Practical uses of high-durability DC arc plasmatrons

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Abstract. The novel DC arc plasmatrons, with tungsten rod cathodes and nozzle anodes, and ways of their application are described in this article. The initial successful device was a T-plasmatron with a T-form of its gas-flow channels. Its specific anode erosion rate was lowered by four orders of magnitude, as compared with traditional arc plasmatrons. The result of a specific anode design, arranging technological gas and plasma-forming gas interactions, decreased this parameter to $4 \times 10^{-10}$ g/C. This plasmatron was used in several technological processes, including cleaning the flow of Diesel engine exhaust, etching, and depositing different materials. After these experiments, the A-plasmatron was created, which had a generally axisymmetric form with a three-times greater ability for technological gas activation as compared with the T-plasmatron. The A-plasmatron was also used in the above-mentioned technological processes and demonstrated higher possibilities for each process. The extremely clean plasma flow of this plasmatron was studied using integral and local plasma diagnostic results, which have indicated its acceptable application for several processes, including the rather effective and interesting biomedical interactions with human wounds, vegetables, white straw crops and their products.

1. Initial version of the high-durability DC arc plasmatron and its applications for technological processes

The novel DC arc plasmatron, using a hot tungsten rod cathode and cool copper nozzle anode, was initially created in Moscow by engineers from Moscow Aviation Institute, along with physicists from Moscow State University. This device also attracted the interest of physicists from Jeju National University in South Korea. To cooperate with these specialists, we had to protect this DC arc plasmatron through a Russian patent in order to continue our interactions under the patent’s conventional priority. Back in 1991 such protection was impossible in Russia due to unusual organisational problems. Along with Korean physicists, we advanced the plasmatron’s design, protected it under Korean patent [1], and presented our initial studies of the device at Korean International Symposium [2]. This device was considered to be novel because it contained a special anode design that created a vortex with a distributed anode spot, resulting in a sharp decline of its erosion rate to the level of $\sim 10^{-10}$ g/C. A schematic diagram of the plasma generator’s design, called the T-plasmatron in reference to the T-formation of its gas supplying channels, is presented in figure 1.
Figure 1. Schematic diagram of the T-plasmatron.
1. Cathode. 2. Feeding of plasma-forming gas (argon). 3. Water-cooled anode. 4. Feeding of technological gas. 5. Flat technological channel. 6. Plasma jet exit.

The vortex, which contains a distributed anode spot, is positioned to the right of the point where the technological and plasma-forming gases meet and interact within the technological channel of the T-plasmatron. The dimension parameters, shown in Figure 1, are as follows: \( l_{\text{in, e}} \) is the inter-electrode distance, \( l_{\text{an, ch.}} \) is the anode channel length, and \( d_a \) is the anode channel diameter. An exit from the anode channel is created as an abrupt expansion, generating a gaseous vortex that is deflected by the transverse flow of technological gas and deforming the initial vortex by adding a twist. If \( l_{\text{an, ch.}} \) is not too long (in our experiment, we used \( l_{\text{an, ch.}} = 4 \) mm), this vortex will attract an anode arc spot that will widely distribute the lowered anode erosion rate by 4–5 orders of magnitude.

A draft of the T-plasmatron, designed in Korea, is presented in figure 2.

Figure 2. Draft of the T-plasmatron.

The operating T-plasmatron is shown in figure 3.
The anode erosion rate was measured using a direct gravimetric method. Over a period of 18 hours, the anode weight decreased by 2.32 mg, showing $m_A = 3.6 \cdot 10^{-10}$ g/C [2], which was registered with ±3% margin of error. This erosion rate decreased significantly compared with conventional plasmatrons, which have constricted anode arc spots with an erosion rate of $m_A \approx 10^{-5} \ldots 10^{-6}$ g/C [3]. As a result, plasma flow from the T-plasmatron became rather clean and its technical durability reached the level of $10^4$ hours (approximately 1 year) at arc currents of $I \approx 50 \ldots 100$ A.

Examination of the plasma vortex within the technological channel, using photographs and analysing imprints left on the channel surfaces, showed that the plasmatron’s transection was completely filled with plasma, which is important for any technological processes, including plasma-chemical reactions. Plasma vortex imprints left in the technological channel of the T-plasmatron can be seen in figure 4. Please keep in mind that similar imprints were present on the flat surface of the part that was removed in order to show the inside of the technological channel.

**Figure 3.** Operating T-plasmatron.

**Figure 4.** Opened flat technological channel of the T-plasmatron, showing the plasma vortex imprints on the right-hand side.
Initially, the T-plasmatron was used to clean the exhaust steam of a Diesel engine, chemically activating its fuel with plasma. This experiment was carried out using Diesel fuel mixed with air supplied into the T-plasmatron’s technological channel and then to the engine’s inlet sleeve. Within this channel the said mixture turned into a hydrogen-rich synthesis gas, \( \text{H}_2+\text{CO} \), which can be seen exiting the pipe connected with the T-plasmatron’s technological channel (figure 5).

![Figure 5. The T-plasmatron uses technological gas – a mixture of diesel fuel and air.](image)

This synthesis gas was supplied through the said inlet sleeve, along with the rest of the fuel-air mixture. However, the temperature of the ionized synthesis gas at the plasmatron’s exit was rather high, as can be seen in Figure 5, and it should be lowered by a water-cooled DOVER heat exchanger (figure 6). The temperature of the gas exiting this heat exchanger reached approximately 40°C.

![Figure 6. DOVER B10Hx20/1P-SC-S heat exchanger, installed between the T-plasmatron and a Diesel engine.](image)

In this experiment, plasma was used to clean the exhaust stream of the Kookje 3T90Lt-AC Diesel engine (made in Korea), as shown in figure 7.
The engine was tested with a fuel flow rate of ~ 150 ml/min. Flow rates of up to 4 ml/min of Diesel fuel and 12 ml/min of air were supplied into the technological channel of the T-plasmatron at its DC arc power, up to 1.2 kW, resulting in a 12% reduction of NOx content in the engine exhaust, which was not high enough.

Another technological process using the T-plasmatron was represented through plasma-chemical etching of a ~1 μm thick photo-resist TDMR-AR87 (made in Korea) and a mono-crystal silicon wafer, which was arranged in a vacuum chamber with a pressure of 3 mbar, using oxygen technological gas for the photo-resist etching and Freon CF₄ for the silicon etching. These gases were fed into the technological channel of the T-plasmatron to create the plasma-chemical processes. The flow rates of each technological gas was approximately 20 nl/min, with an argon flow rate of 2 nl/min. At an arc power of 2 kW, the rate of photo-resist etching reached approximately 1.3 μm/min, and the etching rate for mono-crystal silicon was approximately 1 μm/min [4]. Photo-resist etching within the vacuum chamber is depicted in figure 8.

Note that this plasmatron can be used for plasma-chemical deposition on any type of film.
2. Second model of the high-durability DC arc plasmatron, A-plasmatron, and its applications for technological processes
To arrange for more uniform and effective interactions between technological and plasma-forming gases, an anode spot vortex was created using a flat circular technological channel surrounding anode channel at its exit. The resulting axisymmetric plasma generator was called the A-plasmatron (alluding to the word, ‘axial’), the schematic diagram of which is depicted in figure 9.

![Figure 9. Schematic diagram of A-plasmatron. 1. Cathode. 2. Feeding of plasma-forming gas (argon). 3. Water-cooled anode. 4. Flat technological channel. 5. Plasma jet. 6. Feeding of technological gas.](image1.png)

A draft of the A-plasmatron is presented in figure 10.

![Figure 10. Draft of the A-plasmatron.](image2.png)

A view of the operating process is shown in figure 11.
Measurement of the A-plasmatron’s copper anode erosion rate showed that it remained on the same level, ~ 10^{-10} g/C, as it was determined for the T-plasmatron. It was interesting to repeat the same technological processes that were arranged with the T-plasmatron. First, we attempted to clean the Diesel engine’s exhaust stream by feeding H_2+CO, the hydrogen-rich synthesis gas created by the mixture of Diesel fuel and air fed into the technological channel of the A-plasmatron. Arrangement of this experiment is shown in figure 12.

This experiment showed that the NOx content of the engine’s exhaust stream was lowered by approximately 30%, being a more effective process. It demonstrated that the A-plasmatron’s ability to...
activate technological gas was three times higher than for the T-plasmatron. Beside this experiment, the technological processes of ~1 μm thick photo-resist TDMR-AR87 and mono-crystal silicon wafer etching were repeated, using the same parameters as for the T-plasmatron. The results obtained indicated that the photo-resist etching rate was approximately 3.5 μm/min (using oxygen), while the mono-crystal silicon etching rate was approximately 3 μm/min (using Freon). The photo-resist etching rate increased up to 6 μm/min with the mixture of O₂ + CF₄ technological gases. This process is depicted in figure 13.

![Photo-resist etching by A-plasmatron at a vacuum pressure of 3 mbar, using a mixture of O₂ + CF₄ technological gases.](image)

Figure 13. Photo-resist etching by A-plasmatron at a vacuum pressure of 3 mbar, using a mixture of O₂ + CF₄ technological gases.

The A-plasmatron was also used for plasma-chemical depositions of films, including SiO₂, Si₃N₄, etc. The high quality of this device was described in the PCT application for the year 2006 and was then protected under US patent [5] having exceeded the world level.

3. Use of A-plasmatron in biomedical processes
The clarity of the A-plasmatron’s plasma along with its increased ability to activate technological gases has stimulated a search for possible use of this device within the biomedical field [6]. The results of the integral and local diagnostics of the A-plasmatron’s plasma flow are presented in this work.

Three different technological gases were used in the experiments [6]: argon, nitrogen, and air. The flow rate of each gas was 10 nl/min, with argon having a flow rate of 2 nl/min, at the DC arc current of 50 A. The most interesting results were obtained with the air technological gas. Measurements of the plasma irradiation spectrum, taken at a distance of 5 mm from the A-plasmatron’s nozzle, showed substantive contents of the chemical radicals, NO and OH, in the plasma flow, as depicted in figure 14.
These measurements showed that, at a distance of 5 mm, the densities of NO and OH were higher than they were when measured beside the A-plasmatron’s nozzle. This fact seemed to be quite interesting. Nitrogen oxide (NO) can be considered as a universal regulator of multivarious biological and physiological processes; in particular, it can accelerate the healing of human injuries. Accordingly, new medical direction suggests the use of NO-therapy, for which the A-plasmatron might be very beneficial using air as its technological gas. The OH radical can also be used to solve biomedical tasks at optimal concentrations and dosing exposures.

The qualitative spectral information about this plasma was verified quantitatively through a chemical bubbler, depriving plasma from its axis and from peripheral area of plasma flow at a distance of 50 mm from the A-plasmatron’s nozzle. The results showed that the concentration of NO at the axis and periphery of plasma flow were approximately 1.88 and 128 ppm, respectively [6], which was not a small concentration.

Local plasma diagnostics for temperature measurements was carried out using an infra-red imager, Fluke TI-19. These measurements showed the axial temperature distribution for a distance range \(d=0-50\) mm from the A-plasmatron’s nozzle exit, and the radial temperature distribution at a distance of \(d=5\) mm. These temperature results are presented in figure 15.

![Figure 14. Plasma irradiation spectrum in the UV range (200-400 nm), 5 mm from the A-plasmatron’s nozzle exit [6].](image)

**Figure 14.** Plasma irradiation spectrum in the UV range (200-400 nm), 5 mm from the A-plasmatron’s nozzle exit [6].

![Figure 15. Plasma temperature distribution within the A-plasmatron’s plasma flow: a) axial distribution at \(d = 0-50\) mm, and b) radial distribution at \(d = 5\) mm.](image)

**Figure 15.** Plasma temperature distribution within the A-plasmatron’s plasma flow: a) axial distribution at \(d = 0-50\) mm, and b) radial distribution at \(d = 5\) mm.
The relatively simple methods of widely varying the A-plasmatron’s output plasma parameters make it a universal apparatus using it for technological processes with temperature-sensitive technological materials, like polymers or biomedical substances. Arranging an acceptable scale of its plasma flow parameters allows for a selection of convenient locations where to process objects of different kinds.

Within the biological field, the A-plasmatron’s plasma flow was used to check its influence on storage times for bread and potatoes. These experiments successfully illustrate that, in addition to the traditional method of blowing an ozone-air mixture to remove mushroom florula, the A-plasmatron’s plasma flow, generated using air technological gas, eliminates not only the mushroom florula, but also bacterial florula, allowing for an extended storage time of any biological objects.

4. Conclusions
a) Both plasmatrons described in this article can be used for plasma-chemical processes in the fields of microelectronics and semiconductors. Serious attention should be paid to the A-plasmatron due to the raised activation degree of its technological gases.
b) This plasmatron can be used as a space apparatus because of its high durability (up to 1 year).
c) Besides, it can be used as a biomedical apparatus for the purpose of medical healing and plasma blasting of vegetables, white straw crops and their products due to its generation of pure plasma with effective contents of NO and OH radicals generated by air technological gas.

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