Gas Temperature Measurements in an Atmospheric Pressure Micro Plasma Jet

Asst. Lect. Qais Thanon Najim Algwari
Department of Electronics
College of Electronics Eng. / University of Mosul

Received: 22/3/2012 ; Accepted: 21/6/2012

Abstract:

The rotational (T_R) temperature of N_2 molecules, which is an inductor to gas temperature, was measured in atmospheric pressure micro-plasma jet in *He* with trace amounts of O_2 excited by radio-frequency (RF) power. The influence of different parameters such as input RF power to the plasma, different O_2 admixtures ratio and the RF pulse modulation frequency, on the gas temperature T_g was investigated. The results show that the control of the operating conditions of the plasma jets enables the tailoring of gas temperature.

قياس درجة حرارة الغاز في البلازما النفاثة الدقيقة عند الضغط الجوي

م.م.قيس ذنون نجم الجواري
قسم الإلكترونيك
كلية هندسة الالكترونيات / جامعة الموصل

ملخص البحث:

تم قياس الطاقة الحركية الدورانية والتي تعرف بدرجة الحرارة الدوارنية لجزيئات N_2 والتي تمثل درجة حرارة الغاز في بلازما الهليوم (مع كميات ضئيلة من O_2) عند الضغط الجوي المتولدة في النفاثة الصغيرة والمثارة عند الترددات الراديوية. شملت القياسات تأثير العوامل المختلفة، مثل طاقة الموجات الراديوية المسلطة على البلازما، نسب خلط مختلفة من O_2 والتضمين النبضي للترددات الراديوية (RF)، على حرارة الغاز. وأظهرت النتائج أن السيطرة على ظروف تشغيل نفاثات البلازما الدقيقة توفر درجة من التحكم في حرارة الغاز.

Introduction:

In plasmas, the density and velocity distribution functions are the main features can be used to describe the excited and ground state particles like atoms, ions and molecules. These features may not be the same for different species and states in non-equilibrium plasmas. Distribution functions can also be used for describing populations of different excited states. In the local thermodynamic equilibrium, i.e. Maxwell-Boltzmann situation, the conventional concept of temperature can be used. This is often the case for the atmospheric pressure plasma where the idea of temperature is meaningful to consider as effective quantities. In the literature of the atmospheric plasma, one finds reference of many different effective temperatures namely: Gas, rotational, vibrationl, and the excitation temperature, of certain groups of excited atomic levels [N Britun et al. 2007]. Hence, in non-equilibrium plasmas the concept of temperature may have a certain physical meaning, but often it is rather artificial.

Determination of the gas temperature or attempts to do that by emission and absorption spectroscopy is rather common in plasma diagnostics [J. R¨opcke, et al. 1998], [G.M. Jellum, et al. 1991], [J. Wiesemann, et al. 1997]. The using emission spectroscopy for the rotational temperature measurement is a well known and widely used method of temperature determination in gas discharge plasmas [N. K. Bibinov, et al. 2001].

In atmospheric pressure plasmas where the highly collisional nature is domain, it is reasonable to assume that the rotational temperature of the gas is in equilibrium with its translational temperature; as such the rotational temperature is a useful indicator of gas temperature.

There are different kinds of atmospheric pressure cold plasma jets have been developed with different electrode configurations, as well as power input e.g. RF, kHz [J. Waskoenig, et al. 2010], [Q. Algwari, et al. 2011]. Micro-plasma jet (µAPPJ) is one of such configurations. It is a capacitively coupled, non-thermal radio frequency discharge, usually operated at 13.56 MHz. When operated with a Helium and Oxygen gas mixture, the jet produces high densities of reactive atomic oxygen radicals in an ambient pressure environment and at low gas temperatures, promising high potential for technological exploitation. It is also ideally suited for treatment of temperature sensitive surfaces, for example, in biomedicine [D. O'Connell, et al. 2011]. This plasma's offer a cheaper and easier alternative to low pressure non-thermal plasma's as there is no longer a need for expensive, bulky vacuum technology. The work presented here will be confined to study the influence of the operational conditions on the gas temperature in non-thermal micro-scale atmospheric pressure plasma jet (µAPPJ).

Experimental apparatus

Figure 1 shows the schematic configuration of the micro-scale atmospheric pressure plasma jet (µ-APPJ). The micro atmospheric pressure plasma jet used in the present study consists of two plane parallel stainless steel electrodes capped with quartz windows along the sides, forming a core plasma channel 30 mm in length, with a 1 mm × 1 mm cross section. The employed set-up provides excellent optical access, making it ideally suited for diagnostics development. The jet is driven with an excitation frequency of 13.56 MHz with up to 67W power from an RF broadband amplifier via an impedance matching network. The plasma ignites around 25W input power, forming a homogeneous discharge across the length of the electrodes. At higher powers (> 70W), the plasma switches to a spatially constricted mode with a high current density, causing damage to the electrodes.

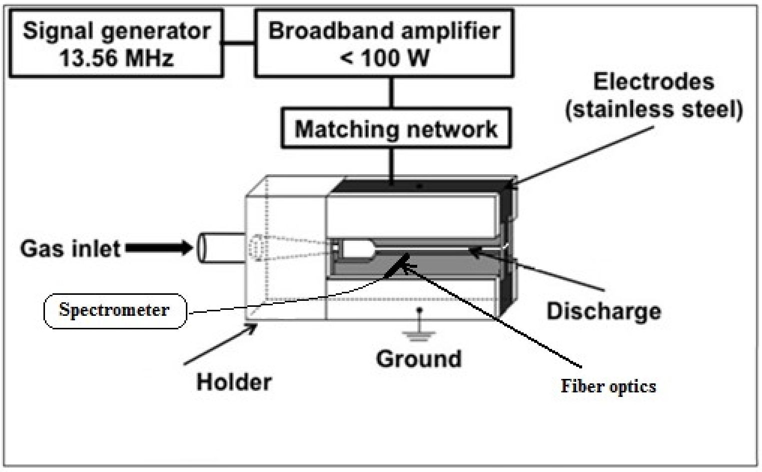

Fig. (1): Schematic of the RF-driven micro-atmospheric pressure plasma jet.

For the present study of the gas temperature measurement using emission spectroscopy, optical emission spectra of the core plasma of the μ-APPJ are measured using a sensitivity calibrated spectrograph (Ocean Optics HR4000 series - with *Toshiba* 3648 pixel linear CCD array detector) which covers a wavelength range from 320 - 418 nm. The light emission is collected perpendicular to the discharge channel through an optical fibre with a 600 μm diameter, and guided to the 5 μm entrance slit of the spectrograph. The effective spatial resolution of the fibre was measured to be about 1.4 mm. A time and space average across the discharge gap is obtained, with integration times typically in the order of one second. Ocean Optics provides a software package, *Spectrasuite,* which can be used to collect and record data from their spectrometers. The user sets the acquisition period and the iteration count. The software records the selected number of samples and gives the average count of that set of measurements, thus compensating for random fluctuations. The readout from the linear CCD array is in arbitrary units known as counts. Each count corresponds to a bundle of photons.

Atmospheric pressure helium gas with 99.996% purity was continuously fed through the micro discharge jet channel. The gas flow was controlled using a mass flow controller type (MKS247). Typical flow rate used in this work is 2 standard litres per minute (slm) which is equivalent to a flow speed of 33.3 ms^{-1}. This flow rate provide a laminar gas flowing in the discharge system because the Reynolds number is much lower than 2000. In order to investigate the influence of oxygen on the gas temperature, a small amount of oxygen, up to 0.625%, is added to the working gas.

Results and Discussions

As aforementioned at atmospheric gas pressures it is reasonable to suppose that the rotational temperature is the same as the gas temperature. It has also been reported that in the case of atmospheric pressure *He* with N_2 impurity, the equilibrium time between the rotational spectrum of N_2 and that of the surrounding gas is about 5 ns [N. K. Bibinov 2001]. The intensity of the nitrogen molecular rotational line corresponding to a transition from an upper level J' to a lower level J'' depends on gas temperature T. The value of the gas temperature is deduced from the measurement of the rotational distribution of the nitrogen molecular emission band ($C^3\Pi_u$ – $B^3\Pi_g$) around 380 nm was compared to simulation data. A computer fitting program is used to fit the simulation data curve to the N_2 ($C^3\Pi_u$ – $B^3\Pi_g$) rotational band. The program examines line positions, line strength factors, shape and strength of the band tail to calculate a rotational temperature.

Figure 2 illustrates the typical spectrum of the rotational band of molecular nitrogen recorded from plasma emission at the mid of the micro-plasma channel in He-O_2 discharge at operation condition of 2 slm gas flow rate and 67 W of the applied RF power.

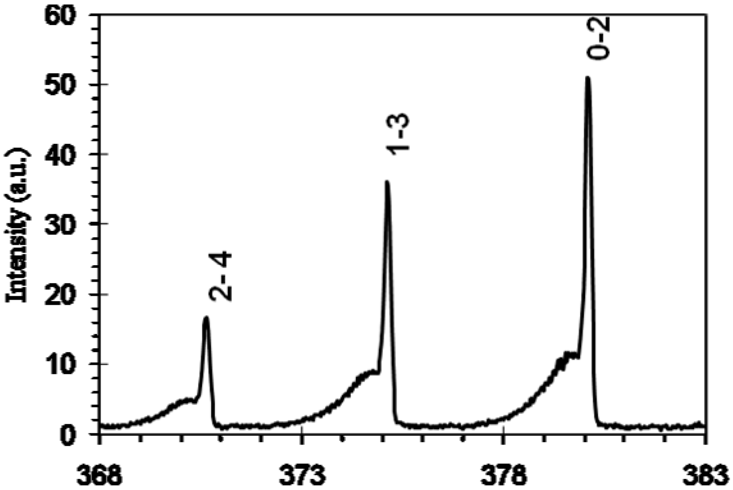

Fig. (2) Measured N_2 rotational bands spectrum of the discharge in mid of the plasma channel showing corresponding vibrational numbers at 2 slm gas flow and 67 W applied RF power.

The corresponding vibrational numbers are showing on the peaks of the spectrum. The high resolution of the spectrometer allows to clearly distinguish the (0-2), (1-3) and (2-4) branches from each level J of the atmospheric band. Although the working discharge gases are only helium and oxygen, the nitrogen emission comes from the back diffusion from ambient air because the discharge system works in open air environment.

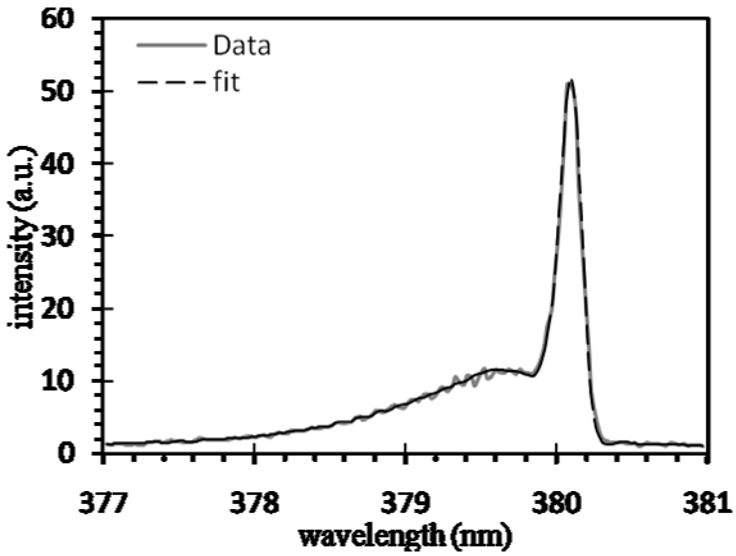

Fig. (3) The N_2 (0 - 2) rotational band of the spectrum in Fig. 2 (dash line) and the computer program fitting curve (gray line).

Figure 3 shows the N_2 (0 - 2) rotational band of the spectrum in Fig. 2, with the simulation data are overlaid on the experimental data and indicate a best-fit rotational temperature of 325.1 ^{o}K.

In order to investigate the influence of the applied RF power on the gas temperature in the plasma channel the gas flow is kept at constant flow rate of 2 slm with gas admixture of (He + 0.5% O_2) and the N_2 rotational bands spectrum is recorded for different values of input RF power.

Fig. 4 shows the evolution of the gas temperature as a function of the applied power, measured in the mid channel of the RF-µAPPJ. It can observe an increasing of the gas temperature with applied power. This might be related to energy consumption through molecular vibrational and rotational excitation, as well as dissociative processes not directly contributing to the plasma ionization.

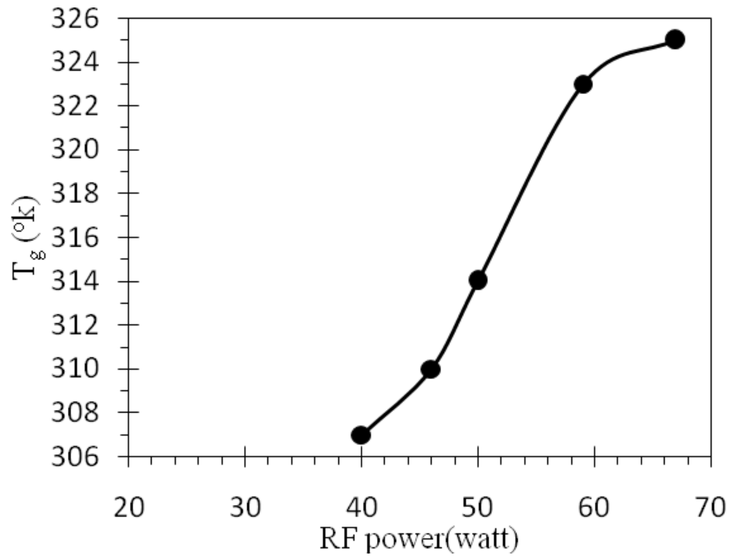

Fig.(4) Gas temperature T_g variation as a function of RF plasma power while operating plasma jet at helium flow of 2 slm and an O_2 admixture of 0.5%.

From [J. Waskoenig, et al. 2010], the electron density increases linearly with the applied power, while the reduced electric field (E/N) stays nearly constant. Thus, as the plasma volume is constant, increasing power means higher power density. This leads to higher gas temperature.

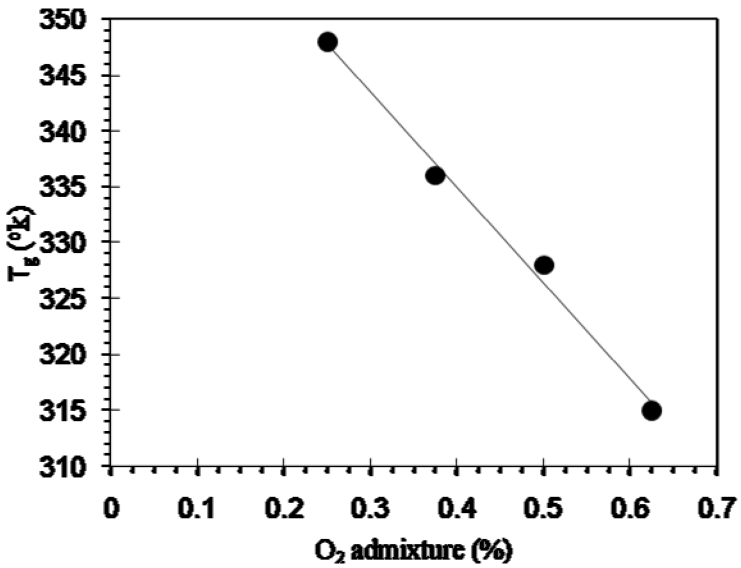

Fig.(5) Gas temperature as a function of the oxygen admixture while operating the RF plasma jet at 13.56MHz, with a He flow of 2slm and input power of 67W.

The fraction of O_2 admixture in atmospheric pressure *He* plasma plays a big role in chemical reactions of the plasma [Pitchford 2005]. So, it is necessary to investigate the influence of O_2 fraction on gas temperature. Figure 5 shows the evolution of the gas temperature T_g as a function of the O_2

admixture, measured in the mid channel of the RF-μAPPJ, 67W of the applied powers.

Generically, it can be observed a decrease of the gas temperature with increasing O_2 fraction. Varying the O_2 fraction is also likely to change the electron density and the reduced electric field (E/N), and the chemistry becomes even more complicated [Pitchford 2005].This could cause a quenching in plasma and hence the gas temperature decreases.

In order to obtain more manipulate of the gas temperature, the micro plasma jet is run in a pulse modulation mode. The RF input signal modulated with a square pulse frequency varied from 100 Hz up to 5000Hz. Figure 6 shows the variation of the gas temperature as a function of pulse modulation frequency at 2 slm *He* flow rate with O_2 admixture of 0.5% and input power of 67 W. It can be observed an exponential decreasing in the gas temperature with increasing the pulse modulation frequency.

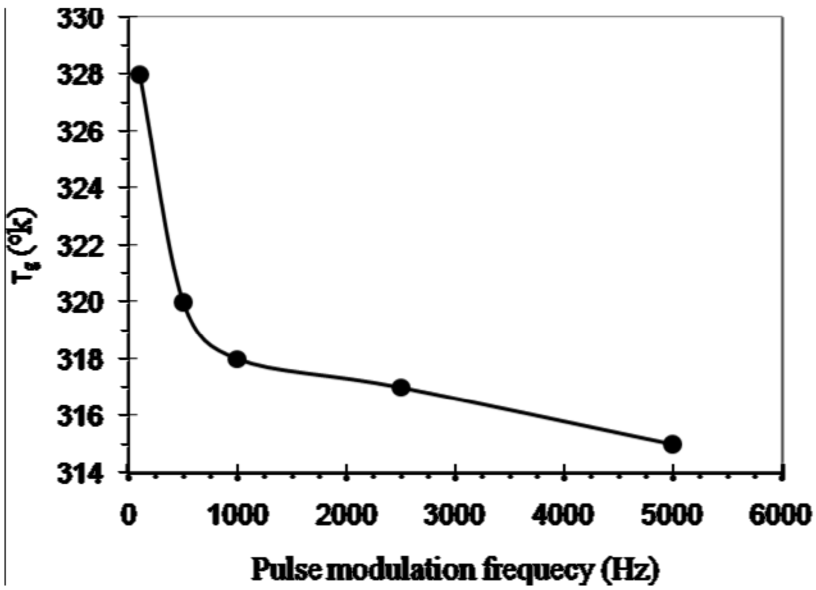

Fig.(6) Gas temperature T_g as a function of pulse modulation frequency while operating the RF plasma jet at 13.56MHz, with a He flow of 2slm and input power of 67W.

On-off Plasma switching causes a reduction in electron density and quenching in the most of reactive species of the discharge. At low modulation frequency, the plasma ignition required high electron energy and hence more power consuming in the plasma which causes increasing in gas temperature. As the modulation frequency increases the density of reactive species will increases compared to the previous state and hence less power required igniting the plasma.

Conclusions

The N_2 (0-2) rotational band may be used as a thermometer which easily appears in atmospheric pressure helium plasma. The gas temperature T_g has been measured in atmospheric pressure helium, with small amount of oxygen, discharge. An increase in gas temperature was found with input RF power increasing whilst a decrease in gas temperature with increasing the ratio of O_2 admixture. It was found that running the RF micro plasma jet with a pulse modulation mode provide additional degree of control of the gas temperature.

Acknowledgments

The author thanks Plasma Physics Centre, Queen's University of Belfast (UK) for providing the diagnostic setup. The author also thanks Dr. Kari Niemi (University of York, UK) for supporting in computer fitting numerical simulation program.

References

1) Q. Algwari and D. O'Connell (2011), "Electron dynamics and plasma jet formation in a helium atmospheric." *Appl. Phys. Lett.* 99 p. 121501.

2) D. O'Connell, L.J. Cox, W. B. Hyland, S. J. McMahon, S. Reuter, W. G. Graham, T. Gans, and F. J. Currell (2011), "Cold atmospheric pressure plasma jet interactions with plasmid DNA" *Appl. Phys. Lett.* 98 p. 043701.

3) G.M. Jellum, J.E. Daugherty, and D.B. Graves (1991), "Particle thermophoresis in low pressure glow discharges ." *J. Appl. Phys.* 69 p. 6923.

4) J. R¨opcke, M. K¨aning, and B.P. Lavrov (1998), "Spectroscopic diagnostics of molecular microwave plasmas." *Journal de Physique IV* 8 p.207.

5) J. Waskoenig, K. Niemi, N. Knake, L. M. Graham, S. Reuter, V. S. von der (2010), "Atomic oxygen formation in a radio-frequency driven micro-atmospheric pressure plasma jet." *Plasma Sources Sci. Technol.* 19 p. 045018.

6) J. Waskoenig, K. Niemi, N. Knake, L.M. Graham, S. Reuter, V. Schulz von der Gathen and T. Gans (2010), "Atomic oxygen formation in a radio-frequency driven micro-atmospheric pressure ." *Pure Appl. Chem.* 82 p.1209.

7) N Britun, M Gaillard, A Ricard, Y M Kim, K S Kim and J G Han (2007), "Determination of the vibrational,rotational and electron

temperatures in N_2 and Ar–N_2 RF discharge.” *J. Phys. D: Appl. Phys.* 40 p.1022.

8) N. K. Bibinov, A. A. Fateev, and K. Wiesemann (2001), “Variations of the gas temperature in He/N_2 barrier discharges .” *Journal of Physics D: Applied Physics* 34 p.1819.

9) M. G. J. Pitchford, and L. C. Hagelaar (2005), “Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models.” *Plasma Sources Sci. Techn.* 14 p.722.

10) I. P. Wiesemann, K. Vinogradov (1997)“Classical absorption and emission spectroscopy of barrier discharges in N_2/NO and mixtures .” *Plasma Sources Sci. Technol.* 6 p. 307.