THERMAL PLASMA and NEW MATERIALS TECHNOLOGY

Volume 1:
Investigations and Design of Thermal Plasma Generators

Editors:
O P Solonenko and M F Zhukov

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Preface

Continuous interest in high-temperature technologies is based on all those important advantages which have become evident in chemistry and metallurgy and in applications requiring the deposition of coatings, cutting, surfacing, microwelding and other processes. The range of these applications will undoubtedly continue to increase.

The problem of intensifying technological processes requires the development of materials capable of reliable operation at high temperatures of the environment and at high travel speeds, in corrosive media and under other extreme conditions. These problems can be solved by greatly improving conventional and, most importantly, developing new functional materials with specific properties.

Gas-discharge plasma and devices generating it are used on an increasing scale in modern technological processes throughout the world. Plasma technologies make it possible to carry out more efficiently a large number of chemical and metallurgical processes, organize complex processing of raw materials, develop almost waste-free technologies and produce materials with completely new physico-mechanical and chemical properties. They enable industrial systems to be miniaturized and increase appreciably the rate of technological processes. Evaluating the economic efficiency of plasma technologies, experts note the possibility of reducing the investment, metal and energy requirement, manual labour and working areas as well as the efficient combination of plasmochemical production with energy systems for equalizing the electric energy requirement. In addition, these technologies are highly flexible with respect to processing various types of raw material and transition from one power level to another.

The problems of examining, developing and using thermal plasma generators for various purposes are being studied extensively in the USA, Canada, France, Japan, England, China and other countries.

Soviet and now CIS scientists have also contributed significantly to the investigations and developments in this promising area of science and technology. In a number of cases, these studies are unique and have no analogue anywhere in the world. In other cases, they suitably supplement foreign data thus contributing significantly to better understanding of the physical phenomena and potential possibilities of specific plasma systems and technologies.

However, many of the results, which are of considerable interest, remained closed to the world community of scientists and engineers. One of the main reasons for this situation was that the majority of the original data were published in monographs and journals in the Russian language and, consequently, were not accessible to a large number of foreign colleagues. The publications scattered throughout the proceedings of various foreign conferences, symposia and seminars are not capable of providing a comprehensive picture with respect to both the volume of investigations and developments and the internal logic of investigations in the context of the relationship with the results obtained abroad.

Understanding this situation, we asked the leaders of scientific schools and groups, controlling the level of investigations and development in the area of thermal plasma and its applications in the former USSR, to consider preparing review studies including the most important results obtained by the individual authors. The majority of scientists supported this initiative, regardless of the objective difficulties formed after 1991.

We believe that this two-volume book "Thermal Plasma and New Materials Technology" will help to fill this gap and we hope that it will be read extensively by foreign experts and help establishment of direct contact between them and the leading scientific groups of the former USSR.

It is well known that science has no boundaries. We hope that the work of the authors of the review particles and our humble effort in coordinating the preparation of this book for publishing, with the support of Cambridge Interscience Publishing, will confirm this and will help to expand the mutually beneficial international scientific and technical corporation in the area of high plasma technologies.

A Russian saying says: "Better late than never!"

O P Solonenko and M F Zhukov
Scientific Editors

Contents

Preface 5

M F Zhukov, Linear Direct Current Plasma Torches 9
V S Engel'sht, The Theory of the Electric Arc Column 44
O Ya Novikov, Electric Arc Stability 68
A N Timoshevskii, Material Erosion and Dynamics of Electric Arc Discharge in Cylindrical Electrodes 83
M A Samsonov, Thermophysical Processes in Electric Arcs with Metal Vapours 96
A Zh Zhainakov, Mathematical Modelling of Electric Arc Plasma Flows 121
V M Lelevkin, Mathematical Modelling of Radio-frequency, Microwave and OpticalDischarge Plasma 141
S N Kharin, Mathematical Models of Transient Arc Erosion and Intraelectrode Phenomena 167
I G Panevin, Near-Electrode Processes 204
V F Put'ko, Electric Arc Behaviour in Dynamic Magnetic Fields 229
Zh Zh Zheenbaev, The Present State and Prospects of Development of Plasmochemical Processes in Kirghizstan 250
G Yu Dautov, The Low-Current Low-Temperature Plasma Generators 266
A V Pustogarov, Plasma Torches with Regenerative Cooling by Plasma-Forming Gas 293
A S Koroteev and M A Lomovtsev, High-Power DC Plasma Torches 315
Yu S Svirchuk, Three-Phase Electric Arc Plasma Torches 351
F G Rutberg, High-Power Three-Phase and Pulsed Plasma Generators 369
V A Konotop, Investigation of Characteristics of Coaxial Electric Arc Heaters 387
I M Zasypkin, Electric Arc Hydrogen Heaters 424
L M Sorokin, Radio-Frequency Capacitively-Coupled Plasma Generators: Research, Development and Applications 469
G V Lysov, Atmospheric Pressure Microwave Plasma Torches 488

LINEAR DIRECT CURRENT PLASMA TORCHES

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This review deals with the dynamics of interaction between the electric arc and the gas flow, magnetic field, electrodes and structural elements of linear plasma torches. Shunting, *i.e.*, electric breakdown between the arc column and the chamber wall as well as in the arc–arc gap, is the typical electrophysical process. Various designs of linear plasma torches have been grouped in three principal classes. The main similarity criteria taking into account the effect on the electric arc flow are presented. These criteria are then used to generalize the electrical characteristics of the arc and the thermal characteristics of plasma torches. Methods of protecting the chamber walls against strong convective thermal fluxes and methods of reducing the intensity of radiant heat transfer are suggested.

1 Introduction

In recent years, the development of technology has been characterized by the rapid growth of the extent of application of high temperatures, high gas flow velocities and high pressures. Traditional methods of heating the gas by chemical reactions or energy of Joule heat release in metallic conductors are insufficient to meet modern requirements. The electric arc being a concentrated and high-temperature source of thermal energy turned out to be the most promising. It was discovered in 1802 by V V Petrov, Professor of St.Petersburg Medical Surgical Academy, and found wide application in the first half of the 20th century in welding and cutting of metals as well as in electric arc melting of metals from ores.

In the middle of the 20th century, the electric arc again attracted widespread attention, this time due to the problems of gas heating in aerodynamic tubes in modelling the flight of aircraft at supersonic velocities and in investigating the conditions of re-entry of spacecraft into the atmosphere of the Earth and other planets. The significant theoretical and experimental results, obtained in the 60s, resulted in an even wider application of the electric arc on a qualitatively new science and engineering level. The range of problems now includes the development of new plasma technology production processes.

Today, the electric arc is a unique means of stationary heating of the gas and can be used for an infinite period of time. Advances made in the stability theory of arcing and the development of new electric power supply sources have resulted in almost 100% conversion of supplied electric energy to the thermal energy of gas.

A thermal plasma generator, or a plasma torch, is simultaneously an electrotechnical and a thermal apparatus. It is a highly flexible instrument, since its thermal, energy and service characteristics cover a wide range. The plasma torches are used in technological processes; therefore, they should meet additional requirements, such as

(*i*) heating of a wide spectrum of gases, from inert (He, Ar and others) to chemically active (O_2, air, Cl),

(*ii*) efficient performance of the apparatus at high gas pressures (>10^6 Pa),

(*iii*) safe life of the most significant elements, electrodes, with the highest heat release rate, should be as long as 100 hours, and in some cases even 1000 hours,

(*iv*) easy variation of arc power (gas enthalpy),

(*v*) permissible heat losses to the wall of the electric-arc chamber should not higher than the values governed by the economics of a technological process and the physico-mechanical characteristics of material,

(*vi*) burning stability of an arc as an element of an electric circuit.

There is no universal design of a plasma torch which may meet all the above requirements. It is necessary to develop a class of designs covering a wide range of the required power, from several kilowatts to tens of megawatt.

In order to produce a plasma torch which would incorporate all the above features, one needs to understand and describe reliably the most characteristic physical processes. These processes occurring in the electric arc chamber are defined by a variety of both internal interactions between the arc, the gas and the bounding wall, and external factors, including dynamical magnetic fields.

The problem of reducing the extent of electrode erosion or the problem of safe electrode life is particularly difficult to solve. This is related to thermal fluxes through reference arc spots, the physico-mechanical characteristics of electrode material and changes of these properties at high temperatures, as well as to the character of displacement of the reference arc spot over the surface of both "cold" and "hot" electrodes, *etc.*

The use of high-power plasma torches in different technologies has stimulated a search for ways of increasing thermal efficiency and developing effective methods of protecting the plasma torch channel walls against strong magnetic fluxes induced by convective heat exchange between high-temperature gases and arc radiation.

The work on designing highly efficient plasma torches extends beyond the investigation of physical processes of interaction between the arc and its environments and finding methods of protection against undesirable phenomena. In order to design a plasma generator having the required characteristics, it is necessary to be able to predict its electrical, thermal and other parameters.

A complete mathematical solution of the problem of interaction between the arc and the plasma torch walls, the gas flow and the magnetic field is likely to be amongst the most complicated problems of continuum mechanics. Particular attention should be paid on turbulent flow calculations. Nevertheless, there are some theoretical results available which are in good agreement with the experimental data if the experimental conditions and the assumptions of a theoretical model fit. Thus, it is convenient to calculate the parameters of an arc being in a cylindrical channel free-of-gas flow or with a small gas discharge when the channel flow is laminar. A laminar zone of an arc situated in a submerged jet may also be calculated quite accurately. The first attempts to calculate turbulent gas flows in the channel in the presence of an electric arc were made in Ref.1.

Unfortunately, the theoretical results may be used in practice at present only with a large number of assumptions, since the real conditions of arc burning are more complicated and vary more appreciably than the predicted conditions. Therefore, along with theoretical research, particular attention was paid to finding similarity criteria and methods for processing the experimental data on their basis. It has been established that for a complicated process occurring in the discharge chamber of a plasma torch, one may single out a small number of more significant criteria reflecting the characteristic processes of interaction between the arc and the gas flow or/and bounding surfaces. Semiempirical generalization methods serve as a basis for engineering methods of designing linear and other plasma torches, selecting the power supply and developing highly efficient thermal plasma generators. It is now necessary to start developing a system of plasma torch computer design, to find optimal variants applicable to technological processes and reduce the number of finishing tests. In this article we shall consider linear scheme plasma torches.

2 Special features of the electric arc burning in a long channel

The simplest design of a linear plasma torch comprises a cylindrical tube with a heated gas flowing through it and two electrodes between which an electric arc is ignited (Fig.1). The gas is usually supplied tangentially into the discharge chamber.

One of the fundamental physical phenomena in the discharge chamber is the interaction between the electric arc and the gas flow. This is responsible for the gas flow structure and the character of arc changes along the channel.[2,3,4] The structures of a flow and a discharge have three peculiar zones. In the first of them (section 0-1) the arc is stabilized on the channel axis, where the gas is rapidly heated and a low-temperature layer forms (I). The thickness of this layer increases in the downstream direction. It is characterized by high hydrodynamical stability and prevents heat transfer between the cold medium 2 and the electroconducting arc zone 3 heated to the highest temperature. This is the reason for a relatively low strength of the electric field E_i in this section. At its end, the tangential velocity field is rearranged and vortex stabilization of the arc on the axis is attenuated. The turbulent boundary layer 4 forms on the discharge chamber wall. Initially both flows are separated by the free turbulent flow zone 2 and do not interact each other. This is confirmed by the complete absence of transverse (radial) arc pulsations.

At the end of the initial section (section 1), thermal and near-wall boundary layers join, thermal layers are intensively disturbed and a large amount of hot gas disperses in the radial direction. Figure 2 displays Töpler (a) and schlieren records of arc ignition in the air jet ejected from the nozzle into the submerged space. The picture of a thermal layer disturbance is qualitatively analogous to that observed in a cylindrical channel. The electric arc 5 subject to turbulent pulsations of gas mass begins

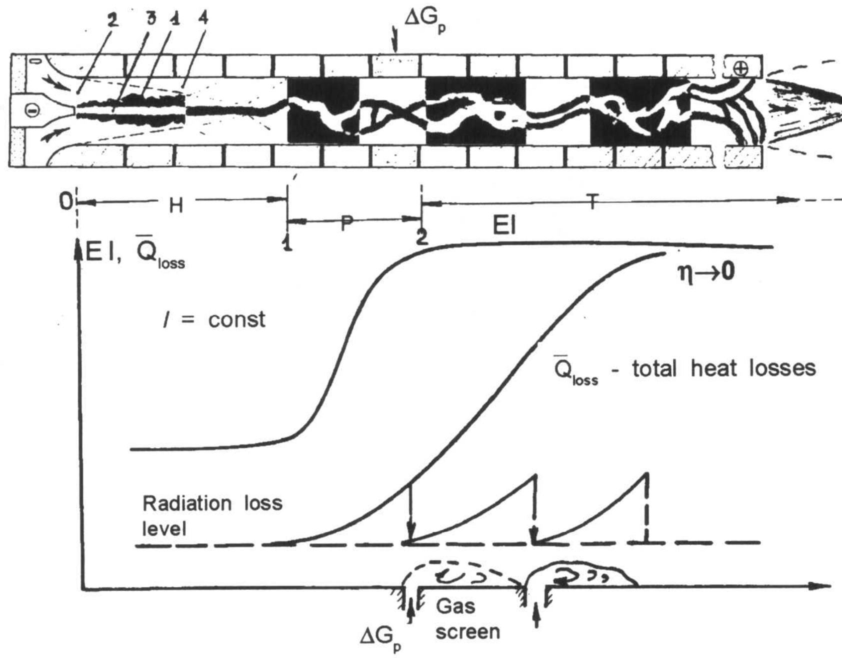


Fig.1 Schematic of a linear plasma torch and qualitative distribution of its energy characteristics along the chamber axis (z).

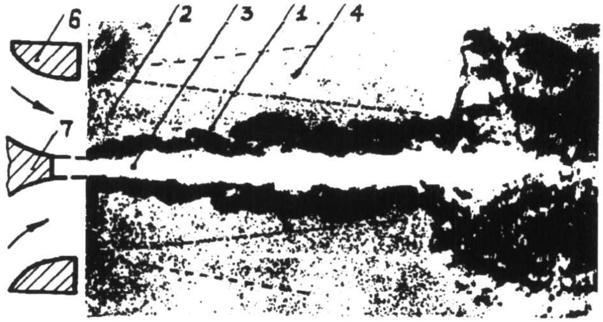
to oscillate in time and space.

The second characteristic zone (1-2), shown in Fig.1, is often called the transient one. A periodical process sometimes develops at the beginning of this zone; this process is characterized by the appearance of an arc of swirl form as a result of a magnetohydrodynamic instability of the arc column as a whole. In the downstream direction the swirl form is disturbed and transforms in random oscillations due to turbulence and arc–arc shunting. In the transient section, the extent of flow turbulence increases several times as compared to the initial section. In the discharge chamber, both smooth and rough-walled, there is always an abrupt increase in the degree of turbulence in the transient region of gas flow.

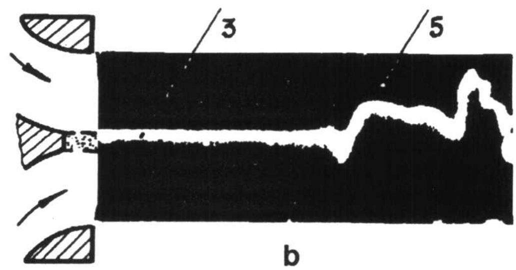
The third zone (behind section 2, Fig.1) fully corresponds to the developed turbulent flow. Here the arc is divided into a large number of conducting channels.

The electric field strength in the initial section is constant. The thermal flux to the chamber wall is mainly defined by the arc and high-temperature gas radiation. The length of the first zone (in the case of a swirled gas flow) does not exceed 12–15 diameters of the discharge chamber.

The transient zone is characterized by a monotonic increase of "the technical" strength of the electric field, defined by the ratio between the contact potentials of two washers to the length of the base corresponding to the distance between the mean cross-sections of the washers. This increase is due to intensification of heat transfer between the arc and the gas, the difference between the actual arc length and the length of the measurement section as a result of deflections and splitting of it into



a



b

Fig.2 Töppler (a) and schlieren (b) photographs of the arc burning in a turbulent gas outflowing from the nozzle into the submerged space. 5) electric arc form on the transient section, 6) nozzle, 7) electrode.

several current-conducting channels, *etc*. The radiant thermal flux to the chamber wall is gradually increased by the thermal flux induced by convective heat transfer which is intensified downstream.

The electric field strength reaches its maximum (E_T) in the transient zone before the third, turbulent section, and then, downstream, it remains constant (at a constant gas flow rate). For relatively low currents, the value of E_T is higher than E_H by a factor of 2 or 3. The arc is further divided and the number of conducting channels increases. At a large length of the discharge channel and with no special measures aimed at reducing the specific thermal flux to the wall, the latter approaches the specific energy released by the arc starting in some cross-section of the channel, *i.e.* local thermal efficiency tends to zero.

The above-described flow structure of the gas and the arc throughout the channel is simplified but principal. It will be used as a basis for making a number of important conclusions.

3 Shunting

Shunting, *i.e.* an electric breakdown between the arc and the chamber wall (Fig.3), is the most characteristic physical process in the arc burning chamber. Large-scale shunting 2 defines the arc length, the length of the failure zone on the surface of electrode A along the discharge chamber, pulsation (Fig.4) and other characteristics of the arc and the plasma torch. It is responsible for the formation of the drooping V–A characteristic and other phenomena.[3,5] The arc–electrode surface 4 shunting in the near-wall gas layer referred to as the small-scale shunting, defines mainly the erosion rate of electrode material. The arc–arc electric breakdown 3 formed in the arc loop also belongs to small-scale shunting. It also affects the erosion rate of the electrodes. Small-scale shunting causes additional arc voltage pulsations whose amplitude and frequency differ by an order of magnitude from those conditioned by large-scale shunting. The arc spot on a cold copper water-cooled electrode irregularly moves in the direction of the gas flow as a result of small-scale shunting in the near-wall layer. It is almost stationary in the intervals between shunting, although the small-scale shunting processes in the loop, degeneration of some areas and generation of new ones continue during this period. Moreover, the arc–arc shunting impedes the displacement of the arc spot and thus accelerates electrode failure. The downstream motion of the closing part of the arc due to near-wall shunting 4 is terminated only by large-scale shunting.

Figure 4 displays the typical oscillograms of arc voltage in a linear plasma torch with a gas-vortex stabilization covering one period of large-scale shunting 1. The oscillogram shows less extensive voltage pulsations 2 due to arc–arc shunting or arc–surface shunting in the near-wall layer. The values of the gas flow rate and arc current also influence the amplitude and frequency of voltage pulsations. As current increases, the amplitude decreases and frequency increases; the opposite is true when the gas flow rate increases.

If the motion of the radial section of the arc in an axial plasma torch is governed by both the longitudinal velocity component and the circumferential one, the section becomes helical with a convexity directed to the circumferential velocity component. In this case, small-scale shunting may also take place between the wall and the adjacent arc section (Fig.5).

All the types of shunting result not only in length, voltage and current pulsations, but also in changes of temperature and gas flow velocity. Thus, the gas ejected by

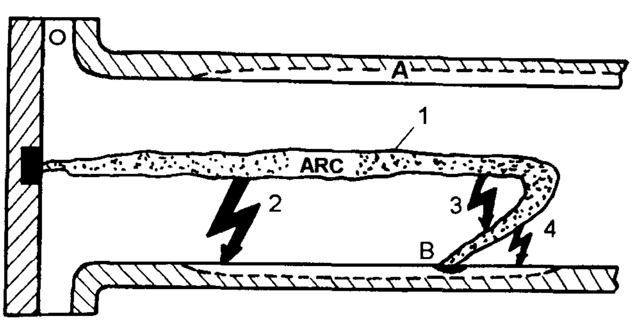


Fig.3 Schematic of arc shunting in an electric discharge.

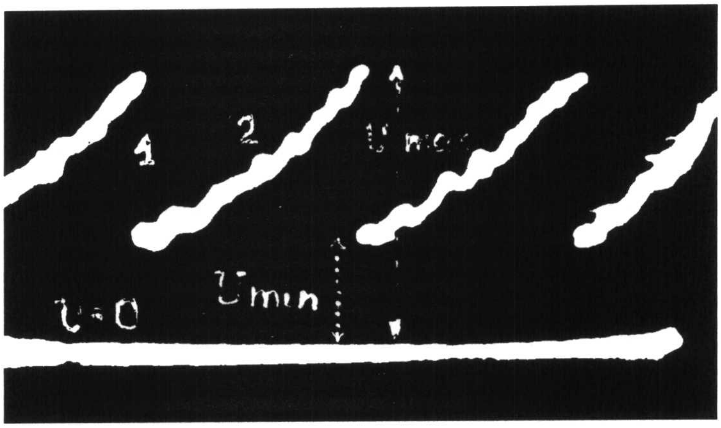


Fig.4 Typical oscillograms illustrating voltage variation for the arc burning in a linear plasma torch.

Fig.5. A photograph of a radial segment of the arc showing small-scale arc–wall shunting.

the nozzle consists of alternating hot and relatively cold regions. Sometimes this circumstance should be taken into account when choosing the geometry of a plasmochemical reactor or plasma torch for spraying or other purposes. Of particular interest is the distribution of the functions

$$V = V_z/V_{z,\,max},\; i = I_z/I_{z,\,max}$$

along the length z of the output electrode. Here I_z and V_z are the time-averaged values of current per unit length of the n-th section and the time-averaged number of 'visits' of the arc spot to the n-th section, $I_{z\,max}$ and $V_{z\,max}$ are their maxima.

A one-chamber plasma torch equipped with a sectioned output electrode/cathode is being developed.

As the experiments show, the functions $V(z)$ and $i(z)$ are the distributions of random values and obey the normal distribution law. The form of the curve of cathode erosion passing through the chamber axis corresponds to the distribution $i(z)$, *i.e.* electrode erosion is associated with the thermal flux through the arc spot rather than the heat transfer from the heated gaseous flow. The situation is similar to the case when the output electrode is an anode. It should be noted that there is a discrepancy between the maxima of $i(z)$ and $V(z)$: frequency $V(z)$ is shifted to higher values of z as compared to $i(z)$.

4 Classification of linear plasma torches

Linear plasma torches belong to the widest class of plasma generators, as regards the power used, choice of working gases and pressure ranges. These factors, along with the nature of the technological process, explain the existence of a great variety of their designs. However, understanding of some of the physical processes occurring in the discharge chamber of a plasma torch has made it possible to group them into three main classes.

The first class incorporates plasma torches widely employed in industry. They are equipped with a tubular output electrode and self-stabilized arc length. Its V–A characteristic falls (Fig.6, curve 1). Mean arc length l_{cy} is the current function (for a constant diameter of the chamber and pressure, given working gas and polarity of the output electrode). The arc length variation mechanism is defined by large-scale shunting occurring in the transient zone of the discharge chamber.

The plasma torches, whose mean arc length is constant for a rather wide range of currents (with the above-mentioned parameters being constant) and always smaller than the self-stabilized arc length ($l_2 < l_{cy}$) belong to the second class. There are several ways of providing a constant arc length. One of them, most popular, is based on cascade design of the output electrode consisting of two cylinders with different diameters, the diameter of the outlet part of the electrode (d_3) being higher than the initial one (d_2) (the direct step). The V–A characteristic of the arc is defined by the E–I characteristic in the channel with a smaller diameter d_2, lies below the V–A characteristic of the arc with the self-stabilized length and has falling and rising branches (Fig.6, curve 2). These plasma torches are widely used in different technological processes and operate steadily on the rising branch of the V–A characteristic without a ballast resistance in the electric circuit.[4,6,7,9]

Which of the processes is responsible for the constancy of the mean arc length ? In order to understand why the sections (regions) of preferable arc shunting are invariable in space over a wide range of determining parameters, such as gas flow rate, pressure and current, it is necessary to take into account hydrodynamical peculiarities of the gas flow behind a forward step, namely, the appearance of the