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Peculiarities of Plasma Assisted Stearine Combustion

O. A. Nedybaliuk[1], O. V. Solomenko[1], V. Ya. Chernyak[1*], E. V. Martysh[1], L. Yu. Vergun[2], I. V. Prysiazhnevych[1], S. G. Orlovska[3], I. I. Fedirchyk[1] and T. E. Lisitchenko[1]

[1]Taras Shevchenko National University of Kyiv, Faculty of Radio Physics, Prospect Acad. Glushkova 4G, 03022, Kyiv, Ukraine.
[2]Taras Shevchenko National University of Kyiv, Faculty of Radio Physics, Prospect Acad. Glushkova 4, 03022, Kyiv, Ukraine.
[3]Odessa National Universiy, Dept. of Thermal Physics, Dvorjans'ka Str. 2, Odessa 65026, Ukraine.

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

During combustion of hydrocarbons with high viscosity there is a problem of their spraying. Traditional gasdynamic jets are not suitable for solving these problems. Therefore, the creation of new plasma-liquid systems that would allow effective spray hydrocarbons with high viscosity is an important and promising direction. Plasma assisted combustion of hydrocarbons with high viscosity was investigated in this work. Plasma jet was used for spraying of high viscosity hydrocarbons. The mixture of n-paraffin and stearine in the solid state is used as the model of the solid paraffin based fuel. Plasma source was rotational gliding arc. Plasma system consisted of the area where the plasma is formed, the area where plasma injected with hydrocarbons and the area with flame. The current-voltage characteristics of the rotational gliding arc discharge were measured. Diagnostics of plasma torch and the flame was carried by emission spectroscopy. Temperature in the flame during plasma assisted combustion of hydrocarbons was measured.

**Corresponding author: Email: chernyak_v@ukr.net*

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1. INTRODUCTION

The idea of using nonequilibrium low temperature plasma for ignition or combustion stabilization seems to be promising today [1]. There are number of papers devoted to results review on different gas discharges, used for plasma-assisted ignition and combustion, namely: streamers, dielectric barrier discharges, radiofrequency discharges, pulsed nanosecond discharges (sparks, dielectric barrier discharges, volume nanosecond discharges). Also, different mechanisms for such phenomena as ion chemistry and chemistry of excited species, are proposed and investigated [2,3]. However, the studies have been mainly focused on gas-phase fuel mixtures, and researches on the stabilization of the solid fuels combustion are practically absent.

In recent years the idea of using paraffin to create new fuel has been realized [4]. It is well-known that paraffin is saturated hydrocarbon which contains only carbon and hydrogen and have the general formula C_nH_{2n+2}. The paraffin can be found in the liquid and solid state depending on the number of $–CH_2–$ groups [5]. The question about its advantage in the comparison to the traditional petrol fuels, despite the availability of the paraffin and its derivatives based fuel is debatable. So, new experiments for solid paraffin and its mixtures should be carried out.

Nonequilibrium low-temperature plasma is divided onto two types by the level of non-equilibrium: plasma with a temperature of heavy components near the room temperature (dielectric barrier discharge, micro-discharge) and the so-called "warm" plasma [4] with a temperature more than 1000 K. “Warm” plasma [4] can be created by various types of discharges: transverse arc [6-8]; gliding arc [9-12] and rotational gliding arc (RGArc) [13-20]. Unlike the gliding arc [9-12], the transverse arc [6-8] has a fixed length of the discharge column, but lesser operating life. The rotational gliding arcs [13-20] subdivide into RGArc with longitudinal motion [13-16] and RGArc without longitudinal motion [17-20] of the discharge column. The rotational gliding arc without longitudinal motion has a fixed discharge column, unlike the gliding arc [9-16], and longer lifetime, unlike the transverse arc [6-8]. Therefore, the rotational gliding arc without longitudinal motion of the discharge column was used in this work.

2. METHODOLOGY

Fig. 1 represents the schematic view of the plasma-dynamic system (PDS) for activation of the paraffin combustion. This PDS is conformable to one, which has been used in [20] and consists of the hydrocarbons plasma injector (1) into which two copper electrodes are embedded (2, 4) through the dielectric (3). The voltage of up to 7 kV has been supplied between the electrodes with the help of the DC power source. The airflow G_1 (6) has been given tangentially to the surface of cylindrical combustion chamber, forming the plasma torch (5). This airflow has been formed by compressor and measured by rotameter. The plasma torch is affected by this airflow, and then the torch starts rotating and gliding on the electrode with its tip (4).

The mixture of n-paraffin and stearine in the solid state is used as the model of the solid paraffin based fuel. The general advantages of paraffin are as follows: it is a green fuel with high caloricity, ecological compatibility, safety of keeping and high chemical inertness to external factors, etc. The main component of such fuel in our experiment was stearine ($C_{17}H_{35}COOH$). Stearine is an environmentally clean fuel that is produced from renewable raw materials. It is solid, hard and burns without soot and almost odorless, and its production process is not costly. Stearine is obtained from animal fats created as a byproduct of processing beef. It can also be found in tropical plants such as palm. Stearine is a side product obtained during the extraction of cod liver oil removed during the chilling process. This fuel (7) is fed through wire grid (8), dispersed by plasma jet and partially reformed to the syngas. After that syngas together with fuel droplets and vapour is injected into the area with G_2 airflow, the flame (12) is formed. The G_2 airflow is given tangentially to the surface of cylindrical combustion chamber through inlet (11), which forms gas vortex (9) and mixes with fuel components.

Optical studies of the flame have been conducted with help of the optical system. It consists of: converging lens (13), light guide (14), the spectrometer S–150–2–3648 USB (15) which measures the spectra in the range of wavelengths from 200 to 1100nm and is controlled by the computer (16).

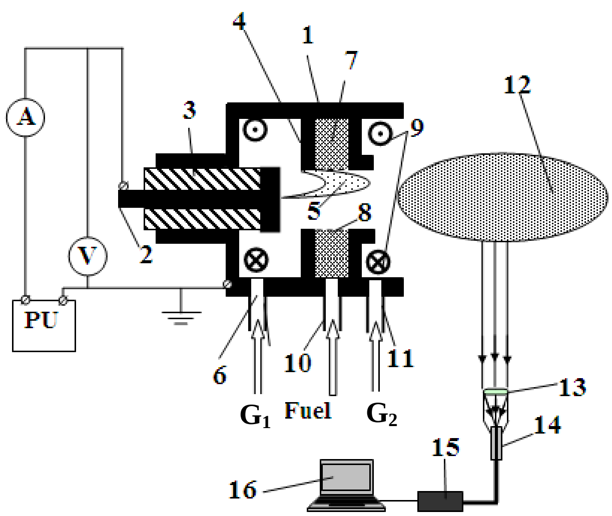

Fig. 1. Schematic diagram of experimental setup

3. RESULTS AND DISCUSSION

Fig. 2 shows the experimental setup photos during plasma stimulation of stearine burning. The G_1 airflow through the discharge is 3 l/min, G_2 air flow – 20 l/min, current – 200 mA, voltage – 0.6 kV. The plasma jet can be operated in both horizontal (Fig. 2.a) and vertical (Fig. 2.b) positions. When the system is in a horizontal position, the torch tip has the shape of few flame protruding tongues (Fig. 2.a). When the system is in vertical position, the torch tip has rounded shape (Fig. 2.b) without flame protruding tongues. This may be due to the fact that in the first case the flame is directed perpendicular to the convective gas flow, and in the second case, the flame is directed toward convective gas flow. This leads to a rounded tip of the torch flame.

a) b)

Fig. 2. Pictures of the experimental setup during plasma stimulation of stearine burning: horizontal position (a); vertical position (b)

Fig. 3 shows the current-voltage characteristics of vortex gliding arc with different values of the gas flow through the discharge gap without fuel. The distance between electrodes is 1.5 mm. As the current is increased, current-voltage characteristics are decreased. For small currents (≤ 200 mA) the air flow value has bigger influence on the current-voltage characteristics than current ≥ 250 mA in the air flow range of 2-6 l/min. At a current of 400 mA discharge almost doesn't feel the air flow impact (Fig. 3). This behavior of the current-voltage characteristics are similar to that observed for the transverse arc [8]. Energy carries out from the discharge region with airflow increasing and to support the fixed discharge current it is necessary to increase the voltage on the discharge. Non-linear current-voltage characteristics dependence from airflow can be connected with the pecularities of the gas flow: 1) a monotonic voltage increasing with the airflow rate 2-3 l/min increasing (laminar gas flow); 2) voltage on the discharge increases (for currents ≤250 mA) or remains almost constant (for currents >250 mA) with further increasing airflow from 3 to 6 l/min (this region corresponds to the transient gas flow regime: from laminar to the turbulent); 3) when the gas velocity becomes bigger than the drift velocity of ions in the electric field, further voltage increasing starts, which is escorted by the appearance of the filament plasma structures directed along the flow. During plasma stimulation of stearine burning with the same flow through the discharge, voltage level is slightly lower than in the absence of stearine.

Research has been carried out by flame emission spectroscopy method. Fig. 4 shows the emission spectrum of the flame during plasma stimulation of stearine burning. Stearine (8 ml) is loaded in the middle of the chamber. The G_1 airflow through the discharge is 5 l/min, G_2 air flow – 20 l/min, current – 300 mA, voltage – 0.4 kV. Optical fiber is focused on the sight line at the distance of 25 mm from the chamber edge which is perpendicular to the direction of the flame. The system has worked in vertical position. This spectrum is continuous. It is known that the continuum emission of dust particles is well approximated by "black body" spectrum [21]. We can determine the temperature of the particles, which are responsible for this spectrum. This operation has been done in the standard way: by comparing the experimentally measured emission spectra with the calculated spectra of blackbody radiation. Calculations have been carried out with usage of Planck radiation formula.

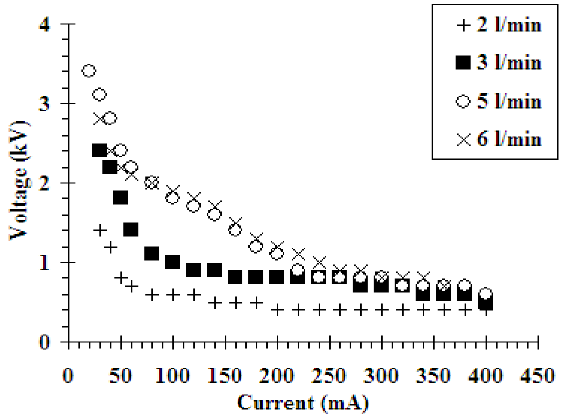

Fig. 3. Current-voltage characteristics of vortex gliding arc, depending on the air flow values

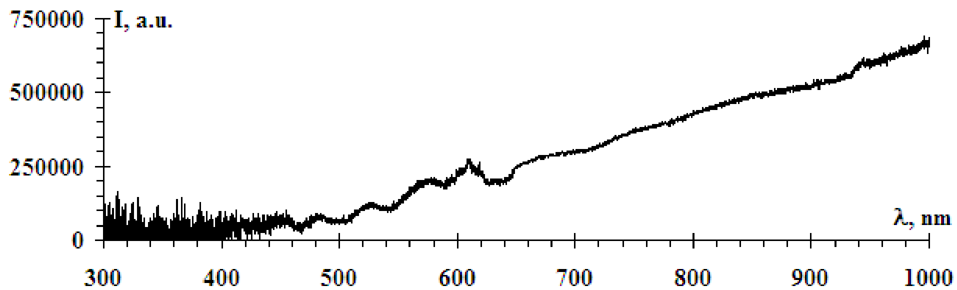

Fig. 4. Typical flame emission spectrum during plasma stimulation of burning stearine

Fig. 5 shows the comparison of the experimentally measured emission spectrum with the calculated spectra of blackbody radiation. All spectra are normalized to the intensity, which is located at a wavelength of 850 nm. Fig. 5 shows that the spectrum corresponds to a temperature of 2450 ± 100 K.

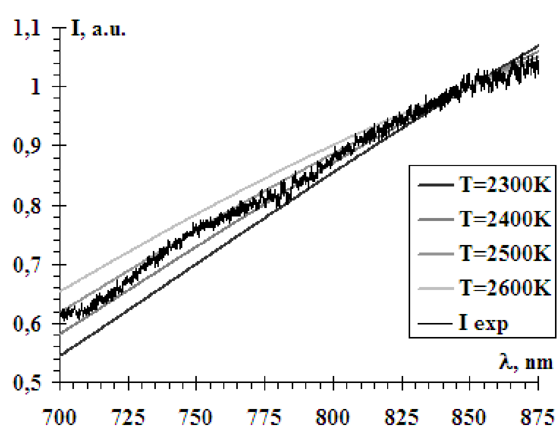

Fig. 5. Comparison of experimentally measured emission spectrum with the calculated spectra of blackbody radiation

In order to explore the stearine combustion process during plasma stimulation, flame video observations have been conducted simultaneously, together with the measurements of the emission spectra. At first, torch flame has been quite short and not observed in the emission spectra. Spectral sensitivity of the device, at the moment when the discharge is switched on, is 30 times higher than the torch radiation maximum intensity. Then, at a certain moment, the size of the torch is raised sharply, and spectral instrument registers minimum signal. Recording of torch parameters starts at that moment. The torch size rapidly decreases and flame becomes dim as the fuel runs out.

Fig. 6 shows distributions: temperature, radiation intensity, length and diameter of the torch flame lengthwise the area of plasma stimulation of stearine burning. The G_1 air flow through the discharge is 5 l/min, G_2 air flow – 20 l/min, current – 300 mA, voltage – 0.4 kV. Optical fiber is focused on the sight line at the distance of 25 mm from the chamber edge which is perpendicular to the direction of the flame. The system worked in a vertical position. The countdown begins from the moment when the discharge is switched on. Radiation intensity (Fig. 6.b) is measured at the fixed wavelength of 850 nm.

All intensities are normalized to the intensity, measured at the moment when the torch flame appears at a wavelength of 850 nm. Flame length – *L* (Fig. 6.c) has been taken from the video. Flame diameter – *d* (Fig. 6.d) is taken from the video and measured at a distance of 25 mm from the chamber edge.

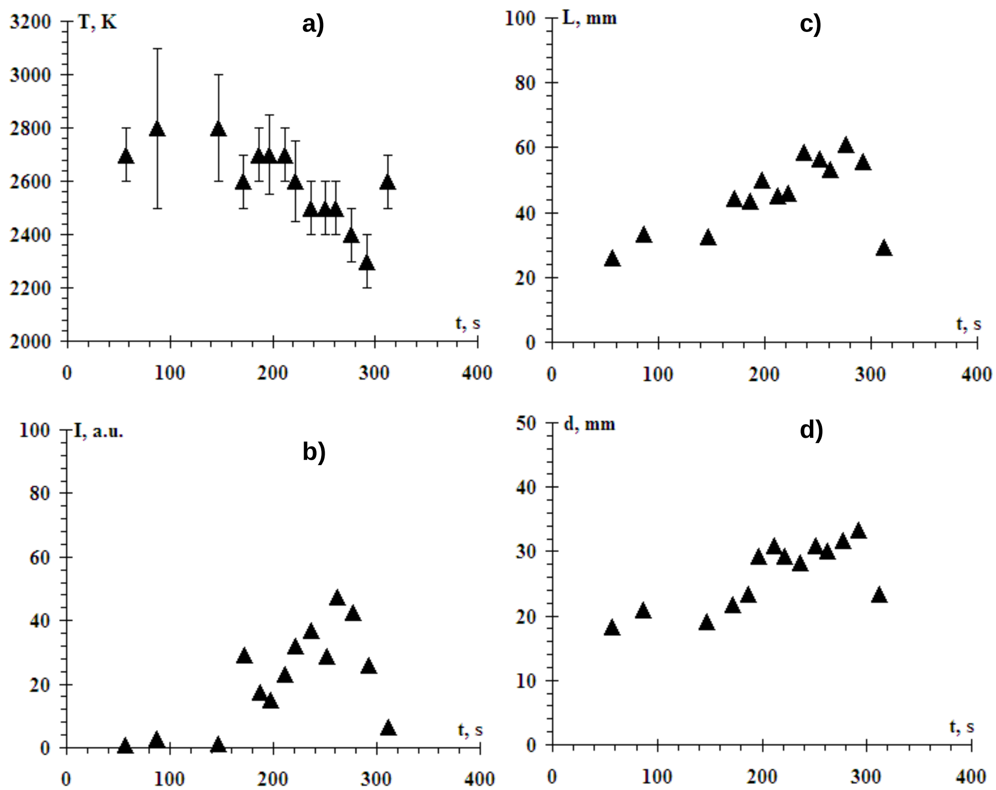

Fig. 6. Distributions of: temperature (a), emission intensity (b), length (c) and diameter (d) in torch flame during plasma stimulation of stearine burning

It has been observed that with radiation intensity increase, flame temperature measured by a solid continuous spectrum (Fig. 6.a, b) decreases. The relative difference between the maximum and minimum temperatures is 20%. Airflows G_1 and G_2 through the discharge have been fixed at particular values and remained unchanged during the experiment. Current and voltage have been constant. The intensity has been changed by 50 times while the diameter (Fig. 6.d) has been increased only by 1.5 times.

The torch length couldn't affect the emission spectra intensity at the beginning of the registration process. This is due to the fact that the measurements have been carried out on the sight line at a fixed distance from the chamber edge. Intensity growth may indicate a growing concentration of the particles, responsible for the continuum emission. Radiation intensity depends not only on the temperature but also on the density of the particles. Fig. 6.a shows that increase in concentration of particles, responsible for continuous spectrum, leads to temperature decrease.

In addition, there're studies which show that the plasma jet output is fastened by the nozzle with 2 mm diameter (Fig. 7). The G_1 airflow through the discharge is 3 l/min, current – 300 mA, voltage – 0.4 kV. G_2 airflow is introduced as well. Flame length in this case is 1.5 times bigger than in the case where the nozzle is absent. The torch has a needle shape with a sharp tip. This indicates that the gas that comes out of the nozzle has a higher speed, than in the case when the nozzle is absent. It gives hope that this jet engine system with solid hydrocarbon fuel will be used in the future. However, the further studies should be carried out in order to determine the optimal length of the combustion chamber for such system.

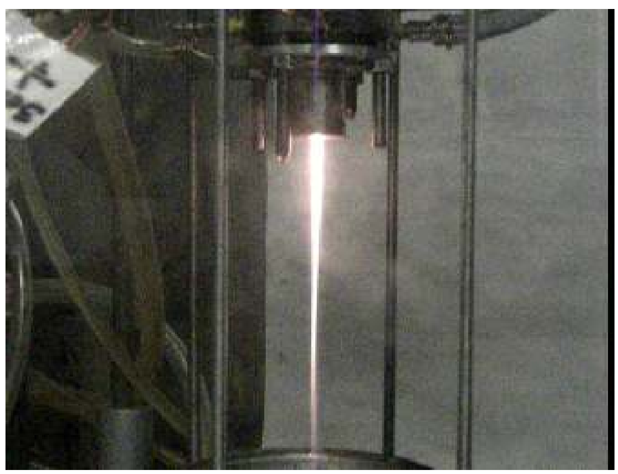

Fig. 7. Picture of the experimental setup, with the nozzle

4. CONCLUSION

The study of the solid stearine combustion carried out with the help of the newly developed plasma-dynamic system showed that:

1. In the range of 2-6 l/min, the value of the airflow has stronger influence on the shape of current-voltage characteristics in the case with small currents (≤ 200 mA), than in

the case with currents ≥ 250 mA. The discharge practically doesn't feel the impact of the airflow at the current of 400 mA.

2. The emission spectrum of flame during stable burning regime is continuous and corresponds to the blackbody radiation spectrum.

3. As the temperature measured by the blackbody spectrum decreases by 20%, (T_{max} = 2800 K), the radiation intensity changes by 50 times. Intensity growth reflects the increasing concentration of the particles, responsible for the continuum emission spectrum.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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