Investigation of the AC Plasma Torch Working Conditions for the Plasma Chemical Applications

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Abstract. The presented design and parameters of a three-phase AC plasma torch with the power up to 500 kW, flow rate of air 30–50 g/s (temperature up to 5000 K) could be used in different plasma chemical processes. Range of measured plasma temperature is 3500–5000 K. The paper presents investigations of the plasma torch operation modes for its application in plasma chemical technologies. Plasma chemical technologies for various purposes (processing, destruction of various wastes, including technological and hazardous waste, conversion or production of chemicals to obtain nanoscale materials, etc.) are very promising in terms of the process efficiency. Their industrial use is difficult due to the lack of inexpensive and reliable plasma torches providing the desired level of temperature, enthalpy of the working gas and other necessary conditions for the process. This problem can be solved using a considered design of a three-phase alternating current plasma torch with power of 150–500 kW with working gas flow rate of 30–50 g/s with mass average temperature up to 5000K on the basis of which an industrial plasma chemical plant can be created. The basis of the plasma torch operation is a railgun effect that is the principle of arc movement in the field of its own current field. Thanks to single supply of power to the arc, arcs forming in the discharge chamber of the plasma torch move along the electrodes under the action of electrodynamic forces resulting from the interaction of the arc current with its own magnetic field. Under the condition of the three-phase supply voltage, arc transits from the electrode to the electrode with change in the anodic and cathodic phases with frequency of 300 Hz. A special feature of this design is the ability to organize the movement of the arc attachment along the electrode, thus ensuring an even distribution of the thermal load and thus achieve long time of continuous operation of the plasma torch. The parameters of the plasma jet of the plasma torch and the single-phase three-phase plasma injector for use in a plasma-chemical unit for production of nano-dispersed materials are described in the paper.
1. Introduction

Plasma torches usage in plasma-chemical technologies most often refers to such areas as plasma processing of hazardous waste (medical, biological, toxic, etc.) by plasma pyrolysis and gasification, vitrification of slag, processing of associated gas with production of synthesis gas suitable as a raw material for electricity generation or liquid fuel production, plasma-chemical synthesis of ultrafine powders [1]. The latter may be of considerable interest because introduction of small (a few percent) amounts of nanopowders in the material leads to significant improvement of operational properties of the alloys [2].

The most widely used oxides are respectively SiO$_2$, Al$_2$O$_3$, and TiO$_2$ [3]. The main prerequisites for the use of ultrafine powders are small particle size commensurate with the size of nucleation, high sedimentation stability of the particles in the melt and the ability to achieve a high number concentration of particles at low mass concentration. Application of ultrafine powders of refractory compounds as modifiers of metals and alloys makes it possible to control the structure of the castings in the a-priori intended direction allowing influence on grain size and shape, distribution and amount of carbide, intermetallic and other phases. Technology modification of ultrafine powders can increase both strength and ductility of cast metal. Substantial change in alloy structure resulting from the modification results in increased operating characteristics: limit strength increases by 10–30%, ductility increases in 1.5–2 times, endurance limit increases by 25–40%. Modifying effects were tested on aluminum and nickel, and magnesium alloys, high-chrome cast iron, corrosion-resistant steels [4,5,6].

A feature of the plasma chemical process for production of ultrafine oxide materials is offered for consideration and implemented on the basis of AC plasma torch with rail electrodes operating in a wide range of powers and flow rates of the oxidizing gas with the possibility of producing electrodes from a variety of materials such as aluminum, and capable of providing high speed heating to the temperature of about 5000K and cooling of the processing material, which makes it particularly attractive for use in the plasma chemical technologies for production of ultrafine materials.

2. Description of the experimental installation

Photo of the working three-phase plasma torch is shown in Figure 1.
The principle of electrodynamic arcs movement in a field of its own current (railgun effect) is the basis of its operation. Quick movement of the arc spot along the electrode under the action of the electrodynamic and gas dynamic forces distributes the thermal load from spot along the length of the electrode that enables the use of water-cooled electrodes made of relatively low-melting material with high heat conductivity and capable of operating in oxidizing environments.

The structure of the plasma torch includes the injector which is a single-phase high-voltage plasma torch of low power. The injector creates in the minimum electrode gap the plasma stream with \( n_e = 10^{13} - 10^{14} \text{ cm}^{-3} \) sufficient to ignite the main arcs and smooth transition of current through zero. Arcs are initiated between the main electrodes in the zone of minimum electrode gap, and then arc attachments move along the arc surfaces of diverge electrodes.

Two arcs burn simultaneously in the discharge chamber of a single chamber three-phase plasma torch with rail type electrodes and they fill the available space.

The dimensions of the three-phase plasma torch: \( L = 60 \text{ cm} \), \( D = 45 \text{ cm} \), diameter of the outlet nozzle 6 cm, minimal distance between rail electrodes is 2 cm, length of rail electrode is 25 cm.

Features of this plasma torch design allow operation in a wide range of power settings and working gas enthalpy Figures 2 and 3.

![Figure 2](image1.png)

**Figure 2.** Dependence of the heat content of the gas from air flow rate at atmospheric pressure. The curves are marked in accordance with the values of the current strength of the electric arc.

![Figure 3](image2.png)

**Figure 3.** Dependence of average mass temperature of the working gas from air flow rate at atmospheric pressure. The curves are marked in accordance with the values of the current strength of the electric arc [4].

Figure 3 shows the dependence of average mass temperature of the working gas from air flow rate. This temperature is determined by the balance of electric energy and the energy that is lost with cooling system. It was found that the arc voltage drop depends slightly on the air flow rate [7]. It means that the electric power of the described plasma torch with the fixed current depends slightly on the air flow rate. So the enthalpy and average mass temperature of the working gas decrease with the air flow rate increase.

Longitudinal and radial temperature profiles in the flame of the plasma torch were obtained using spectral measurements (Figure 4). Figure 4 is a schematic diagram of spectral measurements of the radiation plume of a low-voltage AC arc plasma torch.
Figure 4. Scheme of spectral measurements of the radiation plume of the AC plasma torch with rail electrodes: 1 – plasma torch; 2 – plume; 3 – diaphragm; 4 – lens with focal length 22 cm; 5 – optical fiber; 6 – spectrometer Andor Shamrock SR–303i–A; 7 – CCD camera Andor 420–DU–FK.

The plasma jet at the outlet of the nozzle of the three-phase AC plasma torch is an axisymmetric cone flow (Figure 1). Temperature measurements in the flame of the AC plasma torch with rail electrodes (Figure 5 and 6) are made for different modes. The results of the measurements are presented in Table 1.

The method of the relative intensities in the approximation of local thermodynamic equilibrium was used to determine the electron temperature [8]. The torch is formed outside from the electric arc for this type of plasma generator. So there are no any electric or magnetic fields in the torch area that can lead to the non-equilibrium plasma condition. Moreover, LTE is typical for the air plasma in electric arc at atmospheric pressure [9].

The relative intensities are calculated for four pairs of copper atom’s spectral lines (in nm): CuI 515.32 and CuI 510.5, CuI 521.82 and CuI 510.5, CuI 515.32 and CuI 570.02, CuI 521.82 and CuI 570.02. These temperatures are comparable to the margin of statistical error, which does not exceed 10%.

Radial symmetry of the torch is verified by measurements of the emission spectra of the copper atoms from different angles throughout the length of the cross section of the torch. So it is possible to use the Abel transform to obtain radial temperature profiles [10].

Table 1. Parameters of a three-phase AC air plasma torch at atmospheric pressure.

| Parameter                          | Mode of operation of the power supply |
|------------------------------------|-------------------------------------|
|                                    | 1         | 2         | 3         |
| Short-circuit current of power supply, A | 500   | 700   | 1000   |
| Voltage of the supply network, V    | 480   | 480   | 480   |
| Flow rate of plasma forming gas, g/s | 30   | 30   | 25   |
| Arc current (root-mean-square active value), A | 405 | 560 | 840 |
| Arc voltage (root-mean-square value), V | 240 | 250 | 230 |
| Power no less than, kW              | 125   | 195   | 295   |
| Specific electrode erosion, g/C     | 6.510° | 8.510° | 8.210° |
| Life time of continuous operation without electrode replacement, hour | More than 100 | 85 | 35 |
It can be concluded from Figure 5 that the recorded maximum temperature at the nozzle outlet of the plasma torch is practically unchanged at different flow rates.

As can be seen from Figure 3 at flow rate of the working gas up to 25 g/s the average mass temperature of the plasma jet even at the minimum power is above 2500K, which is also acknowledged by the spectral measurements Figure 5 and Figure 6. As long as the statistical error of temperature measurements was 10 %, the temperature fluctuations along the radius can be attributed to the measurement error.

Therefore, in addition to "traditional" use of plasma torches as a source of high-enthalpy gas flows in waste processing plants or in conversion plasma-chemical technologies aimed, for example, on the production of synthesis gas the use of the plasma torch can be substantially expanded.

High thermodynamic characteristics allow usage of this design as a part of the plasma torch plasma chemical plant for production of ultrafine materials Figure 7.
Figure 7. Plasma-chemical plant on the basis of a three-phase AC plasma torch with rail electrodes.  
1 – supply system of the processed material, 2 – plasma torch, 3 – plasma reactor 4 – product  
collection system, 5 – gas outlet

Plasma torch design allows organization of the processed powder introduction at several points  
relatively to the plasma stream, including directly into the electric arc chamber. The size of the  
cylindrical water-cooled plasma chemical reactor: diameter 300 mm and height 1350 mm. In this case  
the plasma torch body is used as the first step of the plasma chemical reactor.

3. Application

The design features and the ability to ensure high plasma jet temperatures even at the minimum  
power of the plasma torch (about 100 kW) permits the plasma torch application as a part of the  
installation for plasma chemical synthesis of ultrafine oxide powders (Al\textsubscript{2}O\textsubscript{3}, ZrO\textsubscript{2}, MgO, SiO\textsubscript{2}). One  
of the ways of nanoparticles formation is metal vapour condensation at quenching of high temperature  
flow.

Thermodynamic estimation of conversion of precursor compounds into ultrafine oxide powders  
ZrO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}, MgO was carried out for initial evaluation of the applicability of the plasma torch. The  
computation was performed using the program "Chemical WorkBench" ver.3.5, Kinetic Technologies  
Ltd. [11], based on searching of minimum of Gibbs free energy. Precursors: ZrO\textsubscript{2} – ZrCl\textsubscript{4} (zirconium \n(IV) chloride); Al\textsubscript{2}O\textsubscript{3} – Al\textsubscript{2}O\textsubscript{3} (aluminum oxide); MgO – Mg (metal magnesium).

Synthesis of zirconia

Zirconium oxide is required for the production of refractory materials, high-melting glasses,  
various kinds of ceramic, thermal barrier coatings and reaction proceeds according to the equation:

\[
\text{ZrCl}_4 + O_2 = \text{ZrO}_2 + 2\text{Cl}_2 \quad (1)
\]

Initial data for calculation: air specific flow rate of is 0.65 kg/kg of zirconium chloride;  
temperature range is 500–5000K. Specific flow rate shows air flow rate required for the reaction of  
0.65 kg of air for treatment of 1 kg of substance.

Minimum temperature for zirconia production from zirconium chloride by the reaction (1) is 600  
°C. Thus, at 340 °C zirconium chloride sublimes. Production in crucible depends on the composition  
of the product mixture from the temperature as it is shown in Figure 8.
Temperature of phase transition (evaporation) of zirconium oxides is about 4000K. In this case, the mechanism of formation of ultrafine structures will be determined by different parameters, in the first place by the temperature of condensation processes. Prior to this, the main mode of the process development is thermal destruction of the original grain.

**Synthesis of alumina**

Aluminum oxide is used in a wide range of technologies: for optical and structural ceramics, catalysts) etc. Ultrafine alumina is advisable to produce from the coarse grain, so the main task is to achieve a high temperature for the thermal destruction of grain and evaporation. Figure 9 shows the thermodynamic parameters of the alumina heating to a temperature above the melting temperature at the plasma gas flow rate of 1 kg/kg of aluminum oxide. Apparently, the required value of plasma enthalpy for this process is 5 MJ/kg of aluminum oxide.
Synthesis of magnesium oxide

Magnesium oxide is widely used in mechanical engineering, petroleum industry, manufacture of refractory materials and production of certain types of cement.

The process evaluation was carried out of the equation:

$$2\text{Mg} + \text{O}_2 = 2\text{MgO} \quad (2)$$

Specific air consumption – 2.88 kg/kg, reaction is exothermic, so the cost of ultrafine powders will be less. Transition to the gaseous phase of magnesium oxide starts at 3000 K (Figure 10). Simultaneously the formation of magnesium metal starts again.

![Figure 10](image.png)

**Figure 10.** Composition of product mixture at heating of metal magnesium with air.

The temperature of the beginning of the formation of zirconium oxide is 3500 K, alumina – 3500 K, magnesium oxide – 3200 K. Taking into account that the average mass temperature of the working gas for flow rates up to 25 g/s is in the range from 3000 K to 5000 K, and the measured temperature does not fall below 3500K, conditions for the synthesis of these oxides may be created.

Based on the data from [12] it is possible to obtain nanoparticles with size ranging from 10 to 150 nm using the plasma-arc method.

4. Conclusion

It was found during experiments that the high temperature jet area is an ellipsoidal region with dimensions no less than 250x60 mm. The average mass temperature value in this zone is no less than 3000 K. This allows the use of the plasma torch for plasma chemical synthesis of ultrafine oxide powders (\(\text{Al}_2\text{O}_3\), \(\text{ZrO}_2\), \(\text{MgO}\), etc.).
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