Generator of the low-temperature heterogeneous plasma flow

D I Yusupov, M Kh Gadzhiev, A S Tyuftyaev, V F Chinnov and M A Sargsyan
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
E-mail: spr_yusupov@mail.ru

Abstract. A generator of low-temperature dc plasma with an expanding channel of an output electrode for gas-thermal spraying was designed and constructed. The delivery of the sprayed powder into the cathode and anode arc-binding zones or into the plasma jet below the anode binding was realized. The electrophysical characteristics of both the plasma torch and the heterogeneous plasma flow with Al$_2$O$_3$ powder are studied. It is shown that the current–voltage characteristic (CVC) of a plasma torch depends on the gas flow rate. If the flow rate varies from 1 to 3 g/s, the falling CVC becomes gradually increasing. The speed and temperature of the sprayed powder are determined.

1. Introduction

Over the past 20 years the use of thermal plasma in the particle heating process showed their technological advantage in various applications [1–4]. One of these applications is gas-thermal spraying (GTS). High energy flux density ($10^6$–$10^7$ J/m$^3$) and high heat flux density ($10^7$–$10^9$ W/m$^2$) allow to use the particles with different thermal properties as sprayed material and to provide a high efficiency of the spraying process.

Contemporary GTS methods are based on creating a heterogeneous stream mainly through the introduction of powdered materials into the plasma jet, which carries out the heating and acceleration of particles. For this it is necessary to have a reliable low-temperature plasma generator (LTPG) [4–6]. In the LTPGs discharge gap a high-enthalpy plasma stream is created with a chosen operating environment and a temperature range from thousands to tens of thousands degrees. These factors present a great interest for the study of thermal, electrical and optical properties of gases, as well as—the implementation of various plasma-chemical reactions. Due to the above mentioned reasons, the main goal of this work is to develop an efficient heterogeneous flow, low-temperature plasma generator and to develop methods for determining the electrophysical characteristics of a given plasma flow.

2. Experimental setup

As the source of such plasma, a LTPG with vortex stream stabilization and expanding anode channel was constructed (figure 1), which provides high stream performance and service life of the plasma torch [4, 6, 7].

The plasma torch design provides several methods of particle flow (figure 1):
Figure 1. The design for spraying plasma torch.

Figure 2. Complete diagnostic system for the study of heterogeneous plasma jets.

- through ports in the first anode section;
- through ports in the second anode section;
- through different configurations of ports in the cathode.

To study electro-physical properties of both the plasma stream and spraying particles that it carries an experimental stand was constructed, the schematic of this setup is presented in figure 2.
A number of devices are used for diagnostic purposes, such as: high-speed and highly sensitive video cameras operating in the visible and infrared ranges (280 to 1000 nm wavelength), pulse laser (wavelength 527 nm, pulse energy 0.1 mJ, pulse duration 7 ns, pulse frequency 1–10 kHz) is used to illuminate the particles by “laser knife” method, and spectrometer DFS-452 that is used to determine the plasma parameters with and without particles presented in it.

3. Results and discussion

One of the most important characteristics of the discharge in the LTPG is its current–voltage characteristic (CVC). The falling CVC characteristics of the LTPG with longitudinal gas flow and self-adjusting arc length firstly entails strict requirements for electrical power supply for the arc stabilization. Secondly, the current is increased as the arc voltage drops, respectively, the arc power is increased more slowly than the current, while the resource of LTPG is mainly determined by the magnitude of the arc current [4].

To determine the efficiency (figure 3) and CVC (figure 4) of the plasma torch, the values of the arc burning voltage at a given current and the heat fluxes on the water-cooled parts of the plasma torch were determined. Calculation of heat fluxes was carried out based on the measured results of the water flow rate and temperature at the inlet and outlet of the water-cooled LTPG tract using thermocouples and flow sensors. The results of the investigations for the arc current of 300 A are given in table 1.

There $G$—the flow rate of the plasma forming gas; $t_0$—water temperature at the inlet of LTPG; $t_k$—water temperature at the outlet of LTPG; $\Delta t$—water temperature difference; $F$—water flow rate; $Q$—thermal losses for the cooling of LTPG ($Q = F c \Delta t$); $I$—arc current; $U$—arc voltage; $P$—electric arc power ($P = IU$); $\eta$—efficiency of the plasma torch ($\eta = (P - Q) / P \times 100\%$).

Figure 3. The plasma generator efficiency at 300 A arc current for the various plasma forming gas (argon) flow rates.
Figure 4. CVC of the plasma torch at various plasma gas flow rates.

Table 1. Thermal and electrical characteristics of the LTPG.

| $G$ (g/s) | $t_0$ (°C) | $t_k$ (°C) | $\Delta t$ (°C) | $F$ (g/s) | $Q$ (kW) | $I$ (A) | $U$ (V) | $P$ (kW) | $\eta$ (%) |
|-----------|------------|------------|-----------------|----------|----------|--------|--------|---------|-----------|
| 1         | 5.8        | 11.5       | 5.7             | 188      | 4.49     | 300    | 26     | 7.8     | 42        |
| 1.5       | 5.8        | 11.5       | 5.7             | 188      | 4.49     | 300    | 31     | 9.3     | 52        |
| 2         | 5.8        | 11.5       | 5.7             | 188      | 4.49     | 300    | 33     | 9.9     | 55        |
| 2.5       | 5.8        | 11.8       | 6               | 188      | 4.73     | 300    | 34     | 10.2    | 54        |
| 3         | 5.8        | 12         | 6.2             | 188      | 4.88     | 300    | 35     | 10.5    | 54        |

Figures 3 and 4 show that the efficiency and CVC of the LTPG at low flow rates of plasma forming gas (argon) falls starting from a certain current value. When the gas flow rate is increased up to 2 g/s the CVC is practically unchanged, the zone of stable discharge operation at low currents is also extended when compared to the plasma torches with cylindrical channels. With the further increase of the argon flow rate the CVC starts to grow.

To test the plasma torch, experimental stand and the diagnostic methods an experiment on particle deposition was conducted, Al$_2$O$_3$ was used as deposition material, with particles sizes varying in the 20–80 µm range and a flow rate of 0.1 g/s. The particles were deposited on the stainless-steel substrate at an argon flow rates of 1.5–3 g/s and an arc current of 200–450 A. The Al$_2$O$_3$ powder was supplied in the near-cathode and anode regions of the arc.

Moving particles in the plasma flow leave luminous tracks on video images; the length of these tracks is proportional to the particle velocity and the camera exposure time (figure 5). The measuring system based on infrared matrix allows the simultaneous determination of particle parameters such as their speed, size and temperature [8].
Figure 5. A series of images received during the spraying of Al₂O₃ powder with a 300 A arc current: (a) visible range, (b) ir range, and (c) illumination of particles by repetitively pulsed laser.

To determine the temperature of the particles using this system, the system was calibrated using the reference black body in the temperature range of 800 to 3000 K. The minimum temperature that can be determined using this method depends on the camera exposure time (the lower the exposure time is the higher must be the temperature) and geometric parameters.

Our studies have shown that the particle velocities vary depending on the plasma gas flow rate and the arc current in a range from 40 to 100 m/s. The temperature of the particles near the substrates surface at a current of 300 A is on average 2400–2500 K (the melting point of Al₂O₃ is 2317 K).

As the plasma loaded with cold microparticles in the near-cathode region flows downstream it cools down. The plasma cooling effect caused by the heat transfer to the particles was investigated through the section that follows the anode. The comparison of plasma emission spectra with and without Al₂O₃ powder is presented in figure 6.

Plasma electron temperature $T_e$ can be determined using the dependence $\ln(n_k/g_k) = f(E_k)$, where $n_k$—population (concentration) of the radiating atoms in the $k$-th level with excitation
Figure 6. Argon plasma emission spectrum (a) and argon plasma with $\text{Al}_2\text{O}_3$ particles (b) in the spectral range of 375 to 425 nm, recorded from the near-anode zone $Z \approx 50$ mm.

Figure 6. Argon plasma emission spectrum (a) and argon plasma with $\text{Al}_2\text{O}_3$ particles (b) in the spectral range of 375 to 425 nm, recorded from the near-anode zone $Z \approx 50$ mm.

energy $E_k$; $g_k$—statistical weight of level $k$ [9]. The electron density $n_e$ is determined either from Stark width of Ar I spectral lines (if the half-width of such line is of the same order or higher than the hardware function of the registration system) or by absolute spectral intensity of continuous radiation spectrum.

In the region $Z \approx 50$ mm from the cathode, the “Boltzmann exponent” for Ar gas without the $\text{Al}_2\text{O}_3$ particles corresponds to the value of temperature in the plasma stream axis $T_{\text{Ar}}(r=0) \approx 12000 \pm 1000$ K.

The cooling of Ar plasma by $\text{Al}_2\text{O}_3$ particles gives the value of the axial temperature $T_{\text{Ar}+\text{Al}_2\text{O}_3}(r=0) \approx 10000 \pm 800$ K, see figure 6(b).

An important additional source of spectral information about Ar plasma with $\text{Al}_2\text{O}_3$ particles are molecular (primarily $\text{AlO}$, transition $B^2\Sigma - X^2\Sigma$) and atomic spectral lines of metals (besides the obvious A II, Mo I, the lines of Ca I, Ca II, Na I, etc), see figure 6(b).

In the substrate region ($Z \approx 100$ mm), the temperature of argon plasma is minimal and the temperature of $\text{Al}_2\text{O}_3$ particles, which are heated by the plasma, is maximum. Possibilities of the spectral determination of these parameters in such plasma are minimal. The electron temperature can be estimated from the relative intensities of the atomic spectral lines of metal
Impurities (Al I, Mg I, Ca I, Ca II, NaI), if the excitation energy of these lines cover a range of not less than 0.3–0.5 eV. Caution should be exercised when using spectral lines of the resonance series–these transitions should be checked for the absence of reabsorption (check for the small value of optical thickness \( \tau = k_0 R < 1 \), where \( k_0 \)—absorption coefficient at the line center; \( R \)—jet radius). Another possibility to estimate the temperature involves processing of weak molecular bands of AlO (in Ar plasma) or \( N_2(2+) \) and \( N_2^+(−1) \) (in the argon and nitrogen mixed plasma).

4. Conclusion
A generator of low-temperature dc plasma with an expanding channel of an output electrode for gas-thermal spraying is created, in which the powder is supplied into a cathode or anodic arc-binding zone, and in a current-free plasma jet. Methods for determining the velocity, size, and temperature of the sprayed powder particles are developed. It is shown that the particle velocity of \( \text{Al}_2\text{O}_3 \) powder, depending on the gas flow rate and arc current, can reach up to 100 m/s. The temperature of the powder particles near the substrate at a current of 300 A is on average 2400–2500 K.

Acknowledgments
The study was supported by the Russian Science Foundation, grant No. 14-50-00124.

References
[1] Zhukov M F, Koroteev A S and Uryukov B A 1975 Prikladnaya Dinamika Termicheskoi Plazmy (Novosibirsk: Nauka)
[2] Bashkatov V A, Isakaev E Kh, Kreshin M B, Chenchikov A M, Shelkov E M and Shpielrein E E 1982 Electrodegovoi plazmatron USSR Inventor’s Certificate 814250
[3] Isakaev E Kh, Grigoryane R R, Spektor N O and Tyuftyaev A S 1994 High Temp. 32 588–9
[4] Isakaev E Kh, Sinkevich O A, Tyuftyaev A S and Chinnov V F 2010 High Temp. 48 97–125
[5] Glebov I A and Rutberg F G 1985 Powerful Plasma Generators (Moscow: Energoatomizdat)
[6] Tyuftyaev A S 2013 High Temp. 51 160–6
[7] Isakaev E Kh, Tyuftyaev A S and Gadzhiev M Kh 2017 Inorganic Materials: Applied Research 3 27–30
[8] Senchenko V N and Dozhidkov V S 2003 AIP Conf. Proc. 684 831–6
[9] Ochkin V N 2006 Spectroscopy of Low-Temperature Plasma (Moscow: FIZMATLIT)