Visualising gas heating from an RF plasma loudspeaker

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Introduction

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 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 current main 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 kVpp with a conduction current, \( i_{cc} \) between 11-30mA. The rotational temperature, \( T_r \), has been measured previously through spectroscopy and lies in the range of 2800-3600K for the conduction current given previously. The electron density, calculated from the conductance, is in the region of 3x10^{10} 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 28um. A razor, mounted on a travel stage with 0.01mm resolution, was used as the knife edge and for a 92% image cutoff of the knife edge on the source image provides high sensitivity where the smallest deflection angles can be detected.

Calibration

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 98% 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 underbracketing\(^1\).

Radial and axial temperature

The gas density was calculated using the relation \( n = \frac{p}{RT} \), a simple linear relation for \( n\) in air and nitrogen. Despite the difference in the temperatures, the model and measured results share a similar temperature distribution. Refractive index gradients in the plasma causes angular deflection, \( \epsilon \), 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 determined through the relation, \( S = \frac{\Delta I}{I_0} \), where \( I_0 \) is the focal length of the imaging lens, \( f \), and \( I_\epsilon \) 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.

Analysis

The background (reference) image (1) is subtracted from the Schlieren image (2) to give the differential illuminance, \( \Delta I \). 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 \( R(x) = \frac{(x - 1)}{8\epsilon} \).

The gas density was calculated using the relation \( n = \frac{p}{RT} \), a simple linear relation for \( n \) in air and nitrogen for gases, where \( k \) is Gladstone-Dale coefficient for air. The gas temperature was calculated using the ideal gas equation.

The Schlieren method

The Schlieren method utilises the refraction of light in a plasma to provide information on its radial temperature distribution. Refractive index gradients in the plasma causes angular deflection, \( \epsilon \), 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.

Results

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\(^2\), calculation for a weakly ionised plasma would be more appropriate than the simple relation currently used.

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 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 sensitivity of a system, \( S \), is the rate of change in the image contrast with respect to deflection angle and can be determined through the relation, \( S = \frac{\Delta I}{I_0} \), where \( I_0 \) is the focal length of the imaging lens, \( f \), and \( I_\epsilon \) 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.

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Acknowledgments

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 sensitivity of a system, \( S \), is the rate of change in the image contrast with respect to deflection angle and can be determined through the relation, \( S = \frac{\Delta I}{I_0} \), where \( I_0 \) is the focal length of the imaging lens, \( f \), and \( I_\epsilon \) 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.

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