THE EFFECT OF GAS ADMIXTURE ON THE LOW PRESSURE ARC PROPERTIES

A. KAMINSKA

Institute of Electric Power Engineering, Poznan University of Technology
ul. Piotrowo 3A, 60-965 Poznan, Poland
E-mail: Aniela.Kaminska@put.poznan.pl

Abstract. The influence of Ar, N_2, CO_2 and H_2 injected into low-pressure plasma stream on the operating conditions of the plasmatron is studied. Experiments showed that this gas is drawn to the arc area due to arc spot movement, and cyclic arc shrinking and expanding as results of the power supply pulsation. It changes the arc dynamics, voltage fluctuations and anode voltage drop. Based on the analysis of arc resistance, voltage waveforms and optical emission spectroscopy it was proved that the gas introduced into the plasma stream remains in the cold boundary layer, and not mixing with the hot plasma core.

Key words: plasma in gas mixtures, low-pressure plasma, plasmatron.

1. INTRODUCTION

Plasmatrons are widely used in technological applications such as plasma cutting and welding, plasma spray coatings, dc-arcjet CVD reactors, plasma surface cleaning, plasma waste treatment as well as in laboratories to simulate the conditions for vehicles entering planetary atmosphere. These applications require different temperatures, velocity, composition, length and stiffness of the plasma stream. For these purposes various plasmatron constructions and its operating parameters *i.e.* power, pressure, gases are used.

There are two typical configurations of plasma arc (or plasmatron); a transferred arc, where one of the electrodes is outside and usually is the conductive material to be treated, and a non-transferred arc, where the electrodes are inside a plasmatron and the plasma stream leaving the arc is used for processing.

Depending on application, different gases or their mixtures are used. In the *plasma arc cutting* (PAC) system, the plasma stream is formed in oxygen, nitrogen or air. In *tungsten-inert-gas* (TIG) welding, a mixture of argon, protecting cathode with helium or hydrogen is used. For *metal-inert-gas* (MIG) welding, carbon dioxide or oxygen is admixed with argon. In plasma spraying, most frequently nitrogen, helium or hydrogen is added to argon. The processes accompanying the entry of spacecraft are investigated in laboratories in plasma mixtures corresponding to specific planet atmospheres. Although the phenomena occurring in plasmas in mixtures of different gases present a great interest for technology, most of the theoretical and

experimental research deal with homogeneous gas. This is due to complexity of phenomena in mixtures, which makes theoretical modeling and interpretation of experimental results difficult. In particular, the number of chemical reactions that must be taken into account to calculate plasma composition and transport properties increases drastically [1]. The admixture of molecular gas also changes the arc dynamics. For example, addition of nitrogen into argon results in constriction of the anode spot and strong, high-frequency voltage fluctuations [2]. All these phenomena observed in plasmas in mixture of gases are not completely understood.

In this paper, the influence of various gases admixture to the plasma stream on its length and the voltage-current characteristics are revealed. The mechanism of entrainment of gas from the plasma stream into the arc and its influence on arc behavior is analyzed. It is shown that the gas injected into the plasma stream is drawn to the arc area due to arc spot movement and the explanation of this phenomenon is proposed, based on the analysis of plasma flow conditions and electrical properties of the arc. The results of plasma spectroscopy are also used to explain the functioning mechanism of the segmented plasmatron.

2. SEGMENTED PLASMATRON

The segmented plasmatron used in the study is schematically shown in Fig. 1. The cathode is a thoriated tungsten (W+3%ThO$_2$) rod 6 mm in diameter, fixed in a water-cooled housing. The channel of the plasmatron consists of cylindrical annular copper sections, each with the internal diameter of 12 mm and 30 mm in length.
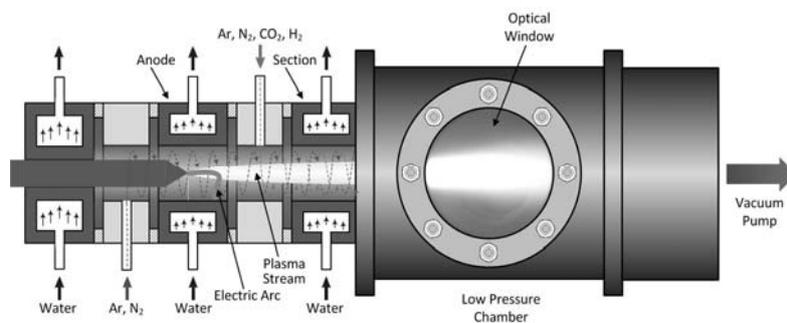

Fig. 1 – Schematic view of the plasmatron mounted to the low pressure chamber.

The sections are insulated by means of rings used to inject gas in such a way that a vortex develops in the plasmatron channel. The first main gas is supplied near the cathode into the arc region and the second gas is injected into the plasma stream, 2 millimeters after the anode section, in the direction of vortex rotation opposite to the primary gas. The main gas is either argon or nitrogen while argon, nitrogen, hydrogen or carbon-dioxide are injected into the plasma stream.

The plasmatron is attached to a low pressure cylindrical and horizontal chamber, 780 mm long with a diameter of 125 mm, equipped with windows for spectroscopic measurements and connection to pressure gauge. The reduced pressure inside the chamber is achieved by two rotary vane pumps, each with electric power 1.5 kW and Roots vacuum pump 4 kW of power. The pressure can be regulated by a valve between 1 and 100 kPa.

The arc is ignited by a high-voltage pulse of about 13 kV and sustained by a DC welding power supply. The detailed description of the electrical circuit is presented in [3]. The arc current is regulated between 20 and 440 A and the arc average voltage changes from 30 to 65 V depending on the kind of gas and flow rate, the pressure and the arc current. The arc voltage also depends on the distance between the cathode and anode. In this study, this distance is about 10 mm and the arc spot can move along the surface of the anode. The arc voltage, current, and static pressure are recorded using a digital oscilloscope Tektronix TDS 5034 with a bandwidth of 300 MHz. The record length is 25000 points and sample interval 4 μs, which corresponds to the recorded time period of 100 ms.

3. PLASMA STREAMS GENERATED BY ELECTRIC ARC

The gas heated in the arc forms a plasma stream with a length dependent on arc current, nature of gas and mass flow rate. The kind of plasma flow is characterized by Reynolds number $Re = \rho u D/\mu$, where ρ is the gas density, u is the velocity, D is the inner diameter of plasmatron channel and μ is the viscosity. Using the mass flow relationship $G = \rho u \pi D^2/4$, the Reynolds number can be expressed as $Re = 4G/(\pi D\mu)$ what means that this number is only a function of gas viscosity and constant mass flow rate.

In the hot core of the argon plasma stream generated by the arc at a current higher than 100 A the temperature is higher than 10000 K and on the boundary of this core the temperature decreases to about 5000 K [4]. The argon viscosity at 10000 K is $0.275 \cdot 10^{-3}$ kg $\cdot$ m^{-1} $\cdot$ s^{-1} [5] and at a gas flow rate 1.8 g/s, the Reynolds number becomes 618. At a temperature of 5000 K, the viscosity is $0.165 \cdot 10^{-3}$ kg $\cdot$ m^{-1} $\cdot$ s^{-1} and the Reynolds number amounts to 1029. Because the estimated $R_e < 2300$ therefore the flow is considered to be laminar. Addition of various gases into the plasma stream leads to changes in temperature and viscosity. However, analysis of the Reynolds number for various gases in the temperature range occurring in a hot core of the plasma stream shows that the flow is laminar in the whole range of the plasmatron operating parameters. Increasing the current and gas flow rate results in a lengthening of the plasma stream. A similar relation is presented in [6,7] where it was shown that the stream with laminar flow lengthens with increasing current and mass flow rate while the length of turbulent flow is less influenced by the operating plasmatron parameters.

Figure 2 shows typical plasma streams generated by an argon arc. Addition of various gases into the plasma stream slightly changes its length, except when hydrogen is added. The stream shrinks and shortens more and more with more and more admixture of hydrogen. It should be noted that the viscosity of argon mixed with hydrogen is similar to the argon viscosity [5] therefore, the Reynolds number still indicates a laminar flow. One of the reasons for such stream behavior is certainly the thermal conductivity, which for argon at a temperature of about 4000 K is 0.12 $Wm^{-1}K^{-1}$ and for hydrogen reaches 13 $Wm^{-1}K^{-1}$ [1]. For a mixture of 80%Ar + 20%H_2 the thermal conductivity is 2.5 $Wm^{-1}K^{-1}$ [5]. With high conductivity, there is a strong heat flux to the plasmatron wall and the convective flux becomes low. Another reason is that even for a small amount of hydrogen mixed with argon the ionization degree drops dramatically [8] and decreases with increasing percentage of H_2 [9].

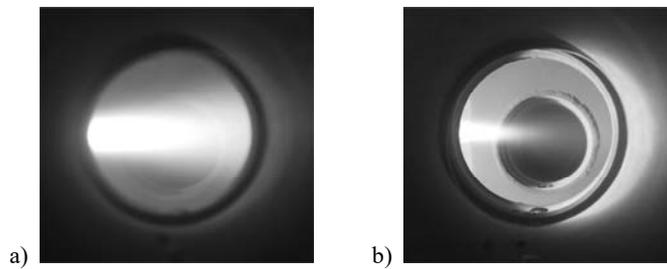a)   b)

Fig. 2 – Plasma streams generated by the arc at a current of 350 A. Argon flow rate injected into the arc 0.8 g/s and: a) argon flow rate into the plasma stream 0.1 g/s, b) hydrogen flow rate into the plasma stream 0.015 g/s.

A simple method of the flow velocity estimation is the Pitot-tube method. However, this method is limited by the melting temperature of the tube material therefore, the method described in [10] is used in the region of the hot stream core. Firstly, this method was applied to estimate the velocity at the stream axis where the measured temperature using optical emission spectroscopy [4] was about 4000 K. The plasmatron operated with an arc current of 240 A, argon injected into the arc and the plasma stream with flow rates of 1.0 g/s and 0.4 g/s respectively. The static pressure in the low pressure chamber was 5.5 kPa. The calculated velocity was 1303 m/s. This value was compared with the velocity measured using the Pitot-tube and the formula $v = \sqrt{2(p_{st} - p_0)/\rho}$, where p_{st} is the stagnation pressure, p_0 is the surrounding static pressure and ρ is the plasma density. The value of 1516 m/s was obtained thus the difference was about 14% and the method [10] of calculation is considered to be sufficiently accurate to estimate the velocity in the region of the plasma stream core. Next, for the same plasmatron operating conditions mentioned above the velocity of the hot plasma flow with the temperature of 10000 K was estimated and the value of 2194 m/s was obtained. The sound velocity determined taking into account gas ionization [11] was 2357 m/s, thus the velocity of the hot stream core generated in plasmatron operated with argon is close to the sonic velocity.

In case of nitrogen and similar operating conditions we get a subsonic flow with a Mach number of about 0.6.

4. INFLUENCE OF GAS INJECTED INTO PLASMA STREAM ON ARC BEHAVIOR

The voltage-current characteristics presented in Figure 3 reveal the influence of a gas injected into the plasma stream, beyond the arc, on these characteristics. Their shape results from very complex electrical, physical and flow phenomena.
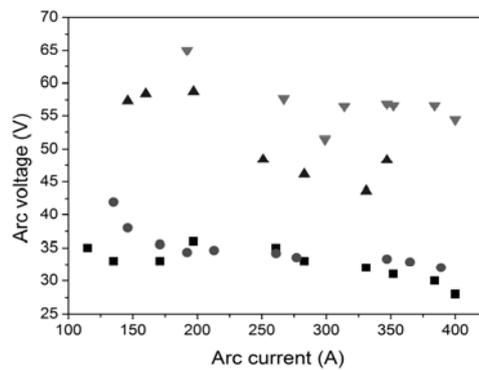

Fig. 3 – Voltage-current characteristics of the arc for various gases injected into the plasma stream at a pressure of 5 kPa; ■ 0.8 g/s Ar + 0.6 g/s Ar, ● 0.8 g/s Ar + 0.6 g/s N_2, ▲ 0.8 g/s N_2 + 0.6 g/s N_2, ▼ 0.8 g/s N_2 + 0.6 g/s CO_2.

One of the phenomena is the anode spot movement. In general, two kinds of an anode spot behavior are observed. The first is that the anode spot moves downstream, the arc elongates, and arc voltage increases. Next, the anode spot moves upstream, the arc shortens, and the voltage decreases. This behavior is called takeover mode. The second behavior called restrike mode is such that the anode spot moves downstream, the arc voltage increases, then the voltage decreases rapidly, which indicates a breakdown in the gas layer between the arc core and the wall. Next, the new arc spot is formed and moves again downstream. Argon arc at high current and small argon flow rate into the plasma stream operates in takeover mode (Fig. 4a). When additional argon with a large flow rate is injected into the plasma stream the cold gas retracted from the stream towards of the arc cools the boundary layer. It is observed that the anodic spot moves a few times upstream and downstream and when the cooling of boundary layer is sufficiently large the breakdown occurs accompanied by a large and rapid voltage drop (Fig. 4b). In the case of Ar-Ar plasma this drop is about 5V.

Other behavior is observed when the molecular gas is injected into the plasma stream (Fig. 5). The arc operates in the restrike mode with the breakdowns in gas layer between the arc and the wall.
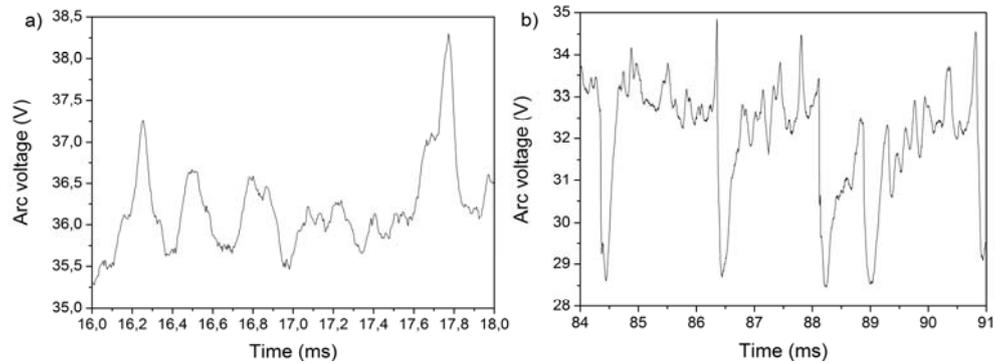
Fig. 4 – Arc voltage waveforms in Ar + Ar plasma at a pressure of 5 kPa and a flow rate into the arc of 0.8 g/s: a) arc operates with take over mode at a current of 293 A and a flow rate into the plasma stream of 0.4 g/s, b) arc operates with restrike mode at a current of 192 A and a flow rate into the plasma stream of 0.6 g/s.

In argon-molecular gas mixture plasma, the electron energy losses are much larger than in argon plasma. The Joule energy reached by electrons is dissipated in elastic collisions not only with atoms and ions, but also with molecules. In addition, the temperature between the arc and the wall decreases due to the dissociation of molecules [12]. In the case of Ar-N_2 plasma the voltage drops associated with breakdowns are the biggest and amount to about 8 V. This is because nitrogen has about 12 times higher breakdown strength than argon [13]. Obviously in considered conditions only a few nitrogen enters the arc region therefore, it is difficult to give some quantitative comparisons. Lower voltage drops of about 5 V similar to those in Ar-Ar plasma occur in Ar-H_2 plasma.
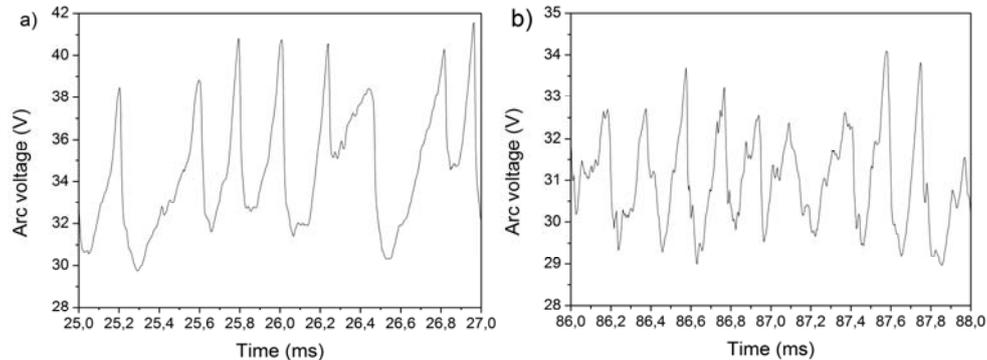

Fig. 5 – Voltage waveforms of the argon arc at a current of 366 A and a pressure of 5 kPa. Argon flow rate into the arc 0.8 g/s. Flow rates into the plasma stream: a) 0.6 g/s N_2, b) 0.015 g/s H_2.

Typical variations of voltage for $N_2 + N_2$ plasma are shown in Fig. 6a. The average nitrogen arc voltage is much higher than the argon arc voltage due to the difference in electrical conductivity of these gases. Injection of CO_2 instead of N_2

into the nitrogen plasma stream results in an increase of average voltage to 60 V (Fig. 6b). The voltage drop observed in fluctuations of $N_2 + N_2$ plasma amounts to 20–30 V and is on average a bit larger in $N_2 + CO_2$ plasma.
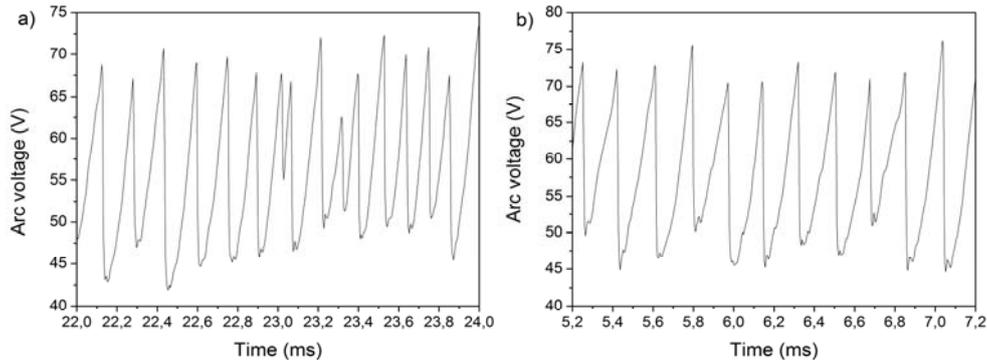

Fig. 6 – Voltage waveforms of the nitrogen arc at a current of 210 A and a pressure of 5 kPa. Nitrogen flow rate into the arc 0.8 g/s. Flow rate into the plasma stream 0.6 g/s: a) N_2, b) CO_2.

As mentioned above, in the segmented plasmatron, the main working gas forming the plasma stream is injected near the cathode into the arc region and another additional gas is injected to the plasma stream beyond the arc. When the anode spot moves upstream, this additional gas is retracted into the arc region due to the arc dynamics, changing the operating conditions of the plasmatron. Another retraction mechanism is provoked by the rectifier output power supply pulsation with frequency of 300 Hz. The power pulsations are also influenced by the electric arc, which represents non-linear resistive load. The substantial pulsation of input power causes both cyclical arc shrinking and expanding, as well as arc shortening and lengthening [14]. In order to explain how the gas injected into plasma stream influence on electric properties of the arc the average resistance is considered. Figures show the arc resistance as a function of current for N_2 and CO_2 injected into plasma stream (Fig. 7a) and two values of N_2 flow rate (Fig. 7b). The practically constant average resistance indicates that the cold gas does not reduce the electron temperature and density in the hot and conductive plasma core. This means that the additional gas is not mixed with the arc plasma, but remains in the region close to the wall. However, the plasma composition and temperature in this region determine the anode voltage drop and the voltage breakdown of the gas layer.

The anode voltage drop in the space charge zone is estimated by well know relationship [15]:

$$\Delta V_0 = -\frac{kT_e}{e} \ln\left(\frac{n_{ea}e\bar{v}_e}{4J_a}\right)$$

where k is the Boltzmann constant, e is the electron charge, T_e and n_{ea} are the electron temperature and density at the limit of space charge zone respectively,

$\bar{v}_e$ is the averaged thermal velocity of electron and J_a is the total current density. Using the electron density and temperature determined from optical emission spectroscopy measurements [4,16] the voltage drop is calculated as a function of a current density. Figure 8 shows that this drop depends on the gas injected into plasma stream and is lower for nitrogen than carbon dioxide.
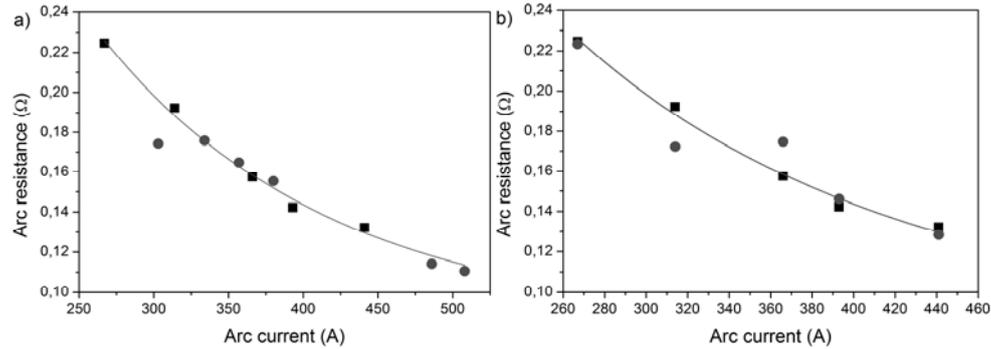

Fig. 7 – Average nitrogen arc resistance as a function of current at a pressure of 5 kPa and a flow rate injected into the arc of 0.8 g/s. The gas injected into the plasma stream is: a) ■ N_2 and ● CO_2 with a flow rate of 0.4 g/s, b) N_2 with a flow rate of ■ 0.6 g/s and ● 0.4 g/s.
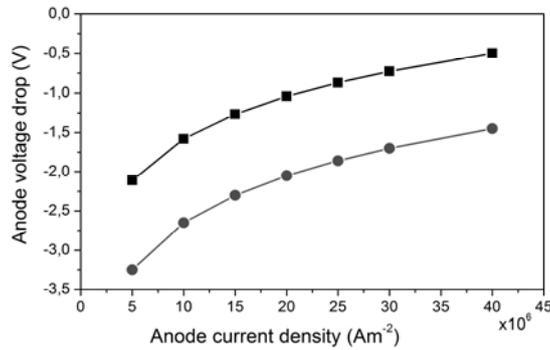

Fig. 8 – Anode voltage drop in the nitrogen arc calculated as a function of anode current density for ■ N_2 injected into the plasma stream and ● CO_2 injected into the plasma stream.

The difference in the anode voltage drop can be one of the reasons for the difference in the amplitudes of voltage fluctuation. The second reason is certainly the voltage breakdown. For carbon dioxide admixture the arc extends more to achieve a higher electric field sufficient to breakdown the gas layer.

5. OPTICAL EMISSION SPECTROSCOPY

OES spectra are taken at a distance of 50 mm from the anode with an HR4000 Fiber Optic Spectrometer from Ocean Optics. The arc is formed in argon with a

flow rate of 1 g·s^{-1}, and argon is injected with a flow rate of 0.6 g·s^{-1} into the plasma stream. During the experiment, the plasmatron operated with an arc current of 180 A and mean arc voltage of about 35 V. Argon static pressure in the low pressure chamber was 5 kPa. The emission spectra of plasma consist of Ar I lines and nitrogen molecular bands. The strongest lines are lines at wavelengths 763.5 and 810.4 nm which originate from the excited levels of Ar I $3p^5(^2P°_{3/2})4s$ and $3p^5(^2P°_{1/2})4s$. The most apparent molecular spectra are N_2 spectra of the second positive system $C^3 \Pi_u – B^3 \Pi_g$ and N_2^+ spectra of the first negative system $B^2 \Sigma_u^+ – X^2 \Sigma_g^+$. Several spectra can be distinguished: 311.7 – 315.9 nm N_2, 337.1 N_2, 353.7 – 357.7 nm N_2, 375.5 – 380.5 N_2, 358.2 – 353.2 nm N_2^+, 391.4 – 385.8 nm N_2^+. The occurrence of the nitrogen spectra in argon plasma results from the air entering into low pressure chamber by a plasmatron leak. The same Ar I lines and nitrogen molecular spectra are recorded when nitrogen is injected into the plasma stream (Fig. 9a). Analysis of the observed molecular spectra shows that N_2 spectra of the second positive system are overwhelmingly more intense than N_2^+ spectra. The study made in [4] indicates that this is a result of the mixing of cold nitrogen with argon at a temperature above 6000 K. This confirms the earlier observation that the gas introduced into the plasma stream is initially in the cold boundary layer and not mixed with the hot plasma stream.
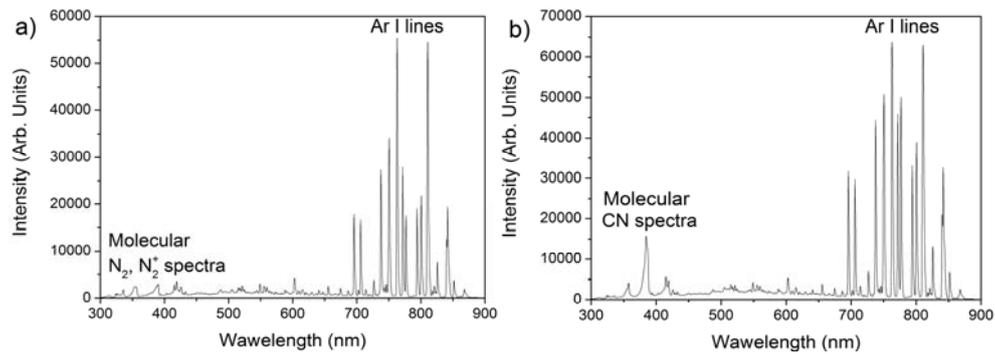

Fig. 9 – Spectra recorded with an HR4000 Fiber Optic Spectrometer:
a) Ar + N_2 plasma, b) Ar + CO_2 plasma.

Figure 9b shows the Ar + CO_2 spectra. The most prominent emission spectra excepting the Ar lines are the molecular CN spectra of violet system $B^2\Sigma – X^2\Sigma$. The results presented in [4] showed that the admixture of CO_2 results in decrease of the electron temperature and electron density. Again no effect on the arc resistance (Fig. 7a) confirms that the injected gas into plasma stream remains in the boundary layer.

6. CONCLUSIONS

The flow in the plasma stream generated by the electric arc is laminar and subsonic in the whole range of plasmatron operating conditions *i.e.* current in the

range of 20–440 A, pressure from 1 to 100 kPa and gas flow rate between 0.4 and 2 g/s. When additional gas is injected into the plasma stream, beyond the arc, the cold gas retracted from the stream towards of the arc changes the behavior and parameters of both plasma stream and arc. Explanation of these effects is proposed based on the study of anode spot behavior with accompanying voltage fluctuations and taking into account the voltage-current characteristics of the arc, the average arc resistance and the anode voltage drop. Study showed that the additional gas does not mix with the arc plasma, but remains in the region close to the wall. This conclusion is confirmed by optical emission spectroscopy measurements.

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