Visualising gas heating from an RF plasma loudspeaker

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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 kVrms with a conduction current, \(I_{\text{rms}}\) between 1-30mA. The rotational temperature, \(T_{\text{rot}}\) has been measured previously through spectroscopy and lies in the range of 2600-3400K for the conduction current given previously. The electron density, calculated from the conductance, is in the region of \(3 \times 10^{10} \text{ m}^{-3}\).

The plasma was imaged using a dual 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 28pm. A razor, mounted on a travel stage with 0.01mm resolution, was used as the knife edge and for a 92% image cutoff and \(F = 750 \text{ mm}\) for the imaging lens, \(f_2\), the minimum detectable deflection angle, \(\varepsilon_{\text{min}}\), is approximately 1\(^\circ\), equivalent to a change of 100K in the gas temperature.

The model was adapted from a convective stabilised DC discharge, with vertical and axial symmetry\(^{[4]}\). 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 \((I_{\text{rms}})\) and averaging of ionisation and rate constants over the RF period\(^{[5]}\). Non-LTE behaviour is accounted for including deviations of the electron energy distribution from Maxwellian, 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 \(N, N_2, O\), and electrons.

**Results**

![Image](image_url1)

The images for 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 region shows 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 \(\pm 1\mm\) should be applied.

**Summary**

The Schlieren method provides 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 model. The technique requires further improvement in the analysis of the line of sight intensity profiles and the model. The technique requires further improvement in the analysis of the line of sight intensity profiles and the model.

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