Visualising gas heating from an RF plasma loudspeaker

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Visualising gas heating from an RF plasma loudspeaker
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Introduction
An electro-acoustic transduction mechanism, an ac moduation (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 through 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 325Hz. Upon breakdown, the plasma is sustained at a voltage of 4-5 kV peak with a conduction current, \(I_{\text{rms}}\), between 11-30mA. The rotational temperature, \(T_{\text{rot}}\), 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 current measurements, 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 provides a narrow band monochromatic source. The area covered by the CCD was 24mm\(^2\) with a pixel resolution of 26pm. A razor, mounted on a travel stage with 0.01mm resolution, was used in the knife edge and for a 92% image cut-off and \(F = 750 \text{ mm}^{-1}\) for the imaging lens, \(f\), the minimum detectable deflection angle, \(\theta_{\text{rms}}\), 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\[1, 2\]. 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\[3\]. Non-LTE behaviour is accounted for including deviations of the electron energy distribution from Maxwellian distributions, 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.

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 of the column 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 0.5 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 output level used here leads to distortion effects around the resistor which impacts on the calculation of the radial position and an uncertainty of \(\pm 1 \text{ mm}\) should be applied.

Analysis
The background (reference) image \(I(1)\) is subtracted from the Schlieren image \(I(2)\) to give the differential illumination, \(I_D\). The deflection angle was calculated from a line of sight intensity profile and Abel inversion converts the deflection angle profile into a radial distribution of the refractive index gradient where \(R(\phi) = (R - 1)\). The gas density was calculated using the relation \(\rho = \frac{
abla \phi}{\nabla \phi_{\text{air}}}\), a simple linear relation used for gases, where \(\nabla \phi\) is the Lorentz–Dale coefficient for air. The gas temperature was calculated using the ideal gas equation.

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\[4\], calculation for a weakly ionised plasma being modulated, further improvements in the optical system may be necessary to improve the sensitivity. 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.

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