Visualising gas heating from an RF plasma loudspeaker

Conference or Workshop Item

Visualising gas heating from an RF plasma loudspeaker

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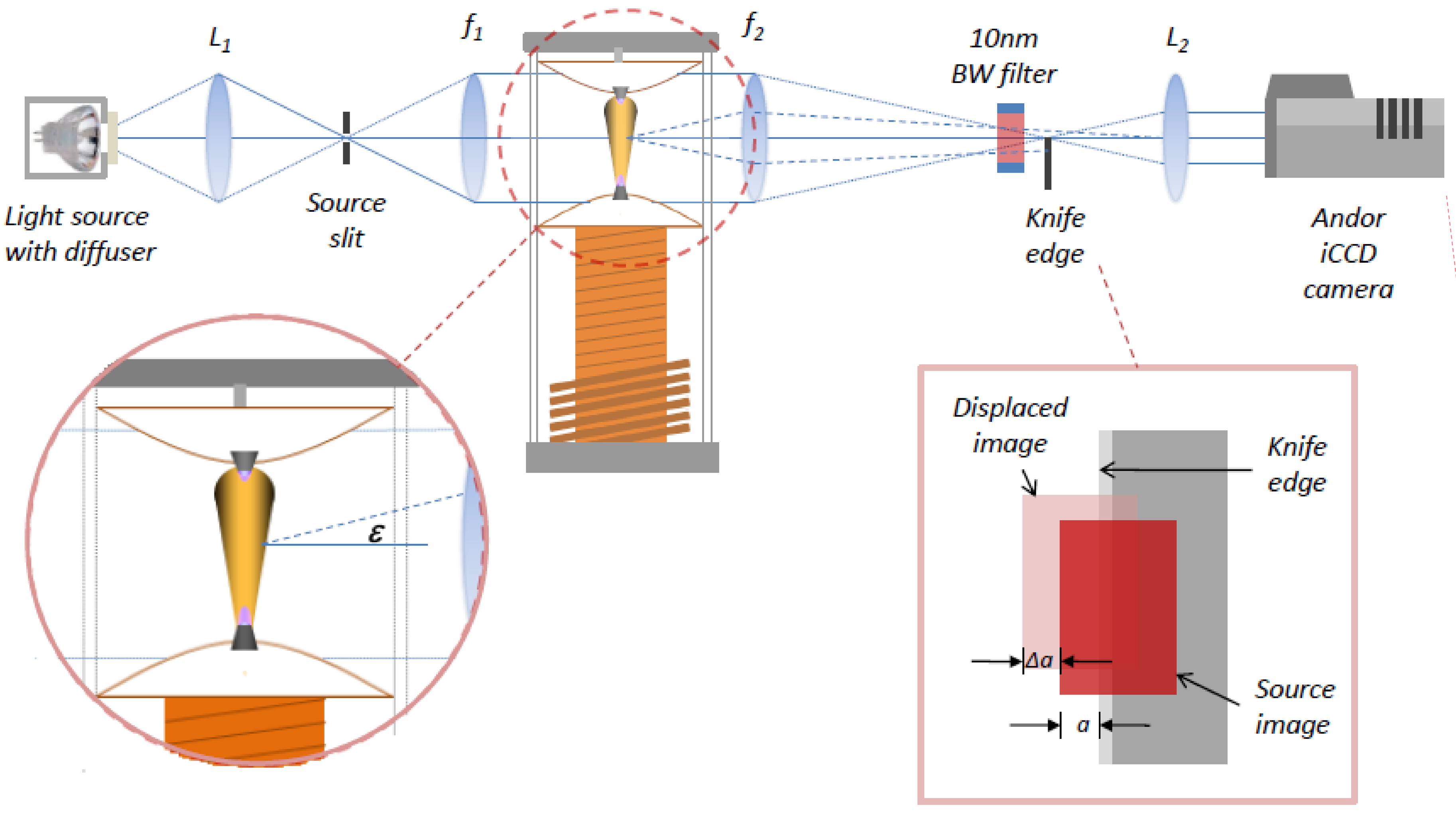
Introduction

In an electro-acoustic transduction mechanism, an ac modulation (here in the audio frequency range) of the electric field in an atmospheric pressure air plasma gives rise to a rapid increase in the gas temperature and dimensions of the gas volume. As in natural lightning, the rapid expansion in the ionised column though the air produces external pressure variations at the modulation frequency.

Spatial and temporal measurement of the gas temperature can identify the nature of the thermal expansion and provide a direct approach to understanding its relationship to the sound pressure wave that is generated. However, the established method through spectroscopic measurement of rotational line emission from nitrogen molecules is limited to the main current channel where relaxation and subsequent optical emission of the excited nitrogen molecules occurs. The wider picture is revealed through the use of the Schlieren method where the refractive index gradients caused by gas heating in the plasma are imaged.



Experiment and model

An atmospheric pressure, air plasma is generated using a solid state Tesla coil operating at a resonant frequency of 325kHz. Upon breakdown, the plasma is sustained at a voltage of 4-5 kV_{p-p} with a conduction current, I_{rms}, between 11-30mA. The rotational temperature, T_{rot}, has been measured previously through spectroscopy and lies in the range of 2800-3400K for the conduction current given previously. The electron density, calculated from the conductance, is in the region of $3x10^{18}$ m^{-3}.

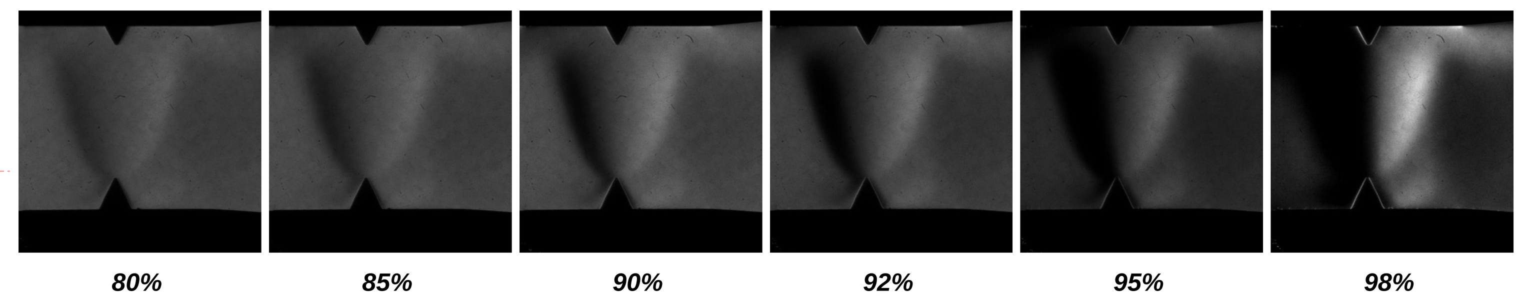
The plasma was imaged using a duel field lens system. A 40W tungsten-halogen bulb with a 632nm filter provide a narrow band monochromatic source. The area covered by the CCD was $24mm^2$ with a pixel resolution of 26μm. A razor, mounted on a travel stage with 0.01mm resolution, was used as the knife edge and for a 92% image cutoff and *F* = 750 mm for the imaging lens, f_2, the minimum detectable deflection angle, ε_{min}, is approximately 1", equivalent to a change of 100K in the gas temperature.

The model was adapted from a convection stabilised DC discharge, with vertical and axial symmetry [2,3]. For this plasma a free boundary exists, stabilisation occurs through natural convection; axial and radial structure are modelled. Adaptation to an RF model was done on the basis of an equivalent rms current input (I_{rms}) and averaging of ionisation and rate constants over the RF period [4]. Non-LTE behaviour is accounted for including deviations of the electron energy distribution from Maxwellian, deviations of the vibrational distributions of molecules from Boltzmann distributions and diffusion of the various species. Energy balance equations accounting for variation in gas 'temperature' and mean vibrational excitation of N_2 molecules . The model includes the balance equations for the number densities of N, O, NO and electrons.

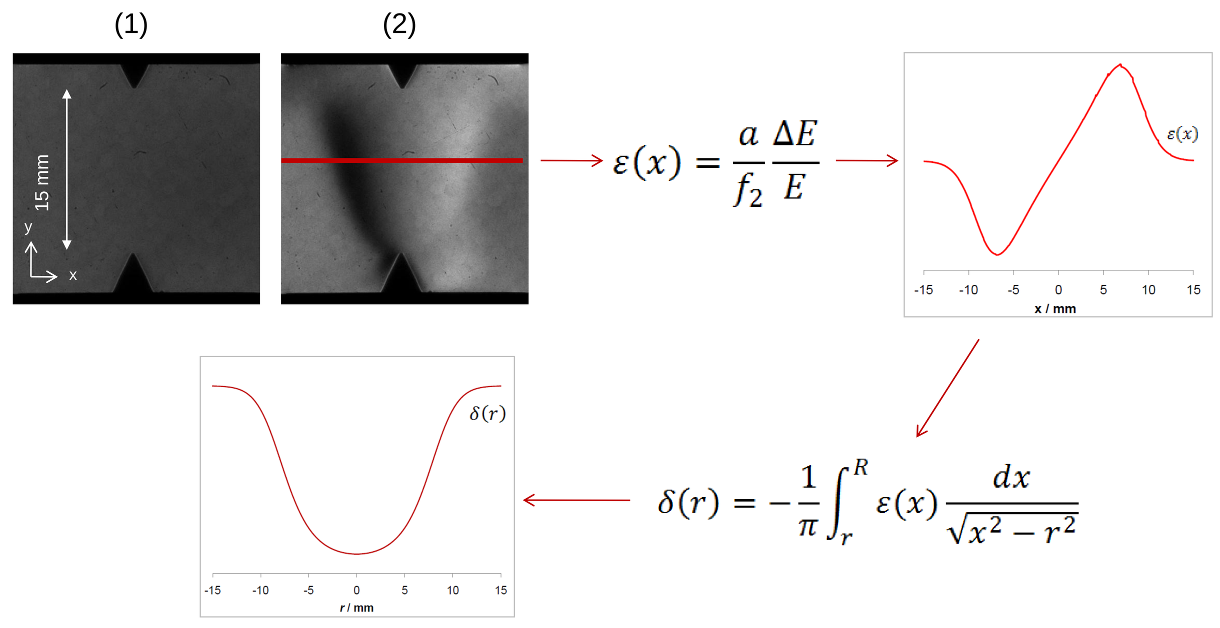
The Schlieren method

The Schlieren method utillises the refraction of light in a plasma to provide information on its radial temperature distribution. Refractive index gradients in the plasma causes angular deflection, ε, of a previously parallel incident beam. The resulting phase differences are converted to an amplitude distribution when projected onto a 2D plane with light and dark contrast regions resulting from the illuminance relative to a reference background illuminance level.

The sensitivity of a system, *S*, is the rate of change in the image contrast with respect to deflection angle and can be determine through the relation, *S* = *F/a* where *F* is the focal length of the imaging lens, f_2, and *a* is the unobscured width of the source image. Use of a long focal length lens in the image plane and high degree of cutoff of the knife edge on the source image provides high sensitivity where the smallest deflection angles can be detected.



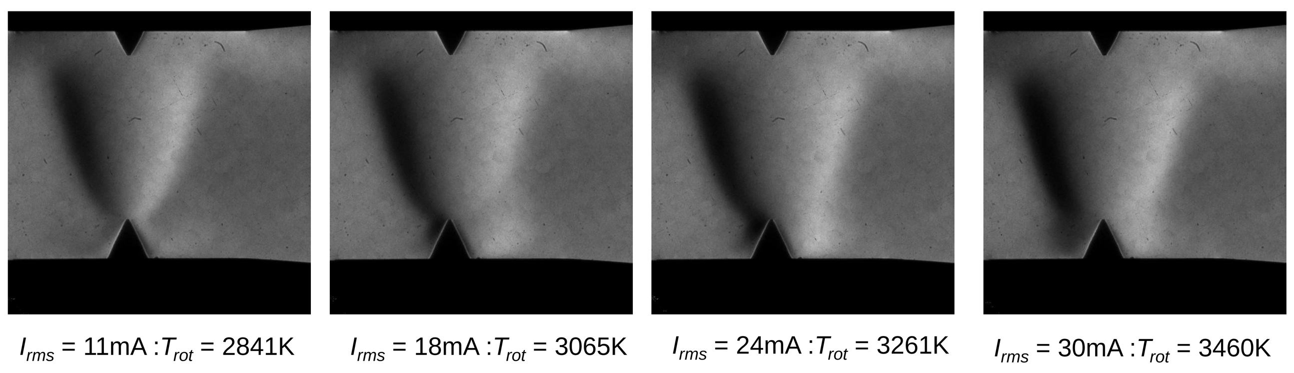
The degree of knife edge cutoff is taken as the ratio of unobscured width to total width of the source image and its effect for several cutoff levels can be seen above. Increasing the cutoff leads to increasing contrast changes. The dark regions above 95% cutoff results from strongest refractions that cause the displaced image to move entirely onto the knife edge. As a result, a change in image illuminance is no longer produced; this effect is known as *underanging* [1].



Analysis

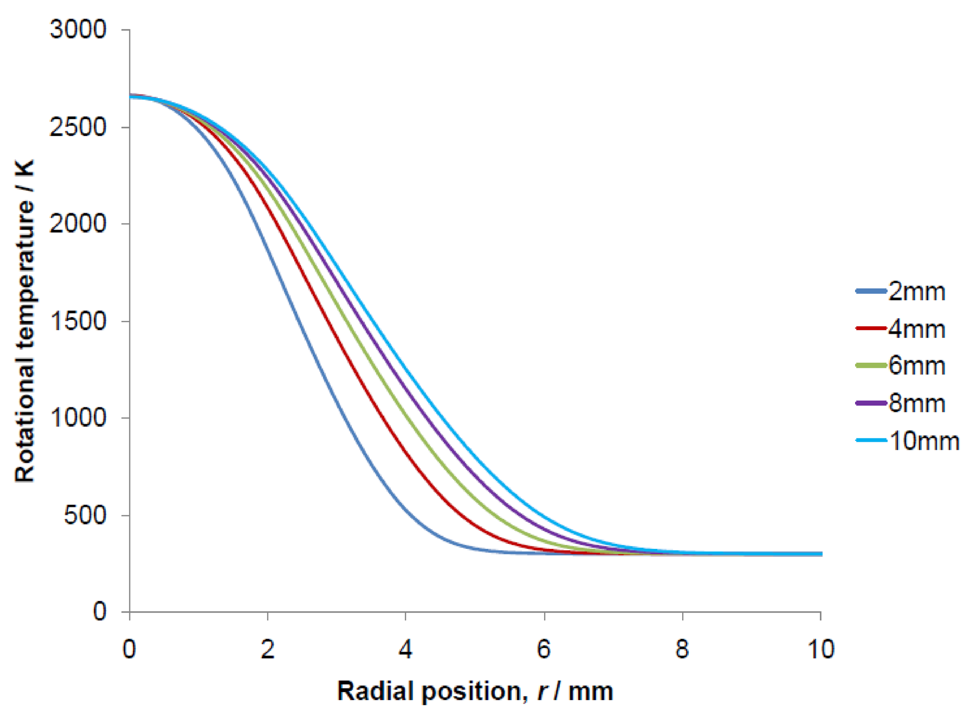
The background (reference) image (1) is subtracted from the Schlieren image (2) to give the differential illuminance, Δ*E*. The deflection angle was calculated from a line of sight intensity profile and Abel inversion converts the defection angle profile into a radial distribution of the refractive index gradient where $\delta(r) = (n-1)$. The gas density was calculated using the relation $(n-1) = k\rho$, a simple linear relation used for gases, where *k* = Gladstone-Dale coefficient for air. The gas temperature was calculated using the ideal gas equation.

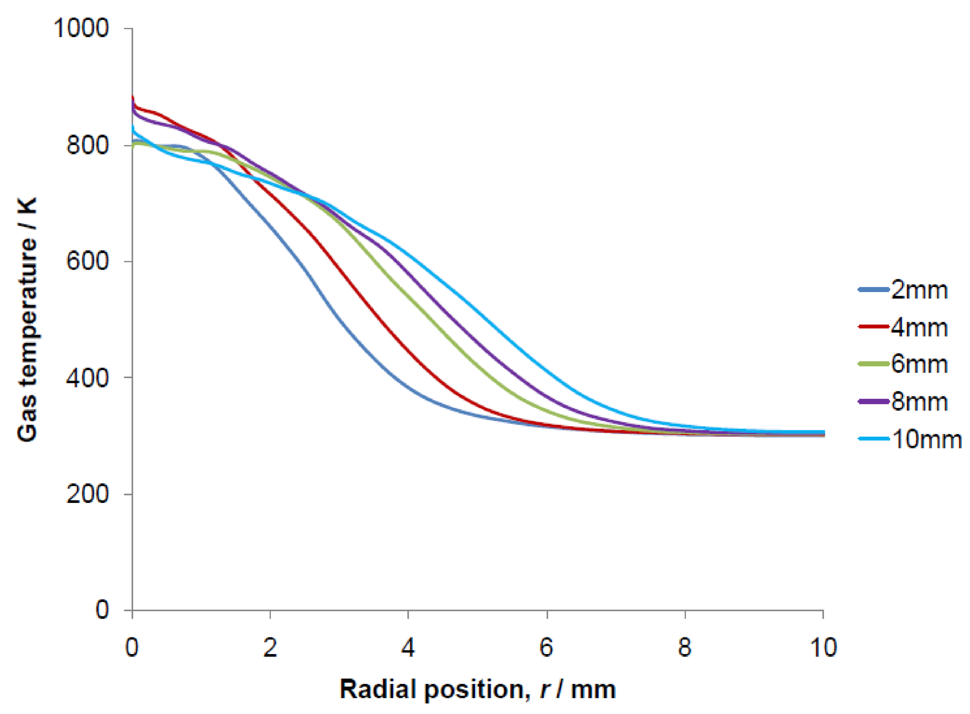
Results

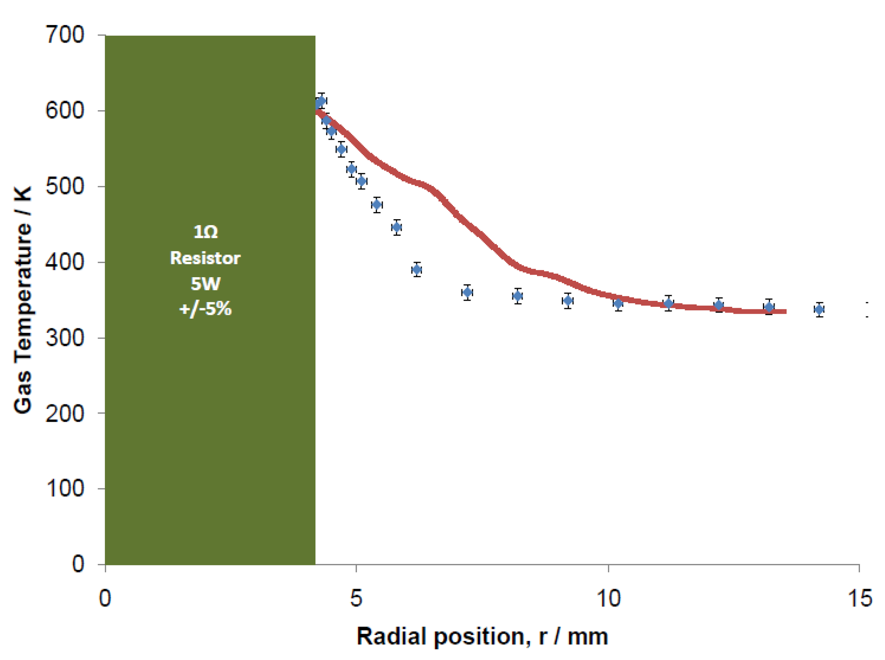


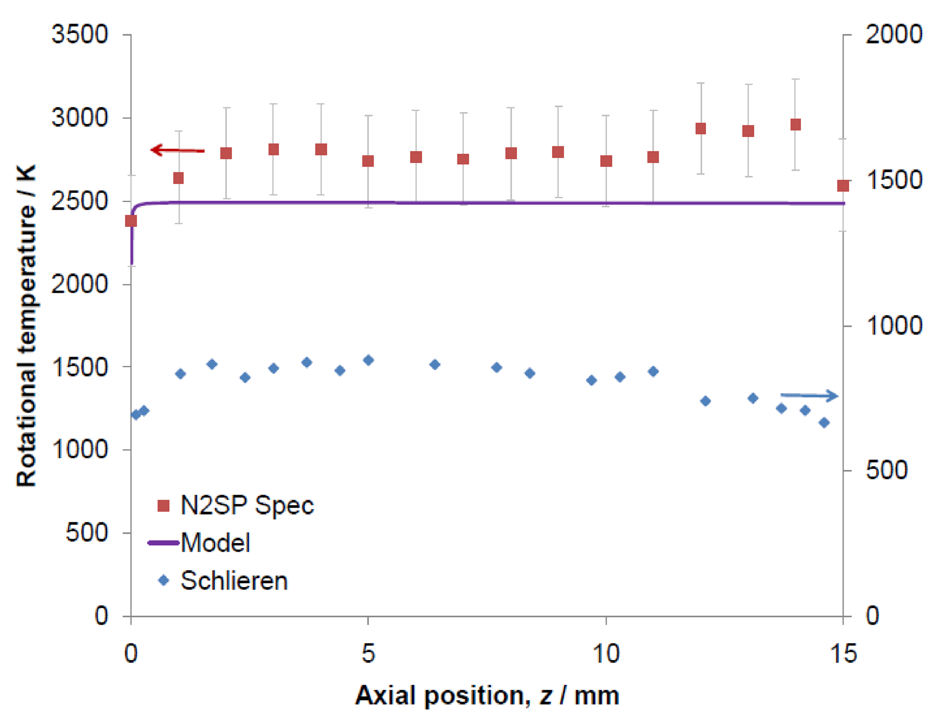
Visual comparison

The images for four input currents show the effects of increased heating in the plasma. The increase in the distance between the light and dark regions indicates broadening of the temperature profile. Increasing intensity between images shows the temperature is increasing in the column. Illumination around the electrode regions show the extent of heating outside of the main column with the illumination around the surface at the top electrode highlighting the spreading of convection currents, also a key factor in the vertical asymmetry.









Calibration

A 1Ω resistor drawing a current of 6A was used as reference heat source to calibrate the system. The temperature profile of the resistor was measured using a thermocouple. Although the temperatures compare well at the surface of the resistor and drop off to a common background temperature, the Schlieren profile identifies additional structure between 2-5 mm from the resistor surface. This may highlight regions of convective heating that may not be detected by a thermocouple due to its response time. Also, the high cutoff level used here leads to diffraction effects around the resistor which impacts on the calculation of the radial position and an uncertainty of +/- 1mm should be applied.

Radial and axial temperature

The gas temperature determined through Schlieren differs by a factor of three from that measured previously by spectroscopy and to that predicted by the model. The difference in the results may occur due to the analysis currently used. Refractivity is affected by the composition of a medium and although the ionisation levels in this plasma should not have an appreciably affect on the refractive index[5], calculation for a weakly ionised plasma would be more appropriate than the simple relation currently used.

Despite the difference in the temperatures, the model and measured results share common features. The radial profiles, calculated at several positions along the vertical axis, shows a steady expansion in the temperature profile reflecting that calculated for the model and results from gas heating and convection within the plasma. The full width, half maximum of the measured and modelled profiles are also comparable.

The temperature variation as a function of the axial position, *z*, shows the lower temperature around the electrode region compared to that in the main column and reflects the differences in the kinetic processes around the electrode region to that in the main body.

Summary

The Schlieren method shows promise as a simple and effective method for understanding the nature of the plasma and has highlighted characteristics of the plasma that have been measured through spectroscopy and predicted in the model. The technique requires further improvement in the analysis of the line of sight intensity profiles and the calculations of the gas density and temperature. Based on the expected change in gas temperature when the plasma being modulated, further improvements in the optical system may be necessary to improve the sensitivity.

Acknowledgments

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