DEVELOPMENT AND INVESTIGATION OF ATMOSPHERIC PRESSURE NON-THERMAL RF PLASMA JET

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Abstract

Non-thermal Atmospheric Pressure Plasma Jets (APPJs) are popular for the generation of various chemically activated species in ambient air. In interaction with the target, these species participate in a variety of favourable chemical reactions suitable for several industrial and biomedical applications. In this context, an accurate estimation of plasma parameters alleviates the optimization of plasma jets for applications. However, the realization of control and optimization of plasma jets for specific applications has a long way to go still, specifically for RF APPJ, where high frequencies introduce additional complexities in plasma diagnostics and source optimization. All this, therefore, necessitates an in-depth understanding of the APPJs and the influence of operating parameters on their characteristics.

In this thesis, a 13.56 MHz RF-based APPJ was designed and fabricated to investigate its characteristics under various operating conditions using argon and helium as feed gases. To boost the open circuit voltage at the plasma terminals and aid discharge initiation at low input powers (~2 W), an indigenously developed LC series resonant circuit is used in *between* the matching network and the APPJ device. This thesis reports a theoretical and experimental investigation on helium and argon plasma discharges in the RF APPJ in continuous wave (CW) and pulse modulation (PM) mode. Various diagnostic tools like electrical (V-I) probes, optical imaging, emission spectra, and thermal and acoustic measurements were employed extensively for the characterization of the APPJ.

The operation of APPJ in PM mode offered a lower gas temperature suitable for certain applications and revealed several unique characteristics of helium APPJ. To effectively describe the plasma features as a function of the modulating frequency (50 Hz -10 kHz), duty cycle (10-80%) and RF input power (10- 50 W) etc., a detailed and systematic study was performed on the PM helium APPJ. This study investigated the influence of RF modulation frequency on helium APPJ's fundamental characteristics i.e., discharge behavior, plasma dimensions, generation of reactive species, and the basic plasma parameters including electron density (n_e), electron excitation temperature (T_{exc}), and gas temperature (T_g). From the experiments, it was observed that operating the plasma jet at low pulse modulation frequencies (around 50 Hz) provides enhanced plasma dimensions (longer and more homogeneous plasma plume), higher electron density and

increased reactive species (viz., He I, O, OH, N_2^+, etc.) as compared to operation at higher modulation frequencies.

On the other hand, a plasma jet operated in PM mode with argon produced a novel helical shape APPJ, which is very different from the conventional smooth conical shape. In particular, this helical shape was observed when operated around ~ 2 kHz RF pulse modulation frequency, ~ 30% duty cycle, ~50 W applied power and ~ 1.5 lpm argon gas flow rate. It is most likely that the helical shape in argon APPJ originated due to periodic heating and cooling of the gas triggered by repetitive application of RF pulses, which imparted periodic thrusts to gas and plasma that can *excite sound or ion acoustic wave*s with non-zero azimuthal mode number (that can be shown to *carry orbital angular momentum* as well) in the plasma-gas mix. It is also possible for the electrostatic sound waves with orbital angular momentum to allow the formation of a helical-shaped jet. A physical model (along the above lines) attempting the origin of the helical shape of the APPJ is proposed along with a thorough experimental investigation to identify the operational parameter regime of the helical shape by employing a wide range of operating parameters.

Electrical diagnostics (voltage and current probes) are commonly used to estimate power dissipation in most conventional plasma loads. However, the use of standard Voltage (V) and current (I) probes with miniature devices like RF APPJs yields highly uncertain electrical characterization on account of the latter's highly capacitive nature of the sheaths at the electrodes. Consequently, one has a very ambiguous estimation of the RF power fed to the APPJ and hence, its plasma parameters. For accurate estimation of the electrical, and plasma parameters, a new calibration technique is conceptualized for V-I probes which avoided the measurement errors in amplitude and phase while utilizing them at RF APPJs. The calibration procedure involves generating a new set of calibration constants for the two probes from which one may determine the true voltage, V_t and the true current, I_t. Following the joint calibration of the probes, the V-I probe measurements yield fairly accurate and reliable estimates of the different electrical metrics like the average power absorbed by the plasma, the complex plasma impedance, forward and reflected wave amplitudes, etc. However, to estimate the plasma density (n), electron temperature (T_e) and other relevant parameters of the APPJ a model of the discharge region of the APPJ device is needed. The only input to such a model apart from the geometry of the device and the feed gas would be the power fed to the APPJ, which can be provided from the V-I probe measurements.

To support and augment the electrical measurements discussed above, an analytical, 2-D model for the APPJ's discharge region (inside the glass tube) is developed in this thesis. The model takes into account the gas flow and it is based on particle and power balance equations. It determined the radial and axial variations of plasma density (n), axial and radial fluxes, electron temperature (T_e), gas temperature ($T_{g)}$ and the total plasma and power flowing out of the discharge region with power fed to the discharge being given by the V-I measurement data. Typically, n is found to be $\approx 3.9 \times 10^{17}$ m^{-3} and $\approx 2.8 \times 10^{19}$ m^{-3} and T_e found to be ≈ 1.8 eV and ≈ 0.8 eV at 25 W of RF power for helium and argon plasma, respectively.