FLUCTUATIONS OF LIGHT INTENSITY IN THERMAL PLASMA JET GENERATED BY WATER STABILIZED DC ARC TORCH

M. Hrabovský, M. Konrád, V. Kopecký
J. Hlína*

Institute of Plasma Physics AS CR, Za Slovankou 3, 182 11 Prague 8
*Institute of Electrical Engineering AS CR, Dolejškova 2, 182 02 Prague 8
Czech Republic

Abstract

Using an optical system with monochromator and linear array photodetector we studied fluctuations of light intensity emitted by various parts of thermal plasma jet. The jet with extremely high plasma velocity and low density was produced in water plasma torch. Three different types of plasma flow disturbances were identified on the basis of analysis of measured signals, that are related to the entrainment of cold ambient gas into the jet, movement of anode attachment region of the arc and oscillations produced within the arc chamber and in the exit nozzle.

1. Introduction

Stability and structure of the flow in dc arc thermal plasma jets are important characteristics determining performance properties of the plasma systems in the applications like plasma spraying or chemical waste decomposition. Instabilities and mixing in thermal plasma jets produced by gas stabilized dc arc torches were studied by Russ et al. [1, 2]. It was shown that low ratio of plasma density within the jet to ambient density is principal cause of intensive mixing and unsteadiness of the jet. The entrainment of the ambient gas is a dominant mechanism affecting the structure and the stability of the jet. The scaling of characteristic frequencies of the jet fluctuations was investigated in [1, 2]. The entrainment of ambient gas and its effect on cooling and deceleration of plasma flow was studied in detail by Pfender et al. [3].

In our present study we investigate fluctuations and structure of plasma jet generated in water plasma torch. Some parameters of plasma jet, especially plasma flow velocity, density and torch power are substantially different from the conditions in the experiments with gas torches described in [1-3]. Our investigation is performed at very low jet density and high plasma flow velocity. The local measurements of optical radiation from the jet provide information about space distribution of fluctuations within the jet and makes possible to detect several sources of the instabilities.

2. Experimental

The oxygen-hydrogen plasma jet was generated in the torch with dc electric arc stabilized by water vortex, that is created in cylindrical arc chamber with tangential water injection. The arc burns between rod graphite cathode and the rotational disc anode located outside the arc chamber 2 mm downstream of the exit torch orifice. The anode surface created by the edge of the disc is flush with the lower edge of the exit torch nozzle, the width of the anode is 15 mm. The diameter of exit nozzle was 6 mm. More detailed description of the torch is presented in [4, 5].

The operating parameters of the torch and the characteristics of the jet are given in Table 1. The data in the Table 1 were evaluated from measurements of electric characteristics of the arc, calorimetric measurements on the stabilizing system and spectroscopic investigations [4]. Besides integral bulk characteristics also centerline values are given for more complex representation of the jet.

Table 1. Torch operating parameters and jet exit conditions

arc current (A)	300	400	500	600
power input (kW)	84	106.8	139	176
net power (kW)	32.04	50.3	65.6	88.3
mass flow rate (g/s)	0.204	0.272	0.285	0.325
bulk mean temperature (K)	13 750	14 500	15 400	16 200
centerline temperature (K)	19 000	23 000	26 200	27 200
bulk mean density (kg/m^3)	$4.15x10^{-3}$	$3.64x10^{-3}$	$3.1x10^{-3}$	$2.72x10^{-3}$
centerline density (kg/m^3)	$1.92x10^{-3}$	$1.23x10^{-3}$	$0.98x10^{-3}$	$0.92x10^{-3}$
bulk viscosity (kg/m/s)	$9.14x10^{-5}$	$7.32x10^{-5}$	$5.3x10^{-5}$	$3.9x10^{-5}$
bulk velocity (m/s)	1 736	2 635	3 247	4 230
centerline velocity (m/s)	2 494	4 407	5 649	7 054
Reynolds number Re	473	786	1 140	1 770
bulk density ratio S	0.0034	0.0030	0.0026	0.0023
Mach number M	0.317	0.445	0.505	0.617

Comparing to the conditions in gas stabilized plasma jets studied in [1, 2], we have one order higher jet power and flow velocity, Mach and Reynolds number are slightly higher, the density ratio is about one third of values in [1, 2].

The optical system used in the experiments is modified version of the that described in [6]. The image of the jet was projected on the input slit of monochromator SPM-2 that was equiped with the linear array photodetector at the output slit. The detector consist of 8 silicon pin photodiodes with the amplifiers. The sequence of jet profiles was recorded by A/D board and processed by a PC computer. The interval between two subsequent profiles was 8μs.

3. Results and Discussion

Fig. 1 presents the time evolution of radial profiles of intensity of H_β line. The profile with two maxima is typical for the jet centerline temperatures higher than 18 000 K. The profiles were used for the evaluation of plasma temperature changes in [7]. The fluctuations of the intensity at various radial positions across the jet can be seen from the lines of equal intensities presented at the bottom of Fig. 1. The position r = 0 corresponds to the lower boundary of the jet adjacent to the anode surface. It can be seen that the lower part of the jet is more stable than the opposite upper part.

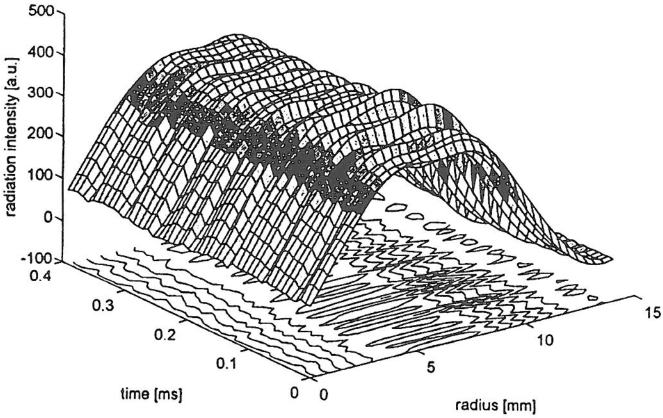

Fig. 1 Time evolution of the radial profiles of radiated intensity in the spectral window λ= 484 - 485 nm (H_β wing) with the corresponding contour plot taken at the position 5.5 mm downstream of the jet exit, arc current I = 400 A.

Power spectra of the signals of diodes in the radial positions corresponding to the lower edge of the jet (diodes 1 and 2) and to the upper edge of the jet (diodes 7 and 8) are seen in the Figs. 2 and 3. The diode 1 was at the position r = 0 mm and the diode 7 at the position r = 12 mm . Fig. 2 corresponds to the axial position z = 5.5 mm downstream of the nozzle exit, Fig. 3 was taken at z = 11.5 mm.

The spectra in Figs. 2 and 3 show some characteristic features that were well reproducible. The sharp peaks with different amplitudes, but at exactly the same frequencies, are visible at all positions in the jet. The frequency of the peaks was the same for all current levels, although the jet conditions varied substantially (see Table 1). These sharp peaks are indications of existence of highly coherent structures in the jet. The dependence of amplitude of the peaks on the axial and radial coordinates can be seen in Fig. 4. Averaged jet profiles are also shown with the indications of positions of the diodes.

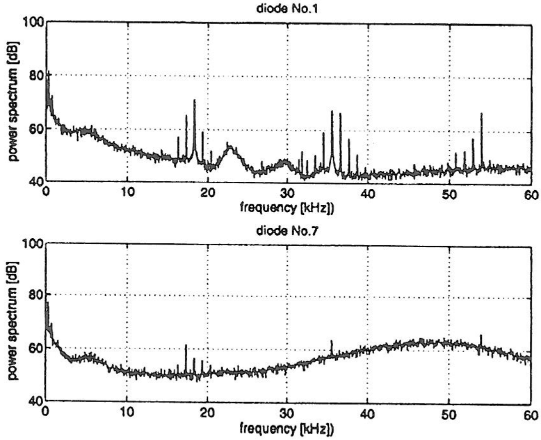

Fig. 2 Power spectra of signals of diodes at the boundaries of the jet adjacent to the anode (diode 1) and opposite to the anode (diode 7) at axial position z = 5.5 mm, arc current I = 400 A.

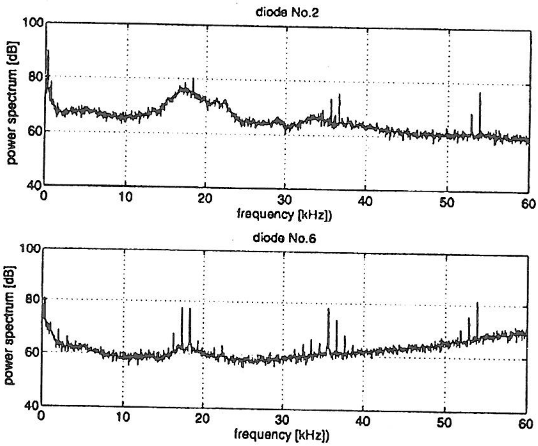

Fig. 3 Power spectra of the signals of diodes at the boundaries of the jet adjacent to the anode (diode 2) and opposite to the anode (diode 6) at axial position z = 11.5 mm, arc current I = 400 A.

As the peaks have maximum amplitude at the nozzle exit and are damped with increasing z, the corresponding coherent structures are produced within the stabilizing arc chamber or close to the nozzle exit. The first resonant frequency for the volume of the stabilizing channel is 24.8 kHz for temperature T = 15 000 K, the possible source of the observed frequencies can be thus inside the arc chamber.

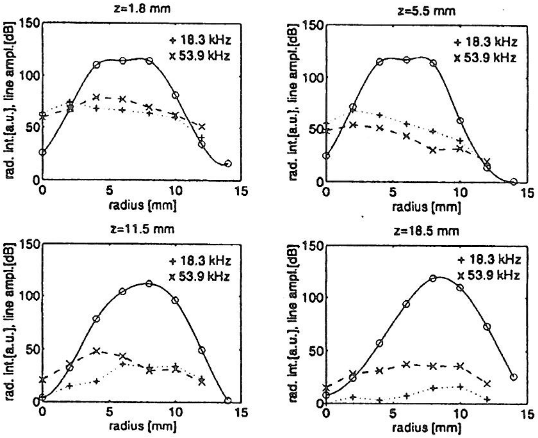

Fig. 4 Averaged jet profiles along with the amplitudes of the spectral peaks 18.3 kHz and 53.9 kHz (background noise subtracted) for various distances z from the nozzle exit.

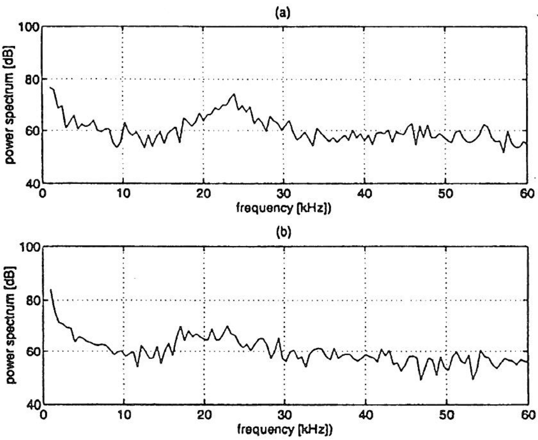

Fig. 5 Power spectra of arc voltage corresponding to the optical spectra presented (a) in Fig. 2 and (b) in Fig. 3.

The broader peaks at the frequencies below 20 kHz in Fig. 2 and above 20 kHz in Fig. 3 are evidently related to fluctuations of arc voltage, as peaks at the same frequencies were found on voltage spectra presented in Fig. 5. These peaks correspond to the sawtooth fluctuations of arc voltage caused by movement of anode attachment region along the anode surface and by variations of the length of arc column. The anode attachment region is strong source of instability of hot core of the jet as we observed by high speed photography [8]. The flow instability is more intensive in the lower part of the jet adjacent to anode and penetrates to the upper jet boundary (diode 6 in Fig. 3).

A broad peak at high frequencies appeared on power spectra of optical signals from upper boundary of the jet close to the nozzle exit (Fig. 2, diode 7). The maximum of the peak continously shifted to higher frequencies with increasing distance from the nozzle exit. These high frequency broad peaks were best pronounced in the upstream part of the jet, they decay in the directions downstream and towards the anode. With increasing current the peak frequency increases and the peak is broader and less pronounced. This behavior suggests entrainment of the cold gas as a principle source of the fluctuations. The entrainment is supressed at the boundary adjacent to the anode surface as the jet is screened from the ambient gas by the anode. Due to low density ratio $S < 0.004$ the entrainment is strong, broad peak indicates less regular structures. The peak is broader and shifted to higher frequencies in the downstream direction as vortices break down into smaller structures. Higher frequencies and broader peaks were found at higher currents as S decreases and Reynolds number and flow velocity increase with increasing current. The non-dimensional frequency represented by Strouhal number was $St_D = f.D/U_b = 0.11$ for peak 48 kHz in Fig. 2. This value is close to the values $St_D = 0.12$ and $St_D=0.17$ found for Ar plasma jets in [1]. The production of vorticity due to entrainment of cold gas can be thus scaled over wide range of plasma jet conditions.

Acknowledment

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