# HEAT TRANSFER IN THE ARC DISCHARGE CHANNEL STABILIZED BY WATER VAPOR VORTEX

**A. Tamošiūnas, P. Valatkevičius, V. Valinčius, V. Grigaitienė**

*Lithuanian Energy Institute, Plasma Processing Laboratory, Kaunas, Lithuania*

## Abstract

An experimental investigation deals with the analysis of thermal characteristics of a linear direct current (DC) arc plasma generator stabilized by tangentially injected water vapor stream. A hot tungsten-rod cathode is used as electron emitter for causing ionization of injected gas. Considering the erosion of the cathode it was protected in assistance of noble gas argon. A step-formed anode was used to minimize the pulsations of arc in the discharge chamber and longitudinal stabilization of arc. Overheated water vapor up to 450 K was used as working gas. The flow rate of water vapor was changed in ranges from (2.63–4.48) · $10^{-3}$ kg/s. The torch operates at atmospheric pressure with current intensity of 115 to 200 A and voltage 220–390 V. Heat transfer characteristics of the water vapor plasma torch were determined and generalized employing the theory of similarity.

**Key words:** heat transfer, plasma torch, water vapor plasma.

## 1. Introduction

Considering the definition of plasma torch [1] as electric arc heater in which electric energy is converted into thermal by means of generation of Joule heat in the discharge, it is important to examine the behavior of the electric arc column burning in the discharge chamber and its interaction with a medium. During the elastic and inelastic collisions between emitted electrons and heavy gas molecules electric energy is converted to thermal, which is transferred to the flow and walls of the discharge chamber. Only energy transferred to the flow is useful. The energy absorbed by walls is considered as thermal losses reducing thermal coefficient of efficiency of the torch. The variation of plasma forming gas, flow rate and the place of its injection as well as current intensity and geometry of the torch enables to determine heat and mass exchange between the arc, the gas and the walls of the discharge chamber.

Heat transfer mechanism in the cylindrical arc discharge channel is very complicated. Complex factors are taken into account studying this phenomenon. According to [2], heat transfer proceeds due to:

- Conduction, in the region of the electrodes where the arc spot contacts with the walls, in radial direction;
- Convection, heating the gas in the radial and axial direction;
- Radiation, especially in the initial region of the arc flown around by tangentially injected gas;
- Diffusion, due to multicomponent structure of the ionized gas.

Taking into account that such a heat losses result in the formation and progress of prevailing plasma processes, the goal of this research is the investigation of heat transfer processes in the electric arc discharge channel stabilized by water vapor vortex.

## 2. Experimental setup and procedure

The electric arc in the discharge chamber is stabilized in assistance of tangential supply of overheated water vapor up to 450 K with admixture of argon (Ar) screening the tungsten cathode from erosion (Fig. 1). The rate of Ar in total gas flow rate can vary from 10 to 17 %, respectively, while the flow rate of water vapor was in the range of $(2.63–4.48) \cdot 10^{-3}$ kg/s. The DC water vapor plasma torch operates at atmospheric pressure with electric arc current intensity varying in range of 115–200 A.

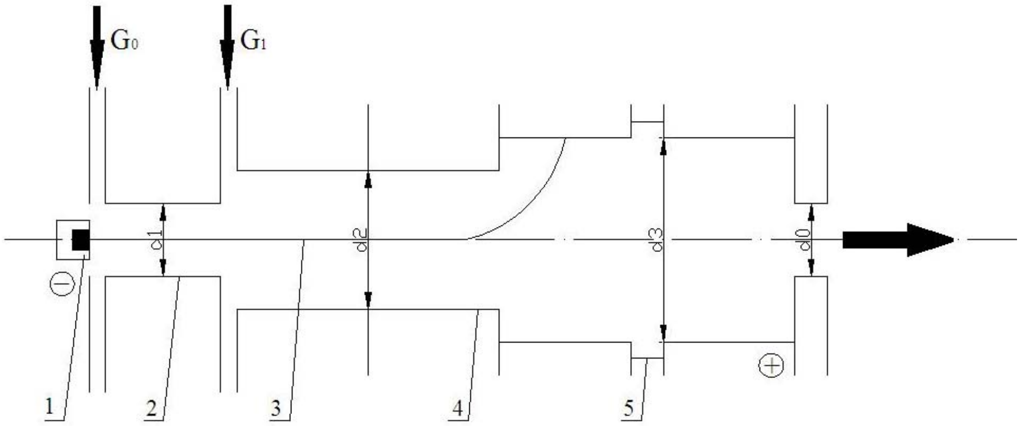

Fig. 1. The schematic sketch of plasma torch stabilized with water vapor vortex. 1) cathode; 2) neutral section; 3) electric arc; 4) step-formed anode; 5) section for radiation measurement. $d_0$, $d_1$, $d_2$, $d_3$ – diameters of discharge chamber. $G_0$, $G_1$ – tangential supply of shielding and working gas, respectively

The main experimental method for determination of the heat losses into the electrode sections of the plasma torch is the calorimetric method. The individual supply of cooling agent (water) to all sections of the plasma torch and the measurement of temperature difference enables to carry out calorimetric measurements of the heat flows in them. The difference in temperatures of the cooling water was measured with copper-constantan (Cu-K) thermocouples.

Heat transfer characteristics of the plasma torch used in this research have been described using theory of similarity [1] which helped to generalize the obtained results and deduce them in form of criterion equations. The experimental results are also compared with the classical heat and mass transfer calculations in the cylindrical arc discharge channel behind the arc burning.

## 3. Results and discussion

In order to investigate heat transfer mechanism in the arc discharge channel stabilized with water vapor vortex it is convenient to distinguish three different sections of the torch, where heat exchange is determined by different heat transfer phenomenon and nature of flow: it is the initial section of the channel, transitional section and developed turbulent gas flow. The length of the initial section is determined by the area of contact of the thermal layer of the arc with the wall boundary layer. In the transition section, the thermal layer is disrupted and the arc column starts to interact with the turbulent gas flow, i.e. gradual transition to the developed turbulent flow starts here. Finally, a steady turbulent flow is found. The process of mixing of the high-temperature gas from the thermal layer of the arc with the cold walls gas starts here. The vortex stabilization of the arc column is disrupted because the regions of reduced pressure on the axis of the channel disappear [1].

The cathode section, the neutral section and part of the anode section (down to the ledge) of the torch could be referred to the initial section. The heat losses in the initial section are almost constant along the channel ant mostly defined by the radiation of the arc. Due to the absence of the engineering possibility measuring high temperatures inside the discharge channel, it was not possible to calculate the heat losses to the walls. Consequently, in this case the use of similarity theory helps to determine total heat losses into the walls of separate plasma electrodes. In comparison between results the experiments were carried out using the same plasma torch stabilized with air vortex.

### *3.1 Heat exchange in the cathode*

The heat losses to the cathode are defined by radiation and conduction of the arc. Heat flow from the arc to the walls of the cathode is determined by equation (1) for radiation (Fig. 2) and the expressed (Eq. 2) for conduction (Fig. 3).

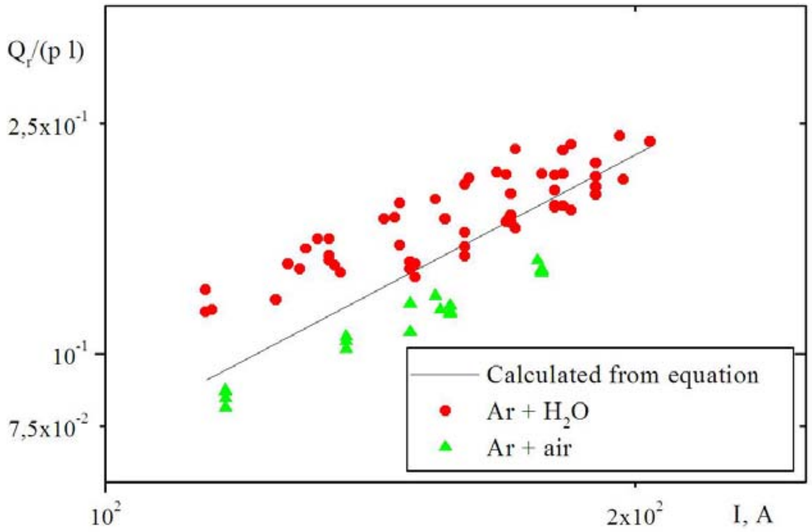

Fig. 2. Dependence of the radiant heat losses into the walls in the initial section of the channel on the working parameters of the arc

$$Q_r/(p \cdot l) = 4.6 \cdot 10^{-5} I^{1.6}, \tag{1}$$

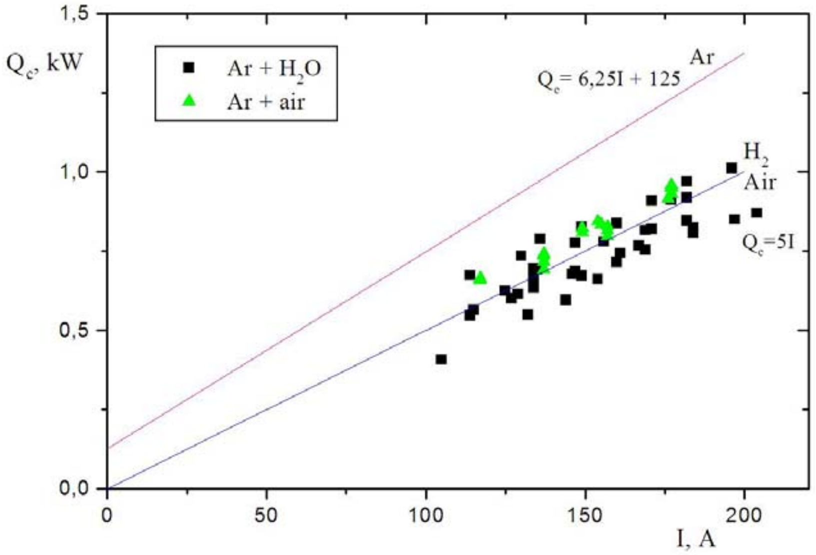

Fig. 3. Heat flow to the tungsten cathode by conduction

$$Q_c = 4.5I + 23, \tag{2}$$

### *3.2 Heat exchange in the neutral section*

A heat loss to the walls of neutral section of the torch consists of the convective and radiative heat transfer. It is assumed that heat transfer by radiation (Eq. 1) remains stable along the overall discharge chamber. Total heat flow to the walls of neutral section (Fig. 4) could be described by generalized equation (3).

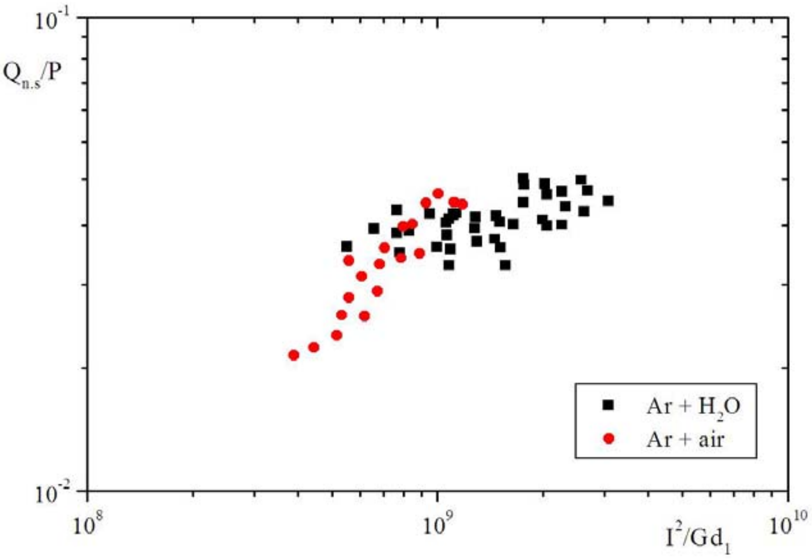

Fig. 4. Total heat flow to the walls of neutral section

$$\frac{Q_{n.s}}{P} = 9 \cdot 10^{-4}\left(\frac{I^2}{Gd_1}\right), \tag{3}$$

### *3.3 Heat exchange in the anode*

The step-formed anode faces the highest thermal stresses providing a significant contribution to the general fraction of the heat losses. In this section of the torch the anode arc spot due to the arc swirling in fixed area meets the walls where the conventional density of the heat flow, related to the area visited by the arc spot, may be maximal. Although the absolute value of the heat flow, supplied through the arc spot, is not high in comparison with the total convective flow. Therefore, because of the step shape of the electrode, total heat flow may be composed of: heat absorbed by the narrow part (*$d_2$* Fig. 1) of the anode wall (Fig. 5, Eq. 4) and heat flow to the wide part (*$d_3$* Fig. 1) of the anode wall (Fig. 6, Eq. 5).

During the experiments it was observed that the arc in the cylindrical discharge chamber mostly burned at the end of the narrow part of the anode or just at the beginning down the wide part of the anode. Therefore, a wide scatter of the points in the (Fig. 5) is due to the periodic shunting of the arc initiating the development of turbulent flow. In this section of the discharge chamber the transition region starts and after several gages shifts to the developed turbulent flow.

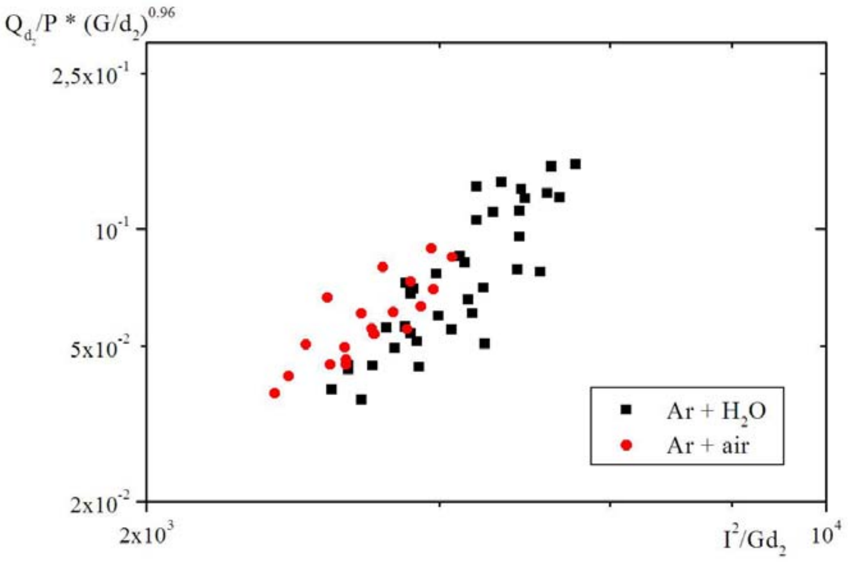

Fig. 5. Total heat flow to the anode (part d$_2$)

$$\frac{Q_{d_2}}{P} = 7 \cdot 10^{-9} \left( \frac{I^2}{Gd_2} \right)^{0.7} \cdot \left( \frac{G}{d_2} \right)^{-0.96}, \tag{4}$$

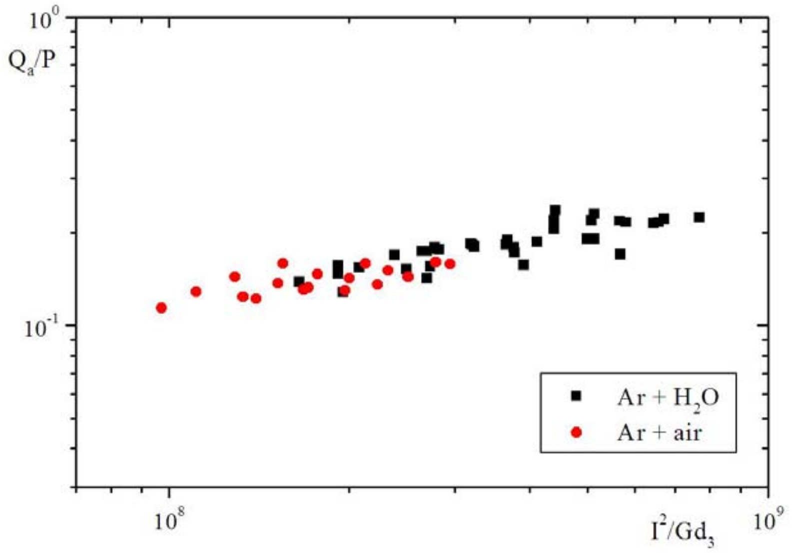

Fig. 6. Total heat flow to the anode (part d$_3$)

$$\frac{Q_{d_3}}{P} = 9.6 \cdot 10^{-5} \left( \frac{I^2}{Gd_3} \right)^{0.38}, \tag{5}$$

It is complicated to determine the length of the transition section. Some assumptions could be made according to the (Fig. 6), where the distribution of the points in the logarithmical coordinates is in a linear position. It means that in the residual section down the anode (part d$_3$) the developed flow depends on the stable parameters of the arc. The density of heat flow to the walls of the discharge chamber rapidly increases and gathers its highest value here (Fig. 7).

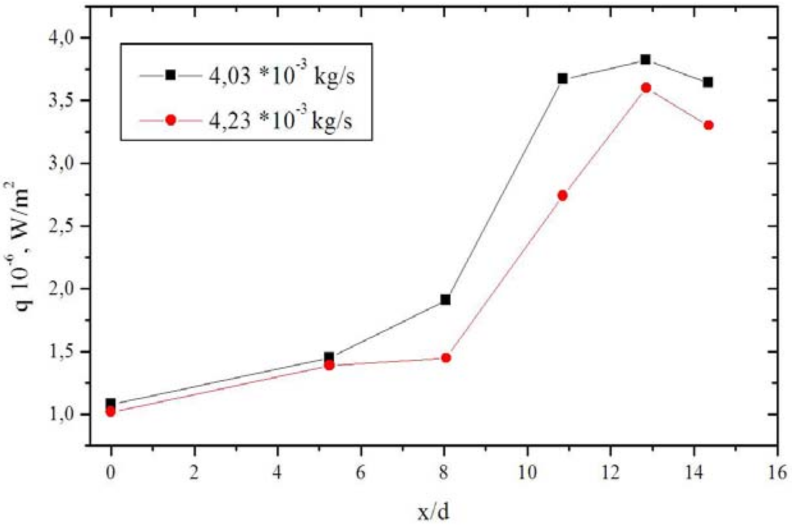

Fig. 7. Distribution of the heat losses along the electric discharge chamber of the plasma torch, $I$ = 170 A, $G = 4.03 \cdot 10^{-3}$ and $4.23 \cdot 10^{-3}$ kg/s.

### *3.4 Heat exchange behind the arc loop*

In the previous section, it was not possible to determine the nature of the flow in the anode according to the obtained experimental results, whether it laminar or turbulent. In this section, a special attention will be given to the heat exchange behind the arc loop (part $d_3$) assuming that the determining gas temperature may be represented by the mean mass temperature of the heated gas.

The main role in the heat losses is played by the radiation and convection, and the influence of conductive heat exchange is not large. As already mentioned in the 3.2 section, the radiant heat flow from the arc into the walls of the discharge channel is approximately the same along the initial section, the transition section and the developed turbulent section. Thus, knowing the value of the radiant losses, it may be assumed that the convective flux to the walls of the anode (part $d_3$) is:

$$q_c = q - q_r, \tag{6}$$

In a wide range of variation of the working parameters: the type of gas, temperature, pressure, the convective heat flow into the wall of the anode (part $d_3$) could be calculated using the equation for the heat exchange of the gas flow with the walls of the cylindrical channel:

$$Nu_d = 0.0255 \mathrm{Re}_d^{\,0.8}\, \mathrm{Pr}^{0.43}, \tag{7}$$

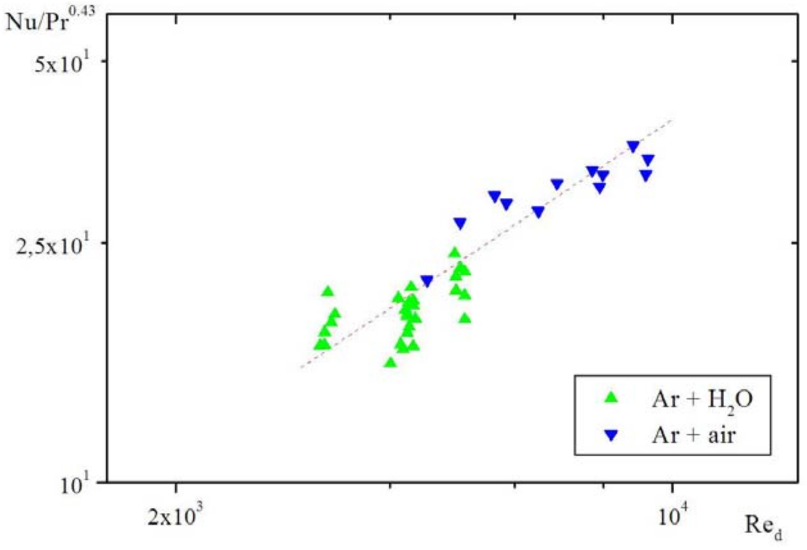

Fig. 8. Convective heat transfer into the anode wall (part $d_3$) in the presence of the developed turbulent gas flow

Calculations according to (Eq. 8) and (Fig. 7) show that the nature of the flow inside the cylindrical channel behind arc burning is turbulent, as it should be in the developed turbulent flow section. The flow is not stabilized; this is evident from the coefficient of equation (7). As conclusion it could be set out, that the experimental results carried out using the water vapor plasma torch correspond to the results of proposed equation in [1, 3, 4] for the convective heat flow calculations in the cylindrical channel.

### *3.5 Total heat losses into the walls of the water vapor plasma torch*

It was convenient also to determine the experimentally obtained total heat losses between the heated gas and the walls of the discharge chamber of the plasma torch stabilized by water vapor vortex (Fig. 9). The total heat losses are described by the following relation:

$$St = \frac{1-\eta}{\eta} \cdot \frac{d}{4l} = 1.36 \cdot \mathrm{Re}_d^{-0.8}. \tag{8}$$

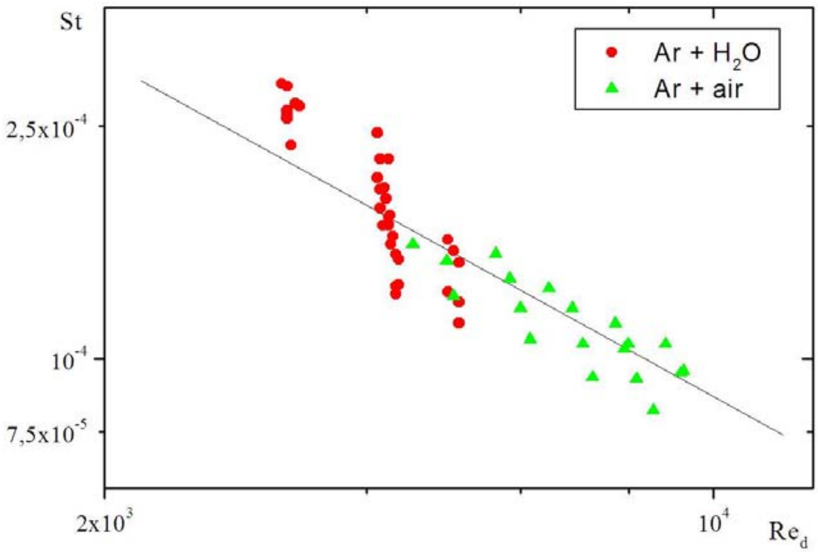

Fig. 9. Total heat losses between the gas flow and the plasma torch walls

According to the obtained results, which are expressed in terms of equation (8), we could say that the flow inside the entire discharge chamber of the torch is transitional. The same tendency is observed using air as plasma forming gas. The experimental results and calculated from equation (8) are in a good agreement with [2].

## 4. Conclusions

Heat loss in the tungsten-rod cathode of a linear plasma torch stabilized by water vapor vortex is determined by equations (1), (2) and exceeds 4–5% of the total heat loss, while the heat loss using air as plasma forming gas is in range of 6–9%.

Heat loss to the walls of neutral section is described by relation (3) and comprises about 10-15% of the total heat loss, whereas heat loss heating the air in the discharge chamber is 8–15%.

Heat loss to the narrow part $d_2$ of the anode is characterized by equation (4) and exceeds 17–34% of total heat loss in entire plasma torch. Meanwhile heat loss using air is in range of 20–29%.

Heat loss to the wide part $d_3$ of the anode comprises 50–60% of the total heat loss and is described by eq. (5). The same tendency remains using air as plasma forming gas.

The most intensive heat transfer within the discharge chamber occurs by convection. The intensity of convection heat transfer is about 90%. The convective heat exchange between the gas flow and the walls of the cylindrical discharge channel behind the arc burning is expressed by equation (7). The experimental results coincide with the results performed by other authors in the same research area. Total heat losses into the walls of the plasma torch stabilized by water vapor vortex are described by equation (8).

## Notation

$Q_r$ – radiant heat losses, W; $p$ – pressure, Pa; $l$ – section length, m; $I$ – current intensity, A; $Q_c$ – conductive heat losses, W; $Q_{n.s}$ – total heat losses to the walls of neutral section, W; $P$ – power of plasma torch, W; $G$ – gas flow rate, kg/s; $d_1$ – diameter of neutral section, m; $Q_{d2}$ – total heat flow to the anode (part $d_2$), W; $d_2$ – diameter of the anode (part $d_2$), m; $Q_{d3}$ – total heat flow to the anode (part $d_3$), W; $d_3$ – diameter of the anode (part $d_3$), m; $q$ – total heat flow into the wall, W/m$^2$; $q_r$ – radiant heat flow, W/m$^2$; $Nu$ – Nusselt number; $Pr$ – Prandtl number; $Re$ – Reynolds number; $St$ – Stanton Number; $\eta$ – plasma torch efficiency.

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