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Flow Diagnostics in Non-thermal Atmospheric Pressure Plasma Jets

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Atmospheric pressure plasma jets generate highly reactive species with lifetimes spanning orders of magnitude. Species flux, relevant for plasma surface interaction, strongly depends on generation and transport processes. In non-thermal plasma jets at atmospheric pressure, flow induced convection determines the transport processes. This work compares diagnostic methods to measure flow in plasma jets.

1. Introduction

Non-thermal atmospheric pressure plasma jets are applied for plasma medicine and treatment of sensitive surfaces. In order to gain better control over the processes of plasma surface interaction, however, particle fluxes need to be determined. For this, species concentrations, and just as importantly the jet flow field, need to be analyzed. To measure the effect of flow in plasma jets, a number of techniques have been developed in the past. In this work, established and novel flow diagnostic techniques will be discussed.

2. Plasma Jets

A variety of plasma jets based on different physics principles has been developed [1]. Radio frequency and kilohertz excited, capacitive coupled or dielectric barrier discharge jets typically require high gas flow to avoid temperature instabilities [2, 3]. Plasma jets excited by nanosecond pulses can operate with very low gas fluxes of a few tens to hundreds of standard cubic centimeters per minute [4]. Special configurations of dielectric barrier discharges generate a jet flow through ion wind and do not require an external gas supply [5]. To measure the flow in a plasma jet,

the diagnostic technique needs to be chosen according to the plasma source.

3. Flow Diagnostic Techniques

Different techniques for flow analysis are presented in figure 1. Generally, two approaches can be distinguished. Approach one aims at determining only gas mixture fractions or gas distribution: e.g. for the identification of turbulent flow regimes, Schlieren diagnostics, Rayleigh scattering, and planar laser induced fluorescence spectroscopy yield reliable results. The second approach aims at determining flow velocity fields in plasma jets. Here, tracer methods such as particle imaging velocimetry and laser electronic excitation tagging can be applied. Conventional anemometry techniques, using probes such as hot wire anemometry or pitot tubes, in most cases are considered too invasive for plasma jet diagnostics.

3.1. Flow Distribution

A comparably simple method to analyze flow distribution, distinguishing e.g. laminar and turbulent flow, is Schlieren diagnostics [6]. In a knife edge setup (fig. 1a), Schlieren systems measure the derivative of the refractive index perpendicular to the edge. The molar fraction χ_i of a species i with a

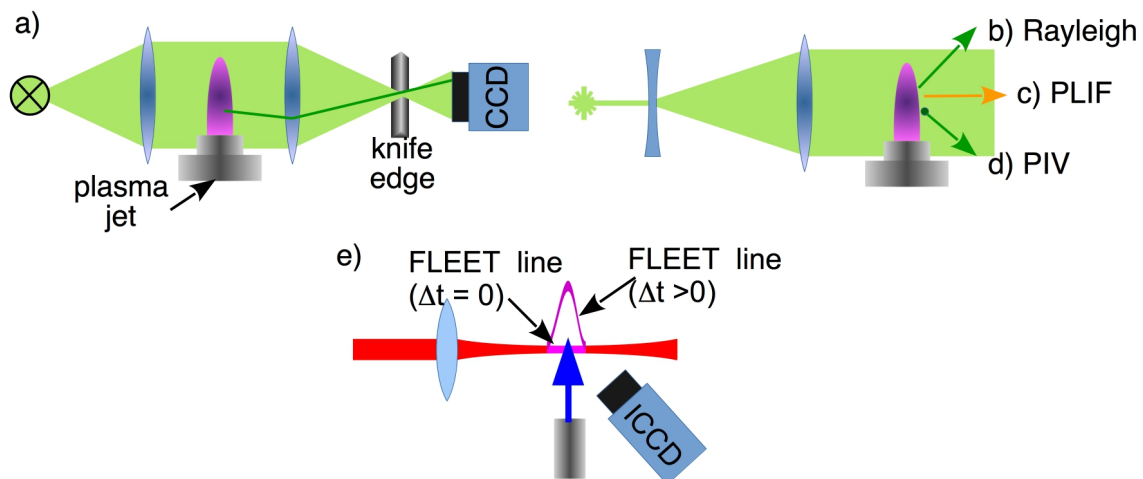


Fig. 1. Schematics of flow diagnostic techniques used for plasma jets. Flow pattern characterisation can be performed by a) Schlieren, b) Rayleigh scattering, and c) planar laser induced fluorescence spectroscopy; flow velocity fields can be measured by d) particle imaging velocimetry or e) laser electronic excitation tagging.

*) at times of measurements

polarizability α_i and density N – and thus its gas temperature – can be derived from the refractive index $n(r)$ gained from an Abel inversion of the measured data through the Lorenz-Lorentz relation:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi}{3} N \sum_i \chi_i \alpha_i$$

Schlieren measurements are line of sight measurements.

Rayleigh scattering presents a 2D-method for measuring flow distribution, where a 2D-laser sheath illuminates the flow region to be studied (See XXXIV ICPIG contribution [7]). The Rayleigh scattering signal of a species is proportional to its mole fraction. In a two-component flow, such as a noble gas jet flow into air, the mixture fractions can be derived from the Rayleigh signal intensity.

A further 2D-resolved flow diagnostic technique is planar laser induced fluorescence spectroscopy (PLIF) [8]. A laser sheath excites either molecules that are present in the plasma jet gas, such as e.g. OH molecules, or tracer molecules, which have to be added to the gas flow, such as e.g. acetone (see fig. 2). The resulting images show the flow pattern and – by taking quencher densities into account – species concentration distribution.

3.2. Velocity field

To measure flow velocity fields, consecutive images need to be recorded with a time difference according to the flow velocity. Tracing the observed volume elements yields flow velocity vectors. A common method for determining flow velocity fields is particle imaging velocimetry (PIV): Small tracer particles are introduced into the gas flow and illuminated. Consecutive camera images trace the paths of the introduced tracer particles. In a recent study, the flow of a DBD flow actuator was analyzed, using 100 μm sized oil droplets as tracer particles and a double pulse laser with order of 100 μs delay as light source [9]. When PIV is applied to plasmas, however, particle charging can influence the plasma and the measurements. Therefore, tracerless velocimetry is of great relevance. Technically, Schlieren and PLIF are suitable for IV in turbulent flow. Turbulent flow leads to eddy

formation; these eddies can be traced as virtual particles. Often, eddy formation cannot be resolved sufficiently or contrast is too low so that flow can only be estimated with Schlieren and PLIF [10].

A novel tracerless flow diagnostic technique is femtosecond laser electronic excitation tagging (FLEET), where electronic excitation leads to e.g. nitrogen dissociation [11]. The nitrogen atoms recombine on a μs timescale to a radiative molecular state. The light emission from the excited molecular state can be used as tracer for the gas flow leading to a one-dimensional flow velocity profile with high spatial resolution.

Figure 2 shows measurement results for the techniques described. Analyzing flow properties with the described techniques, will in future make possible to better determine and control transport and energy dissipation processes in plasma jets.

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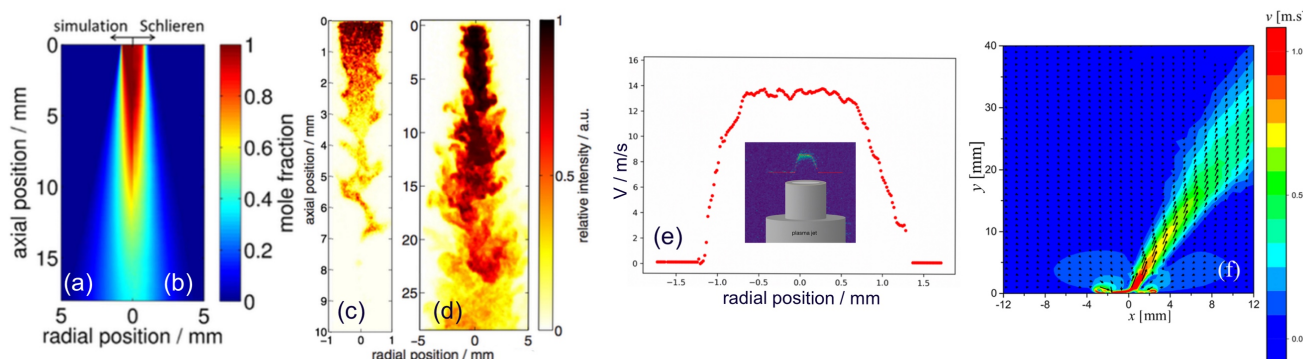


Fig. 2: Computational and experimental results from a) fluid dynamics calculations [6], b) Schlieren [6], c) and d) planar laser induced fluorescence spectroscopy [8] on OH (c) and acetone (d), e) FLEET f) particle imaging velocimetry [9]