Schlieren imaging of an axially-symmetric RF plasma

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1 Introduction

This project investigates the electro-acoustic coupling mechanism that makes a plasma generate sound. Due to its conductive nature, the charged particles in the plasma respond readily to a modulating electric field. As in natural lightning, rapid thermal expansion and heating in the ionised column produces external pressure variations at the modulation frequency. Spatial and temporal measurement of the gas temperature, $T_g$, relative to the modulation frequency can identify the nature of the thermal expansion and provide a direct approach to understanding its relationship to the sound pressure wave generated.

The gas temperature can be determined through spectroscopic measurement of the rotational line emission of $N_2$ Second Positive System from which the rotational temperature, $T_r$, is calculated; at atmospheric pressure, $T_r \approx T_g$ due to short rotational-translational (R-T) relaxation. However, this method is limited spatially to the main current channel where the high energy electrons required for excitation in $N_2$ occur. A fuller picture can be revealed by imaging the plasma using the Schlieren method.

2 The Schlieren method

![Schlieren image](image.png)

Figure 1: The plasma sustained at 18mA (left) and its comparative schlieren image (right)

Schlieren utilises the refraction of light in the plasma to provide information on its radial temperature distribution. Refractive index gradients, resulting from variations in temperature, cause angular deflection of a previously parallel incident beam which is focussed in the image plane. Spatial filtering with a knife edge cut offs part of a source image, providing a reference background illumination with which to detect the intensity variations caused by the object in the test path. The resulting phase differences are converted to an amplitude differences when projected onto a 2D plane (figure 2 - right) and the resulting intensity differences relative to the reference background illumination can then be related back to the original phase object.

2.1 Experimental set-up

A dual-field lens Schlieren system (figure 2) was constructed using a 40W tungsten-halogen bulb (A) combined with a 670nm filter as a near-monochromatic light source with an optical configuration that produces a near-collimated beam in the test area (B). The beam is focussed onto a razor edge and the diverging beam collimated and imaged onto an Andor DH534 iCCD camera (C). The spatial resolution of the camera is approximately 27um/pixel. The razor was oriented vertically and the refractive index gradients in the radial direction are detected.
2.2 Analysis

The cylindrical symmetry of the plasma lends itself well to analysis using an Abel-type transform. A gaussian temperature profile, with peak temperature and standard deviation as the two variable parameters, was used to calculate a modelled deflection angle, $\varepsilon(y)$, using the following [1],

$$
\varepsilon(y) = 2y \int_y^\infty \frac{d(n-1)}{dr} \frac{dr}{(r^2 - y^2)^{1/2}}
$$

The refractivity, $n-1$, and gas density are related through the empirical Gladstone-Dale relation, $n-1 = \kappa \rho$ where the Gladstone-Dale coefficient, $\kappa$, for air is 0.23 cm$^3$/g [2]. The gas density was determined from the modelled temperature profile using the ideal gas equation, $\rho = pRT$. The modelled deflection angle was fitted to a measured data set with the root-mean-square error used to determine best fit. Data was acquired with the plasma sustained at four current settings and for a 3kHz modulation with a modulation depth of 33% on the conduction current.

3 Results and discussion

3.1 The plasma in the steady-state

The surface plots in figure 3 show the radial temperature variation of the plasma for several conduction currents. An increasing current is accompanied by the expected increase in temperature close to the main current channel and broadens the temperature profile through increased convection radially. The vertical
assymmetry is common for all settings and occurs from the convective flow vertically. For an axial position, \( z = 7 \text{mm} \), \( T_g = 2200-3400 \text{K} \) and correlates well to the equivalent \( T_r \) measured spectroscopically [3]. However, the differences occur between \( T_g \) and \( T_r \) around the electrode region by around 40%. This is being investigated further but may result from calculation errors caused by the deviation from cylindrical symmetry in this area. Additional, cooling of the gas molecules may occur from the air drawn in with the convective flow from around the bottom electrode.

3.2 The plasma under modulation

![Figure 4: The time-dependent variation of the temperature profile measured over two periods relative to 3kHz modulation for four axial positions. (Spatial dimension: \( r = 10 \text{mm} \)](image)

The results acquired over two periods relative to 3kHz show a clear variation in \( T_g(t) \) around the electrode but becomes relatively stable with little discernible change in \( T_g(t) \) further up the plasma column. Again, this effect was seen in \( T_r \) where the high modulation depth on the current causes increased convective flow into the main body either disrupting or 'masking' the modulation; with a lower modulation depth \( T_r(t) \) can be detected in the main body though it is less than half that measured around the electrodes. Radially, the temperature varies within a 1mm distance and indicates the gas heating originates from the kinetic processes in the main current-carrying channel. Convection away from this channel maintains the broader temperature profile but there is negligible contribution to sound generation from this region.

4 Summary

The Schlieren method is a simple and effective method for obtaining quantitative measurements of the gas temperature and to gain a general understanding the nature of the plasma. The temperatures correlate well with measurements made independently through spectroscopy and calculation of the overall uncertainty for Schlieren will provide more confidence in the approach. The dominant source of temperature variation (and hence sound emission) occurs within 1mm both axially and radially around the electrode region and may indicate the plasma acts mainly as a point source though the level of contribution to sound generation from the main body needs to be confirmed.

References

