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Comparison of analytical methods to determine the electron density and temperature for a laser-based atmospheric plasma jet

M. Schwander [a], P. Kwiatkowski [b], M. Prieske [a,*]

[a] BIAS - Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Str. 2, D-28359 Bremen, Germany
[b] Universität Bremen, Bibliothekstr. 1, D-28359 Bremen, Germany

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ABSTRACT

Highly dependent on plasma properties and the energy range, different approaches are used for plasma diagnostics. Measurements of the plasma potential, electron density, electron temperature are imperative for a full characterisation. However, when comparing published studies it seems that different measuring systems produce different results for the same plasma. In order to show that by using different measurement methods varied results are achieved, the following analytical methods are applied for a high-energy laser-based thermal plasma: Langmuir probe measurement, bottleneck equation, emission spectroscopy by Finkelnburg and emission spectroscopy by the Saha equation. The electron density and temperature are determined between 10^{17}–10^{20} m^{-3} and 1.1–1.8 eV by the use of Langmuir probes and $1.3{\cdot}10^{21}$ m^{-3} and 1.0–3.5 eV using emission spectroscopy. Comparison to other studies shows that our results are in the same range, according to the method of analysis. It is conspicuous that the choice of a measurement method predetermines the results in a certain range. This indicates that the chosen method has a huge impact on the resulting outcomes.

1. Introduction

Thermal plasmas are widely used in different industrial processes such as tool coating, deposition, welding and cutting. There is considerable interest in measuring the electron density, temperature, ion density, and plasma potential for any given plasma conditions. As mentioned, the various plasma diagnostic methods are mostly used in limited energy ranges. A distinction is made between invasive and non-invasive measurement methods. Commonly used non-invasive measurement methods include optical emission spectroscopy and laser scattering.

Contact measurements offer the opportunity to carry out an analysis not only on the surface, but also inside an extended plasma. Therefore, so-called Langmuir probes have a wide application and provide a convenient and simple way to characterise plasma. The plasma potential can be readily measured using a conducting probe. Nevertheless, every invasive method causes several problems, naturally given the direct interaction with a high-energy and destructive medium.

The aim of this work involves determining the characteristics of a high-energy laser-based thermal plasma, as well as giving a review of commonly used plasma diagnostic methods. Depending on the system, some methods are preferred due to natural boundaries given by the process. There is a certain trend in the use of these methods, because some approaches for plasma characterisation are difficult to achieve by certain plasma parameters.

* Corresponding author.
E-mail address: Prieske@bias.de (M. Prieske).

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2. Experimental methods

2.1. Process ignition chamber

The diagnostics are performed on a plasmajet process, which is usually used for growing diamond films by chemical vapor deposition (CVD) [1] and for depositing thin films by physical vapor deposition (PVD) [2]. The relevant components are summarised in Fig. 1. The power supply and maintenance of the plasma are provided by a 6 kW powered CO_2 laser (TLF 6000) with a wavelength of 10.6 μm. The laser beam enters the argon flooded ignition chamber through a ZnSe window (70 mm ø) and is focused by a copper mirror with a focal length of 175 mm. The initial point of the plasma jet is the focus of the laser beam. The transmitted laser radiation is absorbed by a cooled beam trap. A detailed description of all process parameters is reported in [3]. In Fig. 1, the positions are specified over a length of 19 mm, in which the various measurement principles and calculations were performed to determine the density and energy of the particles.

2.2. Bottleneck equation

Due to the high energy density and poor accessibility owing to the surrounding ignition chamber, no measurements could be performed in the focus of the laser. For this reason, a calculation was performed by assuming a bottleneck [4] as the upper energy and density estimation. It is assumed that the energy can be divided in three independent energy states. These are: kinetic energy of the electrons $[E_e] = eV$,

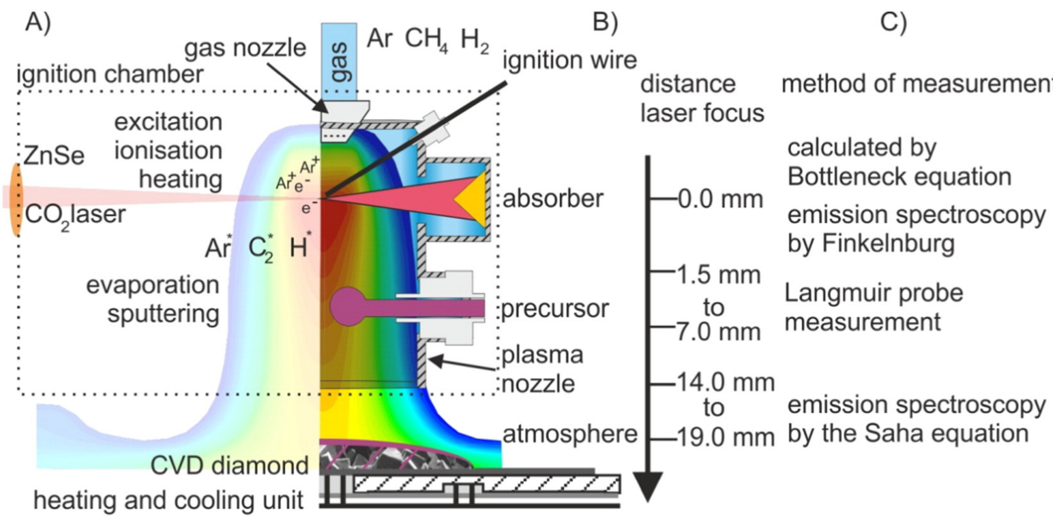

Fig. 1. A) Schematic illustration of the coating process with the description of interaction processes, and B), C) the ability to use different methods of measurement at different distances (BIAS ID 142086).

kinetic energy of the atoms $[E_{th}] = eV$ and ionisation energy $[E_I] = eV$. The kinetic energy of the atoms includes the ionised atoms and the electrically neutral gas. A prerequisite for this consideration is a static condition after ignition of the plasma. The absorbed power $[P_{Ab}] = W$ corresponds to the irradiated laser power $[P_{Laser}] = W$ multiplied by the absorption coefficient of the plasma σ_{Abs}. For the absorbed power, an average power of 3360 W and a volume flow of 20 slm of argon is calculated.

Without consideration of the recombination of the electrons and relaxation of the excited states, the thermal energy transport can be described by the power $[\dot{Q}_W] = W$, the heat radiation $[\dot{Q}_I] = W$ and the mass flow $\dot{m}$. In this case, $[c_p] = J/(kg \cdot K)$ corresponds to the specific heat capacity and the temperature difference ΔT between the inflowing and outflowing gas. Moreover, when the conduction and thermal radiation of the gas is neglected, energy transport takes place only on the mass flow, as shown in Eq. (1).

$$\frac{\partial E_{th}}{\partial t} = c_p \cdot \frac{\partial m}{\partial t} \cdot \Delta T \tag{1}$$

Since the ignition chamber fulfils the function of a "flow box", it corresponds to the mass flow of the constants $[\dot{m}_0] = kg/s$. With the average flow velocity $[v_{c0}] = m/s$, the mass flow is given by the volume flow $[\dot{V}_{c0}] = m^3/s$ and density $[\rho_0] = kg/m^3$ of the inflowing gas through the nozzle surface $[A_0] = m^2$. The mean particle velocity $[\bar{v}] = m/s$ is calculated using the mass of the particles and the local temperature, as given in Eq. (2).

$$\bar{v} = \sqrt{\frac{8k_BT}{\pi m_M}} = \sqrt{\frac{8RT}{\pi M}} \tag{2}$$

The introduced power is absorbed in the spherically symmetrical absorption volume with the radius $[r_{Ab}] = m$, the cross-sectional area $[A_{c1}] = m^2$ and the spherical surface $[A_{c2}] = m^2$. The incoming volume of the gas stream part $[V_{c1}] = m^3/s$ flows into the absorption volume with the average flow velocity. By assuming a constant density, the volume $[V_{c1}] = m^3$ expands through heating to the volume $[V_{c2}] = m^3$. By mass conservation, a balance between inflowing and outflowing gas must prevail. This results in Eq. (3) for the outgoing flow rate, which is dependent on the incident energy and the flowing volume. The remaining parameters are the energy flow by kinetic energy of the atoms $[\partial E_{th}/\partial t] = W$, the specific heat capacity at constant pressure $[c_p] = J/(kg \cdot K)$ and the temperature when entering the absorption volume $[T_{c1}] = K$.

$$\frac{\partial E_{th}}{c_p \cdot \rho_0 \cdot 4 \cdot \pi \cdot r_{Ab}{}^2 \cdot T_{c1} \cdot \partial t} + \frac{\dot{V}_{c1}}{4 \cdot \pi \cdot r_{Ab}{}^2} = V_{c2} \tag{3}$$

2.3. Emission spectroscopy

The integral determination of the plasma temperature and the composition are carried out by the use of optical emission spectroscopy (OES). A fibre-coupled grating spectrometer with the model name STE BC 220/1000 from the company Laser 2000 GmbH is used. Through an entrance slit of 25 μm and a grating with 600 lines/mm, a resolution of 1.5 nm results in the spectral range of 220–1100 nm. The measurements are performed with integration times of 1–100 ms and an accumulation factor of 1–10. Due to the high emission of the plasma, a neutral density filter from Schott AG with a transmission of 0.01% can optionally be added in front of a collimation lens.

The use of the collimating optics can be performed at three positions, as illustrated in Fig. 2A). The measurement can be carried out at an angle to the vertical of 0° (γ), 32° (δ) and 90° (β). To determine the cooling of the plasma jet during excitation, the measuring point β is displaced in the direction of the z axis. Due to the integral measuring principle, the distance to the plasma nozzle cannot go below 2.5 mm.

The measurement inside the ignition chamber can take place through an access that is normally used for the evaporation of additional materials as in Fig. 2A) (α). Instead of the precursor, a single quartz glass rod is introduced with a diameter of 3 mm at whose end the glass fibre of the spectrometer is fixed B). Depending on the used ignition chamber, the measurement is carried out at an angle of 15° or 45°. In order to prevent evaporation of the silica glass, the rod of not more than 3 mm is introduced. Since the optical line of the quartz glass rod is below the laser focus and the distance to the vertical always surpasses 4 mm, the measurement permits only a statement about temperature at a distance of more than 1.5 mm from the laser focus.

2.3.1. Spectroscopy by Finkelnburg

In the case of plasma with a low density, as is the case with atmospheric pressure, the output of electromagnetic radiation can be observed by analysing the emission lines. This cannot be described with Planck's radiation law. Instead of the emission coefficients, the "Effective