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Methods for Evaluating the Effectiveness of Gas Vortex Stabilization in Plasma Torches for Metal Cutting

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Abstract. The well-known recommendations for the design of gas-vortex stabilization systems in metal-cutting plasma torches are considered. Various designs of such systems used in the series PMVR plasma torches developed by the authors are presented. It is noted that the method of efficiency assessment developed by the authors should be based on the calculation of the uniformity distribution of the gas flow velocity. The velocities are calculated in the control sections of the gas-air path in the plasma torch. Various simplified and precise estimation methods are proposed. The velocity distribution in control sections for various modifications of plasma torches are presented. Calculations are made based on the "cold" model of gas flow and its heating by a plasma arc. Recommendations are made on the choice of parameters for evaluating the effectiveness of gas-vortex stabilization in plasma torches. The advantages of the new modernized plasma torches, including those using narrow-jet plasma technology, in terms of the gas-vortex stabilization efficiency are demonstrated. The necessity of using several criteria for evaluating the effectiveness of plasma torches design is noted.

1. Introduction

The development of plasma torches for air-plasma cutting, as is known [1, 2], was carried out in the 60s in the USSR (at the Avtogenmash, Institute of electric welding named after E. O. Paton, VNIIEESO), the USA, Japan, Germany and France. At the same time, the main parameters of metal cutting quality were determined. By the mid-70s, the basic principles of designing plasma torches were formulated and the first classifications were created, including various ways to stabilize the arc discharge [3, 4]. A characteristic feature of most designs used in DC arc plasma torches for metal cutting is the use of a gas-vortex stabilization (GVS) system of the plasma arc [1]. In the case of gas-vortex arc stabilization, gas is introduced into the electrode zone through the channels located tangentially to the walls of the arc chamber. Gas supply can be carried out using either one or two gas flows (working fluid) with different designs of swirlers. In a special device – a “swirler” – a spiral vortex flow is created that compresses the arc stream in the open part of the nozzle and in the arc channel and isolates it from the walls. The use of a vortex flow ensures gas mixing in the arc stream, intensifies plasma formation, and increases the voltage of the plasma jet. The tangentially swirled flow of plasma-forming gas (PFG) stabilizes the cathode spot, prevents shunting of the plasma arc and isolates the initial section of the plasma jet from the walls of the nozzle channel. Also it forms the geometry and kinetic properties of the jet at the nozzle outlet, contributing, in addition to improving the above parameters and reducing the acoustic emission [5]. As noted in [6], the stabilization system must be linked to the shape of the electrode, and the stability of the cathodes used for air-plasma cutting strongly depends on the effect of the cathode spot stabilization within the thermochemical cathode insert created by the vortex system [1, 3].

To form a vortex flow in an arc chamber, swirling systems of various designs are used. They can take the form of cylindrical cartridge covering the cathode with threaded screw channels or collar with a hole whose diameter is close to the diameter of the nozzle forming channel. The slots of swirling system are forming the direction of the gas flow tangent to the circumference of the channel. According to the results of experiments conducted in the late 60s [7, 8], it was noted that to ensure the longevity of the electrodes and high stabilization of the arc position in the nozzle channel, it is necessary that the ratio of the gas velocity tangential component V_t to the axial V_0, which is an indicator of the degree of gas spin, was within 7–12. In this case, if $V_t/V_0<5$, the electrode quickly burns out due to the effects of shunting (closing) the arc on the nozzle surface. However, many questions related to the dependence of the arc spot movement on the speed of the swirling gas flow were still insufficiently studied in those years.

A large amount of experimental data on the study of the operation modes for various plasmatron designs was generalized and optimized by the end of the 70s at The Institute of Thermophysics under the leadership of academician M. F. Zhukov [9, 10]. Two design solutions were proposed for linear plasma torches with GVS: one- and two-chamber arc stabilization zone. It was noted that there is a radial gradient of gas density in the electric arc chamber, which leads to the appearance of an Archimedean force. This force pushes the arc stream into the axial zone of the channel when it is deflected from the axis by disturbing forces. The gas vortex flow stabilizes the arc until the wall-mounted turbulent layer penetrates the axial zone of the chamber. The use of two vortex chambers – the central (main) and butt-end (additional) allows avoiding the limitations inherent for a single-chamber plasma torch on the type of gas and current. This effect is due to varying gas flow rates supplied through the two chambers. Generalization of experimental data on cathode erosion made it possible to determine the best values of the circumferential gas velocity at the entrance to the vortex chamber at 150–200 m/s.

In these works, there were presented the calculation of the electric arc chamber in the plasma torch. These calculations allow to define the flow geometry and parameters, to ensure reliable ignition and stable burning of the electric arc, excluding a heat lock channel during operation of the plasma torch. Based on the results of studies on the vortex chamber aerodynamics, conducted in a wide range of changes in the determining parameters, the following recommendations were made for the design of the plasma torch:

1. Ratio of the cross-section area for the twist ring to the cross-section area of the output electrode diameter should be 3.5–5.
2. Number of holes in the twist ring – at least four with a uniform location around the circle; the total area of the passage sections must be such that at a given full pressure and temperature of the supplied gas, its flow rate is about 0.3–0.5 the speed of sound.
3. Length of tangential channels in the twist ring (to obtain a sharply directed gas jet) must be at least 3–4 calibers.
4. Value of the interelectrode gap is selected based on the following conditions:
   - possibility of its breakdown by the oscillator voltage;
   - ensuring that there is no double arcing when cutting;
   - absence of gas-dynamic locking of the gas flow in the gap section.

Compliance with these requirements ensures good GVS of the electric arc on the axis of the discharge chamber and reliable oscillator start-up of the device. It should be noted that these recommendations remain as the main principles of GVS designing in modern publications [11], but they require, in our opinion, analysis for the loss of pressure in the system and the uniformity of distribution of gas dynamic parameters (the flow rate and pressure of the PFG, etc.) in the vortex flow at the output from it with subsequent design corrections. Dynamic analysis also showed that the electric arc chamber of the plasma torch could be regarded as a heat nozzle, in which the gas is heated by the arc discharge [9], and therefore in the design of arc chamber by gas-dynamic criteria, you must enter the correlation for thermal heating of gas flow.

2. Technique of researches

The above arguments and design recommendations, as already noted, were formulated as a result of generalization of experimental data in the study of plasmatrons. At the same time, the above-mentioned works noted the absence of a strict theory of vortex flow in the electric arc chamber of the plasma torch. In this regard, it should be noted that by the end of the 90-ies of the XX century, the emergence of opportunities for automating numerical solutions to complex gas-dynamic problems allowed us to conduct a number of such developments and generalize the results [12–15]. These studies confirmed the effect of energy separation in a vortex tube due to high- and low-frequency instabilities associated with the formation of large-scale coherent shear vortex structures in the tube. It was also noted that in plasma torches with GVS, the average integral temperature of the jet increases with an increase in the degree of spin. In addition [14] using numerical analysis, it was investigated the effect of the ratio for inlet diameter tangential swirl gas injection nozzle to the diameter of swirl nozzles on the flow in the channel of the plasma torch and found the dimensions of the entrance holes at their various numbers (six and eight). However, a very simplified geometric model of the electric arc chamber was analyzed, and the solutions were in a two-dimensional approximation.

Summing up the consideration of various well-known principles and methods of GVS designing, it should be noted that the problem of the plasma arc stabilization in plasma torches for metal cutting is multi-factorial. In our opinion, there is a gap in the wide variety of research results that affect the efficiency of such plasma torches, related to the study of the gas flow uniform distribution factor across the plasma torches section, both in vortex and electric arc chambers. The research conducted earlier by the authors [3, 16] showed that the applied methods of GVS in such plasmatrons do not ensure the proper uniformity of the PFG flow distribution along the cross section of the gas-air path (GAP), thereby reducing the efficiency of the plasmatron. As a result, the problem arises of studying this factor in standard and upgraded plasma torches, determining its physical and mathematical equivalent, which allows its use for the search for new design solutions that improve the operation of the plasma torches, the efficiency and application breadth of plasma cutting technologies.

For this purpose, one- and two-flow plasma torches of the PMVR series with various systems of GVS are considered. As the base model for gas dynamic analysis, the PMVR -M plasmatron produced by company Polygon (Yekaterinburg) was selected (Figure 1 a), which has proven itself at many metallurgical and pipe production enterprises in the Ural region of the Russian Federation.

a b

Figure 1. PMVR-M plasma torch: a – working model, b – speed distribution by GAP.

The uniform distribution of the PFG flow rate across the cross-section of the plasma torch channels is an important parameter that determines the efficiency of stabilization and shielding of the plasma arc, and ultimately affects the performance and quality of cutting, as well as the reliability of the plasma torch. This distribution was determined by numerical methods in the FlowWorks application of the SolidWorks software in the process of calculating the gas dynamic and thermo-physical parameters of the gas flow along the GAP of the plasma torch. When calculating the velocity distribution over the PMVR-M plasma arc (Figure 1 b), it is seen that the uneven distribution of the gas flow through the swirler channels is due to an asymmetric gas supply to it through a small expansion chamber. This unevenness persists in the nozzle of the plasma torch, thereby affecting the efficiency and quality of its operation.

Using symmetrical supply of plasma gas flow into GVS, two expansion chambers and swirlers with a stepped distribution of gas through the channels of GAP and a tangential flow of gas in the nozzle allows to increase the distribution uniformity in the nozzle of the plasma torch, to improve the kinematic and energy parameters of the arc plasma (jet) for the single-stream torches series PMVR-5. The PMVR-5.1 plasma torch (PMVR-2M in the former nomenclature) uses a system of gas dynamic filters (additional walls with perforations in the expansion chamber) and increases the size of the expansion chamber (Figure 2). In the PMVR-5.2 plasma torch (PMVR-3M in the former nomenclature), two swirlers and two expansion chambers (forming and stabilizing) are used – Figure 3, the PMVR-5.3 plasma torch is supplemented with a symmetrical gas supply to the expansion chamber (via 2 channels) and changing the geometry of the forming swirler – Figure 4.

Figure 2. PMVR -5.1 plasma torch with the GVS.

Figure 3. GVS of the PMVR-5.2 plasma torch.

Figure 4. Experimental model of the PMVR-5.3 plasma torch (design elements).

Additional compression of the plasma jet due to the flow of secondary gas in two-stream plasma torches (“narrow-jet plasma” technology) of the PMVR-9 series (Figure 5) allows to further increase the uniformity and kinematic characteristics of the plasma flow at a small distance over the nozzle of the plasma torch. Developed plasma torches of this type can significantly increase the productivity and energy efficiency of cutting technology, as well as improve the quality of cutting seams [17].

Figure 5. Experimental model of the PMVR-9.1 plasma torch (design elements).

When evaluating the GVS efficiency in metal-cutting plasma torches, you can rely on several key indicators. First, you should pay attention to the implementation of the above recommendations on the ranges and ratios of gas flow rates in the nozzle of plasma torches. However, the width of the declared speed ranges does not allow us to make a qualitative comparative analysis of various GVS designs, and, consequently, to identify their advantages and disadvantages. In this regard, as already noted, it is advisable to take as a key criterion the distribution of speeds and mass expenditures across the GAP section in the plasma torch. It is desirable that these distributions are sufficiently uniform already at the input to the 1st swirler of GAP. However, due to the fact that the main functions of the GVS system are performed in the nozzle, it is advisable to take the section at the input to the nozzle (near the plane of the butt-end surface of the cathode) and the section at the input to the cylindrical nozzle channel (the output section) as control sections (CS) for calculating. A similar principle is advisable to use in the system of two-stream plasma torches PMVR-9, using a double nozzle system (Figure 6). In addition to determining the gas-dynamic parameters, it is also advisable to calculate the temperature distributions in the CS, as well as to see the change in these parameters outside the plasma torch nozzle (within the interaction of the plasma jet with the metal surface).

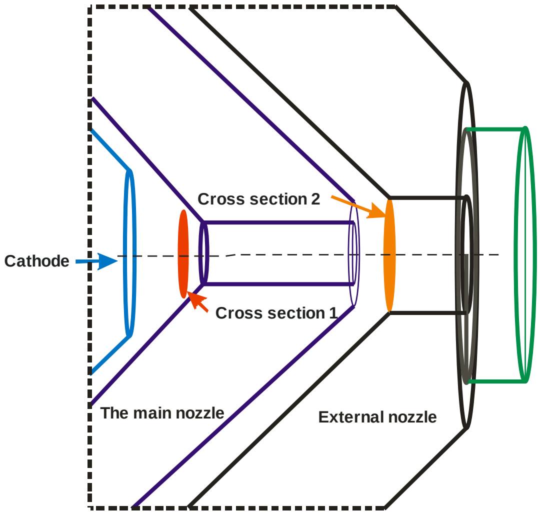
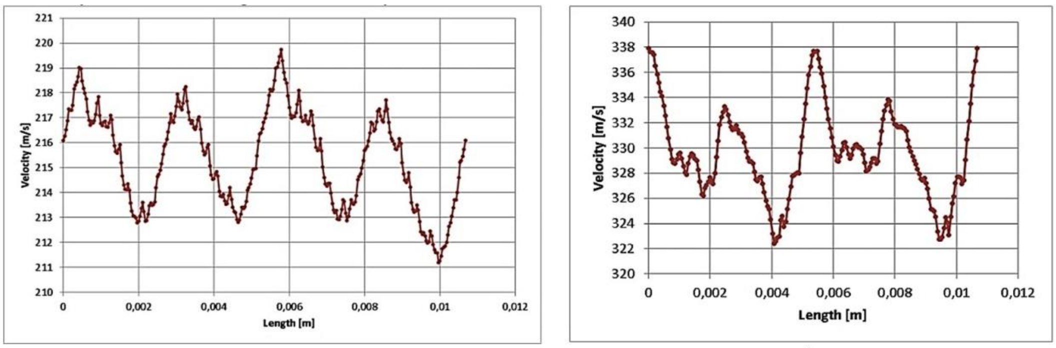


Figure 6. Location of the ring control sections (CS) in the PMVR-9.1 plasma torch.

When calculating the uniformity factors, there are several problems associated with determining the geometry of the calculated trajectory, the number of calculated points, and selecting the uniformity criterion. It has been experimentally established that it is advisable to calculate along the middle line of the CS, using reasonable machine modeling capabilities (50–200 calculated points along the perimeter of the trajectory). If there is a shortage of time and machine capacity, it is possible to limit the calculation to 4 symmetrically located points (relative to the supply line of the PFG to the expansion chamber [16]), but due to the undulating nature of the speed distribution (Figure 7), the accuracy of determining the efficiency of GVS will be low.



a b

Figure 7. Velocity distribution in the control sections (CS) of the PMVR-9.1 plasma torch (Figure 6):a – in section 1, b – in section 2.

In order to find a criterion for evaluating the degree of the flow distribution uniformity when analyzing a large number of control points, the obtained velocity distributions for various plasma torches were analyzed using statistical methods. A statistical hypothesis was made that the presented velocity dependencies obey either the normal or uniform distribution law of random variables. However, testing the hypothesis using the Pearson χ^2 criterion did not provide statistically significant confirmation. It was also not confirmed when analyzing other velocity distributions and when changing the frequency calculation intervals. For this reason, the parameters that are often used when processing large arrays of random variables were considered as criteria:

1) Scope of variation $R = V_{\max} - V_{\min}$,

2) Ratio of variation $L = \dfrac{V_{\max}}{V_{\min}}$,

3) Average linear deviation (ALD): $a = \sum_{i=1}^{n} \left| V_i - \bar{V} \right| / n$,

4) Mean square deviation (MSD): $S = \sqrt{\sum_{i=1}^{n} (V_i - \bar{V})^2 / n}$,

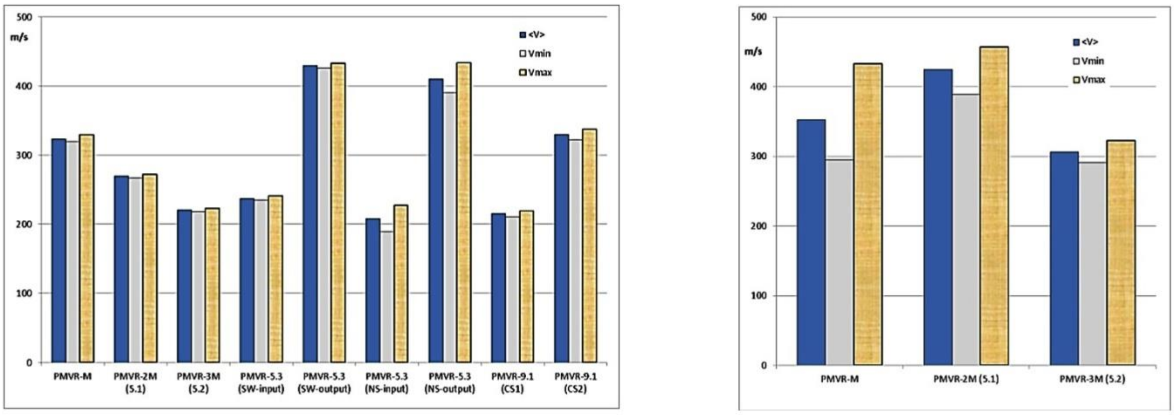
5) Coefficient of variation $F = \dfrac{S}{\bar{V}}$.

For large sample sizes (in our case n>40), $S \approx \sigma$, where σ is the dispersion of the random variable.

It is obvious that the values of productivity, quality, energy efficiency and safety of metal cutting in comparison with the values achieved when working with other plasma torches will also be valid and experimentally confirmed parameters from the point of view of GVS efficiency.

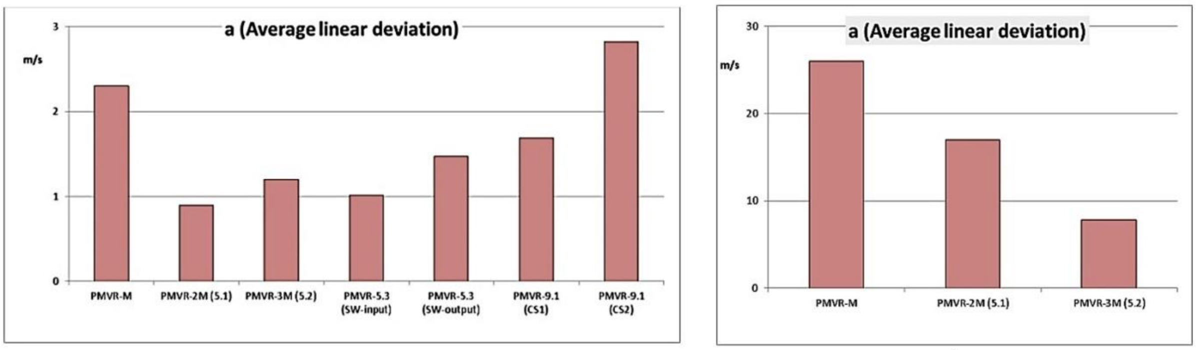
3. Results of research and their discussion

The results of calculations for a number of the GVS efficiency criteria for various plasma torches of the PMVR series are shown in Figure 8–10. The calculations considered 2 modes – “cold” (without arc heating) and “hot” (with arc heating), which allow to identify the influence of temperature on the efficiency of GVS.



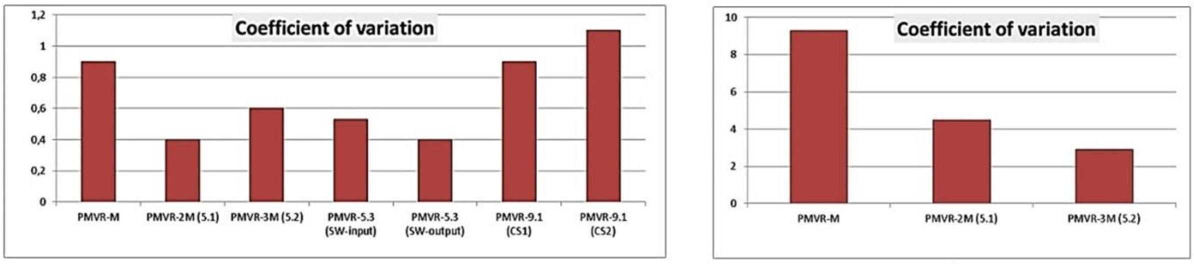
a b

Figure 8. Average, maximum and minimum velocities in control sections (CS) of plasma torches (SW-serial swirler, NW-new (modernized) swirler): a – without heating, b – with arc heating.



a b

Figure 9. Average linear deviations (ALD) of velocities in the control cross sections (CS) of plasma torches (SW-serial swirler): a-without heating, b-with arc heating.



a b

Figure 10. Coefficients of variation of velocity distributions in control sections (CS) of plasma torches (SW-serial swirler): a – without heating, b – with arc heating.

Analyzing the presented results, as well as the design of the corresponding GVS systems, we can conclude that in fact all the models presented correspond to the recommendations stated at the beginning of this article. At the same time, the introduction of the changes described above in the GVS design allows to increase the flow rate of PFG in the plasma torch nozzle (Figure 8) for a number of plasma torch designs, thereby increasing the kinetic energy of the plasma jet and cutting performance. In addition, it can be concluded that a mandatory analysis of the GVS efficiency in the "hot" mode in which the advantages of modernized GVS systems are most significant (2–3 times lower than the values of ALD and F criteria – see Figure 9 and 10). Similar estimates should be made, obviously, for the two-stream plasma torch PMVR-9.1 in order to justify the effectiveness of its operation when heated by a plasma arc. A comparative analysis of other performance criteria generally confirms the conclusions presented here, however, in order to fully justify the effectiveness of a particular GVS design, it is likely to rely on several criteria at the same time, using, among other things, the experimentally determined values of productivity, quality, energy efficiency and safety of metal cutting mentioned above. Additional information about the effectiveness and applicability of a particular plasma torch can also be obtained by analyzing the distributions of plasma jet parameters outside the plasma torch nozzle (see the results obtained by the authors in [18]).

4. Conclusions

It is obvious that the presented results are a justification for the use of machine modelling methods to determine the efficiency of the GVS system in metal-cutting plasma torches and the effectiveness of their design, in general. At the same time, it should be noted that to develop a full-fledged methodology for evaluating the GVS efficiency and design, a broader analysis of both various plasma torch designs and a wide number of parameters of their operation in various ranges is required. For example, to assess the quality of the cathode spot stabilization and focusing, a stabilization criterion can be used, consisting of the determining mode parameters: gas flow, the degree of confusability of the vortex chamber, its diameter, and so on [19]. We should also pay attention to the relationship between GVS and the effect of small- and large-scale turbulent pulsations of the gas flow, which largely determine the probability of arc shunting and the stability for the plasma torch [10]. In this regard, we should also pay attention to the effect of high-frequency acoustic radiation [2], which is largely due to the appearance of this type pulsations. Gas consumption is also an important stabilizing factor that reduces the amplitude of arc vibrations and heat loss [20]. A full-fledged analysis of the GVS efficiency for metal-cutting plasma torches requires taking into account a large number of parameters and criteria mentioned in this article.

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