A low-temperature plasma generator working on nitrogen–propane mixture

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Abstract. A low-temperature plasma generator of a mixture of nitrogen and propane has been developed, with the possibility of supplying propane to the cathode region, to the arc burning zone, and also to the plasma stream below the arc binding zone. The maximum propane flow rate for a given plasmatron design and plasma-forming nitrogen flow rate, at which the arc is stable, was determined. When propane is supplied into the arc binding zone, the decay products are deposited mainly on the electrodes, and when it’s supplied to the anode after the arc binding, the decomposition products are deposited mainly at the anode exit. The study of the microstructure and analysis of the phase composition of the decomposition products of propane were performed.

1. Introduction
At present, low-temperature plasma is widely used to solve not only a variety of scientific, but also applied and technical problems. One rather unconventional application of low-temperature plasma is the plasma gasification of domestic and industrial waste. It is considered as a good application due to the fact that at a temperature of 4–5 kK, any substance is split into electrons, ions and radicals. The main advantage of plasma-chemical technology is its versatility in relation to processed substances and relatively small dimensions, which make it possible to create mobile technological modules. With its help, it is possible to convert various types of fuel, such as industrial, medical or municipal waste, low-grade coal, biomass into synthesis gas [1]. The resulting synthesis gas can be used as fuel in combustion systems, to generate electricity and to produce hydrogen. However, the wide practical distribution of plasma technologies is hindered by the lack of reliable arc plasma torches with a sufficient resource for continuous operation. Microwave plasma torches, which are used in some reactors and have a long resource, can serve as alternatives; however, to achieve an acceptable thermal efficiency of the plasma stream sufficient for complete splitting of the waste, it is necessary to expend significantly more electricity than for a direct current plasma torch. In addition, for this type of plasma torch, the design of power supplies is much more complicated.

A literature analysis of the existing plasma generators of various designs [2–7] and operating at capacities from several kW to tens of MW shows that the most stable operating mode and maximum resource have low-temperature plasma generators (LTPGs) that are using argon as a plasma-forming gas. When disposing of waste, the use of argon on an industrial scale is not
Figure 1. (a) Photo of the outlet of the anode from where the microstructures were collected. (b) Design of the plasma torch: 1—cathode; 2—nozzle; 3—anode; 4—anode holder; 5—cathode holder and gas swirler.

economically feasible, therefore it is advantageous to use available gas mixtures, for example, nitrogen or air with the addition of a mixture of propane and butane. The use of such a plasma-forming gas [8] leads to the formation of a predominantly carbon-containing gas medium in the cathode cavity and on the inner surface of the anode. Positive carbon ions formed as a result of dissociation of propane or butane molecules and ionization of carbon atoms under the influence of a cathode potential drop are deposited on a water-cooled copper surface to form a carbon nanostructured layer, i.e., there is a regeneration of the material of the electrodes, which at times increases the resource. In addition, when using molecular gases as a plasma-forming gas in LTPG, it is also necessary to spend energy on the processes of ionization and dissociation, which leads to an increase in the enthalpy of the plasma and a multifold increase in its thermal conductivity (when methane and carbon dioxide are combined as 1:2, the thermal conductivity increases by 20 times when compared to argon) [9].

2. Methodology

In regards to the above-mentioned task, a LTPG was developed in which nitrogen and propane have a power of up to 50 kW (figure 1), where the plasma flow from an expanding channel enters a water-cooled cylindrical anode. Such design of plasma-torch (with an expanding anode channel) provides high gas pressure at high gas velocities and at low heat loses in water-cooled parts. Advantages of such LTPGs are described in more details in works [10,11].

A study was conducted on the effect of propane on the operation of LTPG and the resulting decomposition products at an arc current of 100 A at the maximum possible consumption of propane for a given nitrogen flow rate, at which the stability of arc burning is not impaired. Propane was supplied together with the working gas (nitrogen), as well as between the nozzle and the anode, and also in the middle of the anode below the arc binding zone (table 1).
Table 1. Experiment parameters.

| Propane injection point                                      | $I$ (A) | $U$ (V) | $G$ (g/s), $N_2$ | $G$ (g/s), $C_3H_8$ |
|-------------------------------------------------------------|---------|---------|-----------------|-------------------|
| Nozzle–cathode gap, together with $N_2$                      | 100     | 85–90   |                 |                   |
| Nozzle–anode gap                                            | 100     | 75–80   | 0.45            | 0.33              |
| Holes in the middle of the anode                            | 100     | 70      |                 |                   |

Figure 2. Characteristic microstructures of $C_3H_8$ decomposition products at the anode outlet: WD—working distance between the microscope and the sample; Mag—magnification; SE—secondary electrons; DHV—down-hole visibility; Det—detector module; TLD—through the lens detector; ETD—the Everhart–Thornley detector; Spot—diameter of the beam (nm).

3. Results and discussion
The experiment showed that when propane is supplied to the anode after the arc binding, the decay products are deposited mainly not at the electrodes, but at the exit of the anode (see figure 1). Typical microstructure patterns of decay products are shown in figure 2.
When propane is supplied with a plasma-forming gas to the discharge gap, the decomposition products are deposited mainly on the electrodes (especially on the anode). The microstructures of the obtained powder components were studied using a scanning electron microscope. The largest fractions were found in the powder from the anode (up to $\approx 2$ mm across), when propane was supplied into the nozzle-anode gap during the operation of the plasma torch, that was operating for 2 min. With an increase in the plasma torch operating time to 4 min, the size of the fractions decreased to $\approx 1$ mm. The smallest fractions were obtained when propane was supplied together with a plasma-forming gas and the operating time was 2.5 min (up to $\approx 0.3$ mm across).

The phase composition of the carbon samples was analyzed by x-ray diffraction analysis using a DRON-2 device (Cu-K$\alpha$ radiation, $\lambda = 0.154056$ nm). It is established that the composition of the samples consists of the following materials:

- graphite represented by several components that differ in the degree of three-dimensional ordering of the crystal structure;
- carbon with a turbostratic graphite structure, containing single randomly oriented graphite layers and packets of parallel, equidistant, but crystallographically unconnected layers;
- a significant amount of metal (copper) with a cubic face-centered crystal lattice;
- unknown impurity phases.

4. Conclusions

To study the effect of propane on the operation of the plasma torch and the composition of the decay products in nitrogen plasma, a low-temperature plasma generator working on a mixture of nitrogen and propane was designed and created. It has been shown that for this LTPG design, the propane consumption has an upper limit when introduced together with the plasma-forming gas and into the arc binding zone (no more than $\approx 73\%$ of the plasma-forming gas flow rate), where the stability of arc burning is not impaired. When propane is supplied into the arc binding zone, the decay products are deposited mainly on the electrodes (especially on the anode), which can have the recovery effect on the electrodes if the mixture is selected correctly. When propane is fed through holes in the anode after the arc binding, the decay products are deposited mainly at the outlet of the anode.

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