The investigation of heterogeneous flow generated by the direct current plasma torch

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Abstract. In the article, the two-phase flow of electric arc gas heater of the linear scheme is studied. The power of the plasma torch can be varied from 200 to 1500 kW. For stabilization of the electric arc a magnetic coil is used. The operation of the plasma torch took place at overpressure in the discharge chamber. Injection of the powder was made near the exit of the nozzle. A powder of SiO$_2$ was used as a disperse phase. The size of the particles was not more than 50 microns. The dispensing device was used for the powder injection. The technique of velocity measurement in high-temperature heterogeneous flow from the registration of flow by the high-speed camera is presented. The results of measurements indicate that the speed of the particles much lower than the speed of the gas. The results of measuring the heat flux along the axis of the plasma torch are presented. The heat flux was measured by means of regular mode uncooled sensors with tablet type calorimeters.

1. Introduction

The application of low-temperature plasma for commercial purposes and for scientific research is constantly evolving. Today plasmatrons are used as a source of heat and chemically active substances in many important areas [1]: in the chemical industry, metallurgy, power systems, for processing materials, for the synthesis of nanoparticles and recycling. The important area of application of the plasma torches is the modeling of the entry of a spacecraft in planetary atmospheres [2–5].

Electric arc gas heaters are the only way to produce high-enthalpy shear flows over a long time intervals [2]. These flows are necessary for modeling of impact on the materials when entering the planet atmosphere at hypersonic speeds. High-enthalpy flow in the plasmatron is created by passing the gas through the arc and the subsequent output from converging or diverging nozzle. The study of parameters of high-speed two-phase flow and their thermal erosion of the structural elements of the thermal protection is of great practical interest.

The investigation of such two-phase plasma flows includes the measurement of temperature, density, flow velocity, temperature and velocity of particles, the distribution function of particle size, mass and volume concentration of the particles and etc. The aim of this work is to perform measurements of the heat flux and velocity of the dispersed phase in a heterogeneous flow formed by electric arc gas heater EAGH-1.2. This plasmatron belongs to a class of low-temperature plasma torch of the linear scheme. This type of plasma torches can work with almost any gas and can be of various configurations of electrodes [6].
2. Experimental setup
The two-phase flow of the electric arc gas heater of the linear scheme with gas-dynamic and magnetic stabilization was investigated. Schematic representation of the plasma torch is presented in figure 1. The equipment needed to operate the plasma torch includes a high voltage power supply, the gas supply system and a liquid cooling system. Electrical power of plasma torch may vary in the range from 200 to 1500 kW. The power supply voltage is up to 2.3 kV, arc current is up to 1 kA. The bulk mean enthalpy of air is 15–20 MJ/kg. The pressure in the chamber of the plasma torch is up to 19 bar.

At the exit of the plasma torch, the special nozzle with the system of powder injection was mounted. The opening angle of the nozzle was 24°. At a distance of 13 mm from the exit of the nozzle, three channels were performed. The channels are perpendicular to the axis of the plasmatron and the angle between the adjacent channels is 120°. During the experiment, these channels were used to feed the powder into the plasma flow. The special dispensing device was developed to work with plasma torch at overpressure in the discharge chamber.

The powder of SiO₂ was used as the dispersed phase. The size of the particles was not greater than 50 microns. The function of the particle size distribution is shown in figure 2. The average particle diameter of the SiO₂ powder is 14.2 µm.

Experiments were carried out at overpressure in the discharge chamber for steady operation regime of the plasmatron: arc current was 1000 A, voltage 1000 V, the flow rate of the working gas $9.5 \times 10^{-3}$ kg/s, the powder carrier gas flow rate was $5 \times 10^{-3}$ kg/s. During the experiments these parameters were maintained unchanged.

3. Heat flux measurements
The heat flux in the various cross-sections along the axis of the plasma flow was measured. The regular mode uncooled sensors with tablet type calorimeters were used. Measurement of the temperature of the covered back of the sensor was made by chromel-copel thermocouple. The diameter of electrodes was 0.2 mm. The accuracy of the heat flux measurement was B10%.

Figure 3 shows the results of the heat flux measurements along the axis of the plasma torch. Square points indicate the measured heat flux for two-phase flow. Circle points correspond to single-phase flow without powder. The line is the approximation for the single-phase flow.

The dynamic pressure on the surface of the sample was $\Delta P = 0.15$ bar for heat flux of $q_{0\Sigma} = 140$ W/cm², and $\Delta P = 0.11$ bar for $q_{0\Sigma} = 80$ W/cm².

4. Velocity measurements
In this work, the velocity of the disperse phase was measured based on the PIV-methods [7]. For this, the flow is registered in such way that the displacements of the particles during some definite period of time can be measured. The main difference of the current article from the standard approach used in the PIV-methods is that the particles are observed in the entire visible region of the flow, rather than in a separate section.

The velocity measurements were based on the registration of heterogeneous flow with high-speed camera PCO DiCam-Pro (CCD camera with image intensifier). The camera records gray-scale images with a resolution of $1280 \times 1024$ px² with 12-bit color depth. The mode of two frames was used in which a pair of images can be recorded with a small time interval. The minimum exposure time is 20 ns, the delay between two recorded images can be from 20 ns to 1 s. The observations were made in the direction perpendicular to the axis of the plasma torch. The distance between the camera and the flow was ~2 m. For the recording, the “Nikor” lens with a focal length ranging from 80 to 400 mm was used. The typical image of the flow with the particles is shown in the figure 4. From the figure 4, the glow of the particles and the high-temperature gas-plasma structures are visible.
The particles may be visible in the images due to scattering of radiation from a gaseous flow or by luminescence due to preheating in the plasma torch. For sufficiently small time interval between successive frames, the spatial distribution of the particles varies slightly. The deformation of the spatial structure of the particle distribution can be characterized only by shifts of certain small areas. Figure 5 shows the enlarged fragments of one pair of images taken.
Figure 4. Images of the plasma flow with particles of SiO$_2$ (exposure time of 0.2 $\mu$s).

Figure 5. The enlarged fragments of the images recorded with the time interval of 15 $\mu$s.

with an interval of 15 $\mu$s. The velocity of the particles averaged over interrogation window is proportional to the relative shift of these windows between images.

The algorithm for automatic measurement of the velocity field of the particles from the recorded images was based on the statistical methods. For processing, the luminescence from the large-scale gas formation in the images was suppressed by the filtering in the frequency domain. Each image was divided into small areas by rectangular grid. For sequential pairs of images the cross-correlation between the corresponding areas was calculated. The calculations were made on the basis of the fast Fourier transform. The relative displacement of the area between images is proportional to the particles velocity averaged over this area.

Figure 6 shows the results of calculating the velocity of the particles for two pairs of images for heterogeneous flow with particles of SiO$_2$. Registered images show significant instability of the flow of the particles. Figure 7 shows the data averaged over 10 measurements.

Figure 8 shows the distribution of velocity of SiO$_2$ particles in a cross-section perpendicular to the plasma torch axis at a distance of 60 mm and 120 mm from the nozzle exit. The
Figure 6. The distribution of the velocity of SiO$_2$ particles measured from the one pair of recorded images of the plasma flow.

Figure 7. The distribution of the velocity of the particles averaged over measurements from 10 pairs of images.

The estimation of the gas phase velocity can be made from the analysis of displacements of the large-scale plasma formation. In this case, it is necessary that the time of the destruction of the large-scale structures was less than the interval between registered images. Figure 9 shows two images of the flow registered one after another. Despite the changes in the plasma formations, the general shift of the structure to the right is seen.

The velocity of the gas phase was determined from the shift analysis of the large-scale plasma formations observed in the flow field. The displacement of the one image relative to the another is determined from their cross-correlation. The high-frequency filter was applied for analyzed images to suppress the influence of particles. The results of velocity measurements of the gas phase averaged over the entire visible region of the heterogeneous flow (~ 120 mm along the axis) are shown in figure 10. The gas velocity averaged over the operation time of plasma torch was 1600 m/s.
**Figure 8.** The distribution of the averaged velocity of particles in a cross-section of the flow at a distance of 60 mm (dotted line) and 120 mm (solid line) from the nozzle exit.

**Figure 9.** The images of the flow registered with the interval of 2 µs (0.200 µs exposure time).

**Figure 10.** Velocity of the gas flow, averaged over the region from 20 mm to 140 mm from the nozzle exit.
5. Conclusions
The results of measurements of the heat flux in different sections of the plasma torch flow are presented. A method for measuring the velocity of the heterogeneous flow based on the registration of the flow by the high-speed camera is discussed. The results show that the time-averaged velocity of the particles is about 400–500 m/s for the all observed region of the heterogeneous flow. The particles are much slower than the flow, the speed of which is about $\sim 1600$ m/s.

References
[1] Mostaghimi J and Boulos M I 2015 Plasma Chem. Plasma Process. 35 421–436
[2] Dubreus T M, Sheeley J M and Stewart J H US Air Force T&E Days 2010 p 1732
[3] Olivas J D, Mayeaux B, Melroy P and Cone D
[4] Ritt P J, Williams P A, Splinter S C and Perepeko J H 2014 J. Eur. Ceram. Soc. 34 3521–3533
[5] Carandente V, Savino R, Esposito A, Zuppardi G and Caso V 2013 Exp. Therm. Fluid Sci. 48 97–101
[6] Camacho S 1988 Pure Appl. Chem. 60 619–632
[7] Raffel M, Willert C E, Kompenhans J et al 2013 Particle Image Velocimetry: A Practical Guide (Springer)