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Design of a hot graphite mixing chamber with a submerged jet for a DC plasma torch

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Received June 19, 2025
Revised August 17, 2025
Accepted August 18, 2025

A hot graphite flow mixing chamber for a DC plasma torch, which ensures heating of a graphite target with molecular gas (nitrogen) to a temperature above 3000 K without „thermomechanical" erosion by forming a more homogeneous steady gas flow, was designed.

Keywords: plasma torch, graphite, homogeneous gas flow, thermomechanical erosion.

DOI: 10.61011/TPL.2025.11.62216.20410

Thermal (arc) plasma generated by a plasma torch is a highly efficient tool that is used widely in various fields of science and technology [1]. One of the key areas of its application is the modeling of operating conditions of materials and structural components exposed to extreme temperatures [2–4]. This method allows for an in-depth examination of the physicochemical processes in materials at high temperatures, which helps improve their performance characteristics and reliability.

To simulate such conditions, large-scale plasma test facilities with DC plasma sources or RF inductively coupled plasma sources have been constructed since the late 1970s [5,6]. Complex and expensive equipment is needed to provide the required heat flux to the surface of samples in such tests [7,8].

The aim of the present study, which is a continuation of [4], is to design a laboratory device capable of damping the pulsations of plasma flow generated by a plasma torch, which is needed to ensure uniform heating of the surface of material samples with a homogeneous air flow to temperatures of 3000 K and above.

A DC plasma torch with a constricted arc has one key advantage: it allows one to reach levels of specific enthalpy. However, it also has a significant drawback, which is the presence of chaotic temporal and spatial pulsations in the generated plasma flow. These oscillations are caused by the dynamic interaction of electric current of the arc with its intrinsic magnetic field, which leads to significant fluctuations of the heat flux density. This translates into pulsations (with a frequency of tens of kHz) in the heating temperature of the studied sample surface, which is especially problematic for brittle materials (e. g., graphite).

Temperature fluctuations induce pulsations in heating of the graphite surface, initiating cycles of expansion and contraction in its grain structure. In a brittle material with weaker intergranular bonds, these cycles lead to disruption of the latter and detachment of individual grains, which are then carried away with the plasma flow. This is the thermomechanical mechanism behind the loss of mass from the sample surface.

Studies into the operation of a DC plasma torch with molecular nitrogen and an uncooled graphite channel of various configurations (with flow manipulation via solid walls, such as helical sections and flow dividers, for minimization of thermomechanical erosion) [4] revealed that a specific mass loss rate of isothermally heated graphite samples cannot be reduced below 10^{-5} g/(cm$^2 \cdot$ s) at temperatures above 2500 K. However, such levels were achieved with an atomic gas (argon).

In this context, a method for mixing the plasma flow without the use of additional external (with respect to the walls of a cylindrical channel itself) solid walls was developed. This approach relies on the use of a hot mixing chamber with a submerged jet. The operating principle is as follows: plasma flow generated by a plasma torch is directed into a closed graphite cavity with one or more side outlets in its upper part (Fig. 1). This radical change in direction of the flow ensures its effective mixing. Experimental data have confirmed that the method is highly efficient: in all

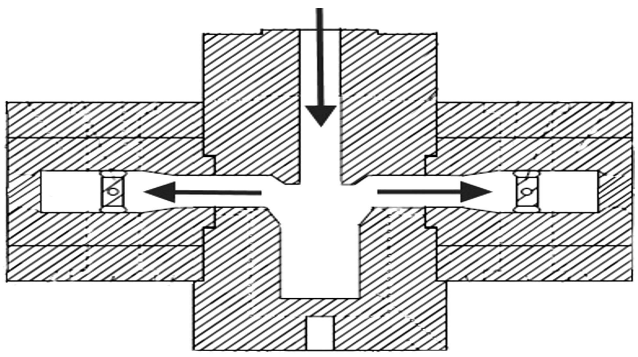

Figure 1. Schematic diagram of the mixing chamber with a submerged jet and two outlet channels directed at the mounted samples.

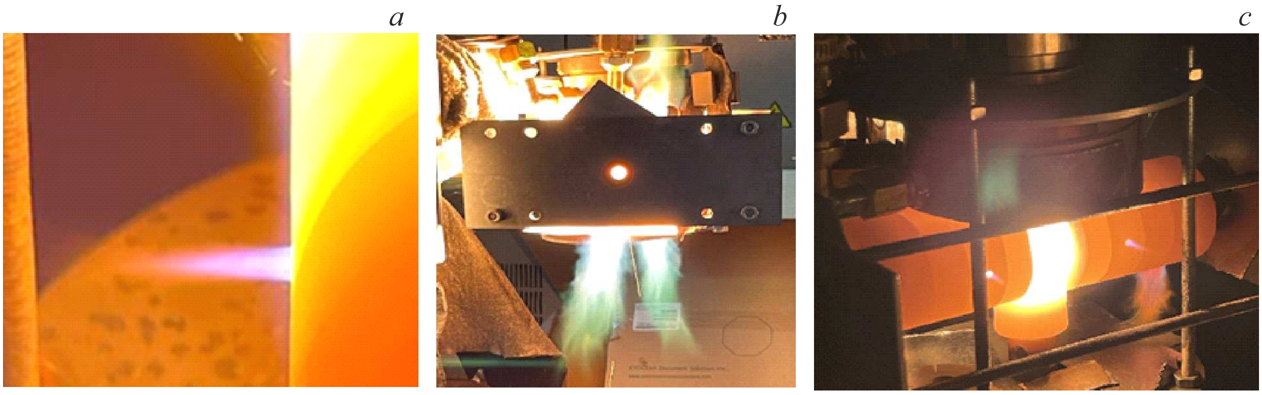

Figure 2. Images of the nitrogen jet from the outer optical aperture with a diameter of 4 mm at an arc current of 250 A (*a*) and jets emerging from the outlets of the assembly (*b*); general view of the setup in operation (*c*).

experiments conducted using this hot mixing chamber, the emission of luminous graphite microparticles, which are produced due to thermomechanical destruction of the surface under the influence of chaotic thermal shocks, ceased completely (Fig. 2).

A three-electrode (cathode with a lanthanated tungsten insert–interelectrode insert–anode) DC low-temperature plasma generator with vortex gas supply, a gas discharge channel diameter of 8 mm, and an efficiency of $\sim 80\,\%$ for nitrogen was used as the plasma source. The plasma flow formed at its outlet had diameter $D = 8-10$ mm, an enthalpy up to 50 kJ/g, and a bulk temperature of 10–11 kK at a total electrical power of the arc discharge up to 50 kW and a plasma-forming gas flow rate of 1–3 g/s [9].

The following key controlled parameters were chosen: (i) the true temperature of (almost isothermally) heated MPG-6 (Ø 8×4 mm) graphite samples with a black body model inside them (a blind drilled hole, Ø 2×6 mm) mounted in the outlet channels perpendicular to the flow (see Fig. 1); (ii) their mass loss. The temperature was measured using a Raytek 1M brightness pyrometer operating at a wavelength of $1\,\mu$m (field of view, 0.6 mm; error, 0.3 % of the measured value +1 K) through a Ø 2.5 mm aperture in the side wall of the channel. The measurement range of this pyrometer is limited to 3300 K. The mass of the sample and all other components of the hot section was measured before and after each test. The plasma flow from the mixing chamber was recorded on video using a high-speed MotionPro camera.

High-speed video recording of the jet flowing out of the mixing chamber with a submerged jet revealed (Fig. 3) that a stable flow is indeed formed at its outlet; according to the video frames, this flow has a near-rectangular radial temperature profile. The glowing tracks are particles of iron oxide from the oxidizing steel mounting flange.

This design solution allows one to connect not one, but several experimental channels with samples to the mixing chamber, increasing significantly the efficiency and reliability of the research. Figures 1 and 2 present the design with two identical channels.

Figure 2, *c* illustrates the state this assembly during testing. It is evident that the mixing chamber heats up considerably (the glow color is indicative of temperatures well above 1500 K on the outer surface at an arc current of 300 A, and melting of steel components due to radiation from the walls was observed); therefore, proper shielding (thermal insulation) of all metal parts surrounding the assembly is needed.

The rate of specific oxidation of the outer surface due to its exposure to airflow as a result of natural convection did not exceed $2 \cdot 10^{-3}\,\mathrm{g/(cm^2 \cdot s)}$ (0.6 mm/min). The specific rate of mass loss from the surfaces of the hot section components and tested samples at sample temperatures up to 2700 K was less than $10^{-5}\,\mathrm{g/(cm^2 \cdot s)}$.

When the arc current becomes stronger than ~ 300 A (at a plasma torch channel diameter of 8 mm), the temperature of the inner surface of the mixing chamber apparently exceeds the sublimation temperature of graphite, inducing a sharp increase in mass loss from this surface. The mass of other components of the hot section and the tested samples then started increasing (due to the deposition of soot, often in the form of spheres).

As before, no cases of failure of well-sectioned assembly elements due to thermal stress were reported.

Thus, a design solution ensuring effective suppression of spatial and temporal temperature fluctuations in the plasma flow generated by a plasma torch was proposed. This suppression helps nullify the influence of the thermomechanical erosion mechanism on the surface of heated graphite samples.

Conflict of interest

The authors declare that they have no conflict of interest.

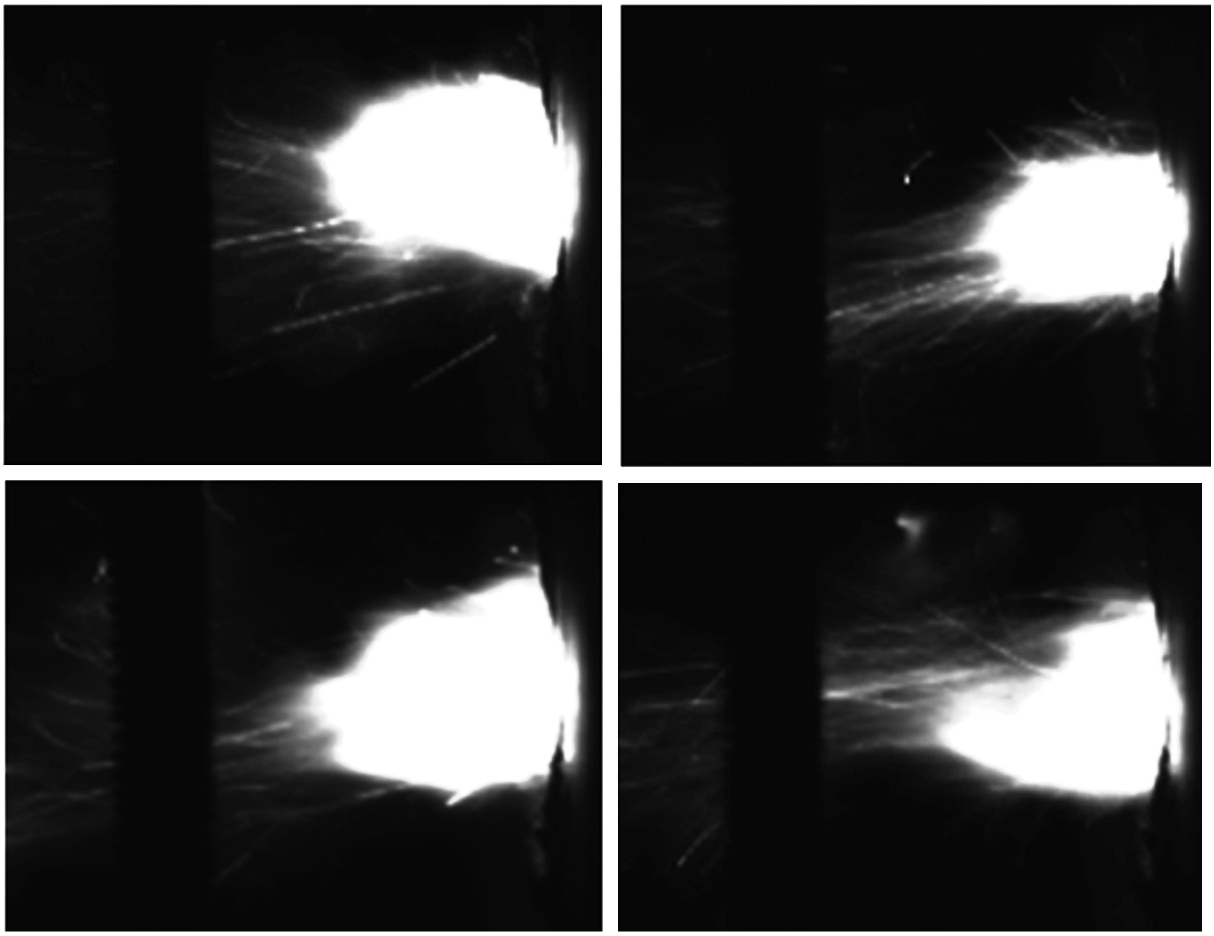

Figure 3. Sequential frames from the video (recorded at 1000 Hz) visualizing a nitrogen plasma jet emerging from the mixing chamber with a submerged jet at an arc current of 300 A and an exposure of 100 μs.

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Translated by D.Safin