined from emission spectroscopy of the 480.6 nm singly ionized Ar transition, and the 738.4 nm and 696.5 nm neutral Ar transitions, respectively.

The electron temperatures measured from Thomson scattering are surprisingly high. The electron temperature is almost twice the gas temperature at the torch exit. This degree of non-LTE was not expected. These data also suggest that even partial local thermodynamic equilibrium (PLTE) does not exist. Equally surprising is the apparently weak connection between the electron temperature and the electron density. The axial dependence of the electron temperature remains almost constant even though the electron density decreases significantly with increasing axial distance as the plasma recombines, as shown in Figs. 4 and 5. This behavior was not predicted by an argon relaxation-kinetics model used to describe the plasma [9]. According to this model, in order to sustain the temperature difference observed the classic electron-ion momentum transfer rate [10] must be decreased by a factor of at least 50. Furthermore, the excited-state Saha equation [11], using the emission results to determine excited-state densities and the measured electron temperatures, predicts that the plasma should be ionizing instead of recombining. This would rapidly cool the

electrons and increase the electron density in contradiction with the observations.

Because of the high observed electron temperatures, the possible influence on the measurements by systematic errors was thoroughly investigated [2]. For example, unrealistically high temperatures could result if accounting for the effects of laser heating of the electrons was done incorrectly. The electron temperature as a function of laser energy curve of Fig. 3 is quite linear. This strongly suggests that non-linear laser-plasma interactions [3] are not occurring, and supports the assumption that the unperturbed electron temperature can be found by extrapolating this function to 0 mJ pulse^{-1} . As a further check, the incident laser beam was defocused, increasing the beam waist diameter by about a factor of 6. This decreased the beam intensity by a factor of 36 and should virtually eliminate laser heating of the electrons. This was indeed observed. Centerline electron temperatures measured at $z = 2 \text{ mm}$ and $z = 20 \text{ mm}$ with a torch current of 900 A were independent of the laser energy and were very consistent with the values presented in Fig. 4. We therefore conclude that laser-heating effects have been accounted for properly. The linearity of electron temperature as a function of laser energy curve also strongly suggests that collisional effects on the line shapes were not significant [2].

An important concern that must be addressed when performing line-shape experiments on a fluctuating system such as a plasma jet is the effect accumulation of many individual line shapes has on the measurement. Two different Thomson line shapes do not superpose to produce a third Thomson line shape. In this experiment, centerline values of the electron density were sufficiently high that a line shape with an adequate signal-to-noise ratio was obtainable from a single laser pulse. From 30 to 50 single pulses were recorded on the centerline at $z = 2 \text{ mm}$ and $z = 20 \text{ mm}$ with a torch current of 900 A. After analysis of the single-pulse line shapes, average values of the electron temperature and electron density were calculated. The individual line shapes were then added together, and the resulting accumulated line shape was analyzed. In all cases, single-pulse data agreed very well with the results of the accumulated line shape.

CONCLUSIONS

Electron-temperature and electron-density profiles of an atmospheric-pressure argon plasma jet were made from analysis of the electron feature of laser light Thomson scattered by the plasma. No obvious source of systematic error in the line shapes was found, and we believe that these results are correct in the context of the line shape theory. These measurements suggest that significant deviations from LTE persist throughout the plasma. Measured centerline electron temperatures are in excess of 20000 K in the torch exit plane, while gas temperatures at the same location are about 12500 K. Furthermore, the electron temperature remains almost constant with increasing axial distance even though the electron density decreases significantly. A comparison of the measured electron temperatures with temperatures

determined from emission spectroscopy indicates that departures from PLTE also persist. There is a large discrepancy between the experimental results and the expected behavior predicted by an argon relaxation-kinetics model. The reason for this discrepancy is presently not understood.

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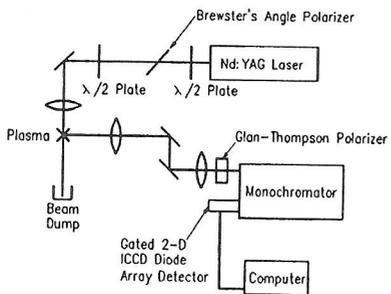


Fig. 1. Experimental schematic.

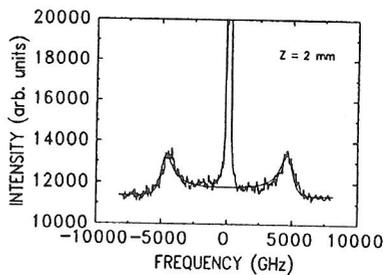


Fig. 2. Experimental electron feature at $r = 0$ mm and $z = 2$ mm.

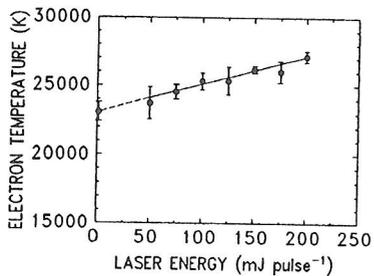


Fig.3. Electron temperature as a function of laser energy.

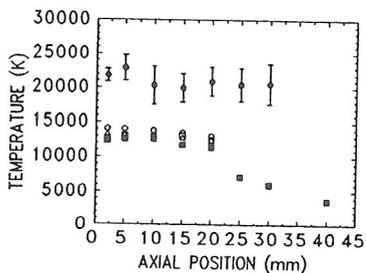


Fig.4. Axial temperature profile at $r = 0$ mm.

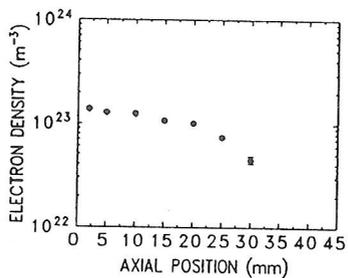


Fig. 5. Axial electron density profile at $r = 0$ mm.