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Behaviour of electric arc in plasma chemical reactor during hazardous waste treatment

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Abstract

The following research has been performed to reveal main peculiarities of an operating electric arc in plasma chemical reactor (PChR) for hazardous waste processing. This confirmed that plasma technology has several advantages over conventional incineration including the presence of higher temperature, independence of heat source from the waste being destroyed or additional fuel, shorter exposure time of hazards in high temperature area. The experimental study was performed in a model of PChR for waste destruction using thermal plasma as a heat source. Investigations described are conducted to study the voltage-current characteristics (VCC) and heat transfer between an electric arc and a flat anode during the free arc operation in nitrogen ambient. Plasma torch (PT) parameters vary in the range of I = 100–600 A, U = 50–450 V, x = 0–400 mm, G = 2–4 g/s at atmospheric pressure using nitrogen as plasma forming gas. It was obtained that the power value of laminar arc increases with increasing arc current and its length. With increasing arc length, the initial part of it starts to operate in a turbulent regime. The region of laminar regime appears in the area where arc power is inversely proportional to arc current. The dependence of the relative fraction of the heat flux transferred by the electrons to the anode on arc current was determined. The distribution of convective heat flux density over the anode heating spot was analyzed and generalized. The experimental data on convective heat transfer in the anode (mean and critical point) were discussed.
Keywords: Plasma torch, free burning arc, hazardous waste treatment, heat transfer, current–voltage characteristics

1. Introduction

The situation worldwide in the field of environmental protection and efficient energy use is constantly getting worse. In order to more efficiently reduce environmental pollution, there aren't enough traditional methods a whole complex of coordinated efficient measures should be applied. The especially means should be applied to the destruction of waste containing hazardous substances [1].

At the present time, the formation of a required uniform ambient for removal of hazardous substances having a melting point more than 1700 K, using traditional technologies is very complicated and expensive. In some cases, the employment of plasma technologies for hazardous waste treatment is more economical, harmless to ecology, human health and protective to environment [2]. When the low-temperature plasma activating energy is applied, it is possible to increase the rate of chemical reactions hundreds of times and to achieve stable high temperatures of 3000–3500 K inside the PChR. However, the development of a new design schemes for plasma arc treatment of hazardous waste or waste with high melting temperature up to 1700 K is impossible without the knowledge and understanding of the features of high temperature processes occurring both in the gas discharge chamber of PT and in the PChR.

The gases, used as heat carriers, greatly differ in their energy characteristics. Therefore, while selecting the plasma forming gas, it is necessary to take into account the following aspects: the possibility of obtaining high enthalpy values, possibility to use gas as a chemical reagent, the inertness in relation to target products. In plasma chemical reactors for materials processing typically are used DC electric arc operating in argon (*Ar*) atmosphere [3]. However, it is well known, that from the economical point of view it is more benefit to use high enthalpy gas such as nitrogen (*N*) [4]. Plasma torches with DC electric arc operating at nitrogen atmosphere are well studied [3–5]. However, the characteristics of the free burning arc in nitrogen ambient applicable in plasma chemical reactors, are studied insufficient. It is very useful to study that because nitrogen arc plasma behavior differs greatly from the free arc operating at *Ar* atmosphere.

The efficiency, heat transfer characteristics and the interaction between plasma jet and material in PChR for waste destruction has been studied in many works, e.g. [6–8]. However, as in the case with electric arc characteristics, the energy balance at the plasma torch anode is mainly investigated while working with an argon arc [9,10]. There appeared also the particular interest is the energy exchange between the plasma arc and the surface, since in this case arc efficiency (η) is higher than in the case when plasma jet interacts with the flat surface. It is also well known that high temperature argon gas has rather low enthalpy and poor energy characteristics. Therefore, the employment of a high–enthalpy molecular gas such as nitrogen for material processing using plasma technology, it is more advantageous [11].

A lot of contribution in solving essential problems of energy production, environmental protection, public health, etc. has properly selected plasma source. However, the application of plasma source requires very complicated, expensive and energy receptive fundamental and applied investigations are necessary for creation of new very effective PT.

Sometimes, when plasma technology as waste treatment mean is investigated, there is difficult to apply laws of the similarity theory or numerical simulation. Therefore, the PT characteristics have to be examining separately for different gaseous atmosphere. So, the main aim of this work was to investigate electric characteristics of free electric arc operating in *N* atmosphere and the transfer of energy of the nitrogen arc to a flat anode in plasma chemical reactor for waste treatment. The careful study of PT parameters employing electro-dynamical electric arc theory and solving problems of plasma flow diagnostics allowed the design of powerful plasma arc generator stable working for a long time in nitrogen gas ambient. In this paper, it is proposed to apply an innovative plasma technology, which enables to dispose all types of waste.

2. Experimental set up and measurement procedure

2.1. Electrical characteristics of free electric arc in the nitrogen atmosphere.

Earlier the plasma conversion process was carried out by authors in a flow reactor [12] consisting of metal case lined inside with the layer of fireproof and heat insulating materials. However, such reactor was not suitable for destruction of extreme hazardous and large dimensions solid substances, because of the relatively short exposure time of material in high temperature zone. Therefore, the authors projected a novel plasma volume reactor to create steady non-transferred plasma ambient.

The shield of the reactor is made up of metal with high temperature ceramic lining. The constructed arc reactor has graphite anode and cooling tungsten button type anode. During the processing of the waste, a PT is generating the high temperature ambient necessary to destroy the chemical bonds in the hazardous material, [13]. The extremely intense energy flux initiated by PT is powerful to destruct the hazardous waste into its atoms, molecules and radicals.

The electrical arc at atmospheric pressure usually appears as a constricted area of electrical and mechanical forces which causes plasma fluid to move away from the arc column. The plasma chemical reactions occur in the reactive zone of the arc in the presence of controlled amount of nitrogen. The final products consisting of a vitrified glass like substance is collected at the bottom of the reactor and used as raw materials for wide range application.

The schematic presentation of free burning arc in it is given is Fig 1. The higher temperatures are reached by the arc convert the organic waste into light organics and primary elements. The experiments were performed in the PChR designed for hazardous waste treatment reacting arc zone.

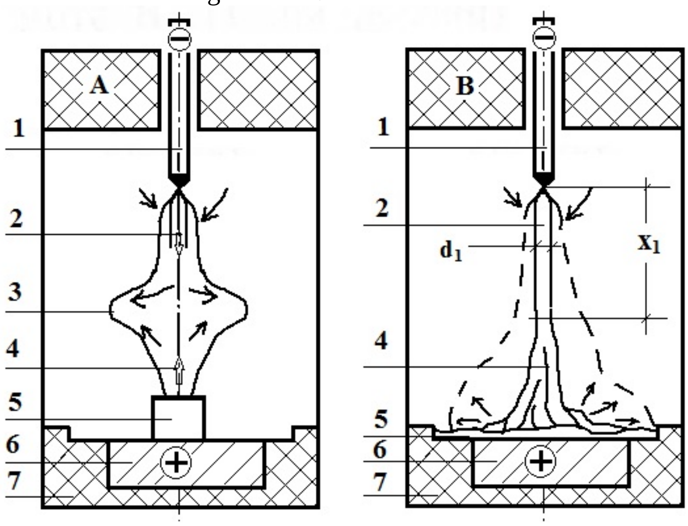

Fig 1. The scheme of free burning electric arc in the plasma chemical reactor. Anode: A – solid waste surface, B – melted waste surface. 1 – plasma torch, 2 – cathodic jet of gas, 3 – plasma “discus”, 4 – waste steam jet, 5 – waste (A–solid, B – melted) 6 – graphite anode, 7 – refractory material

DC electric arc operated between the PT cathode and a bath made from graphite (Fig 1, p.7) located in the bottom of PChR. PT could be moved along the axis of the arc and thus its length was changed. Parameters of the PT varied with following limits: the strength of current I = 100 to 600 A, arc voltage U = 50 to 150 V, PT power P = 10 to 150 kW, arc length x = 0 to 400 mm, nitrogen flow rate G_N = 2 to 4 g/s. Experiments were carried out at atmospheric pressure. The general test bench with plasma source, auxiliaries and supporting equipment is described in details elsewhere in [14].

The operating conditions and operating regimes of PT remain constant during all the experiments. The capacity of PT, total mass flow of *N*, cooling water flow rate G_v and its temperatures were measured employing electronical measuring devices. From this data plasma ambient characteristics were calculated. Physical and thermal properties of *N* were established using [15].

2.2. Heat transfer measurements

Heat generated by the PT brings the waste material to temperatures sufficient to fully melt and destroy them. To study energy transfer from free electric arc to waste the specific experimental plasma torch was constructed (Fig 2).

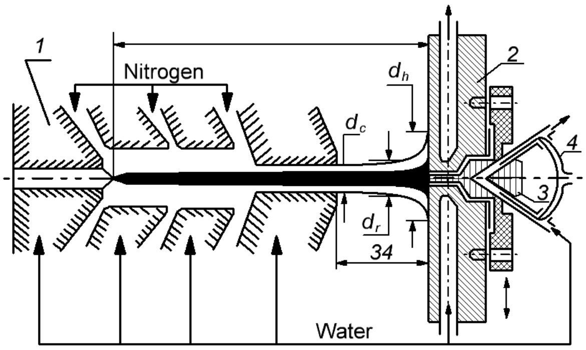

Fig 2. Schematic presentation of the experimental plasma torch. 1 – cathode, 2 – anode, 3 – holder, 4 – heat flow sensors and thermocouples

PT consist of a tungsten cathode and copper sections cooled by water. The cooling flat plate with mounted thermal sensors and thermocouples was used as anode with an external diameter of 40 mm. The sensors were electrically insulated from the anode by fluorine-plastic liners and ceramic backfilling. The anode moved across the arc and thus the sensors measured the distribution of the density of heat flow along the spot of arc heating.

During the experiments the PT arc current was I = 40 – 80 A, the nitrogen gas flow rate G_N = 0.2 – 0.6 g/s and the arc length l = 114 mm. Experiments were carried out at atmospheric pressure. Plasma flow velocity and temperature, heat transfer between plasma flow and reactor walls were calculated from all the measured data using the heat balance equations. Temperature on the arc axis was measured by the absolute intensity method using the optical emission spectrometer AOS-4 developed by IfU Diagnostic Systems GmbH [16]. Arc temperature was determined from nitrogen lines of 491.5, 493.5, 541.2 nm with an error less than 10%. The distribution of temperature along the radius of the arc was determined from the radial intensity of peaks applying the Abel transformation.

3. Results and discussions

3.1. The behavior of free plasma arc in plasma chemical reactor.

Electric arc in plasma chemical reactor is considered to be free since its development in the reactor space is not limited neither by the walls nor by the shielding gas and are stabilized only by the gas flow. Nitrogen in the PT is supplied from cathode side for its protection and its consumption does not influence the arc characteristics.

Under the influence of electromagnetic forces, a gas steam jet of plasma flows from cathode directed towards the anode. Since anode is a surface of a solid processing material (Fig 1a), a steam jets of its material were outflowing from it. This steam jet is thicker than the cathode gas stream, but much shorter. These two jets collided forming a plasma disc. In this case the arc operating was very unstable.

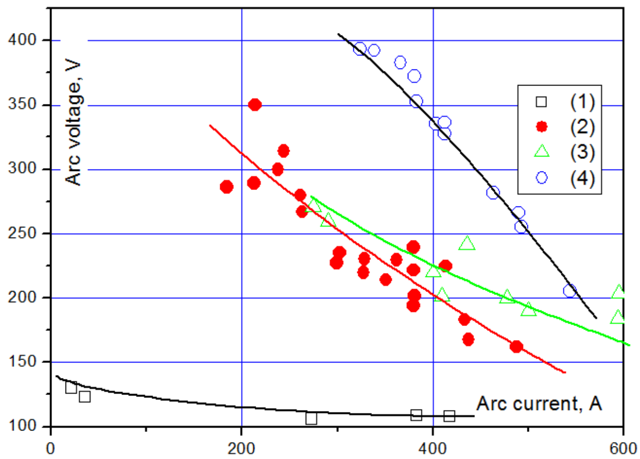

Fig 3. Voltage-current characteristics of free burning arc in nitrogen gas atmosphere at different distances x from PT cathode. 1 – 100, 2 – 250, 3 – 300, 4 – 500 mm

If (Fig 1b) the surface of the melted material serves as anode, the plasma disk did not formed, because the anode steam jet did not have a strict direction. In this case the electric arc operates in more stable mode than in the first case. Therefore, experiments were mainly performed with a melted anode (Fig 1 b).

3.2. The electrical characteristics of a free arc operating in nitrogen atmosphere.

The relationship between the steady state values of arc voltage and current for constant *x* is called as the static VCC. In the PChR, the VCC of a free arc in *N* atmosphere with anode as melted waste were measured at different arc lengths (Fig 3). It is observed that up to *x* = 100 mm the arc voltage is almost independent on arc current, however for *x* = 200–300 mm the VCC significantly depend on arc current *I*.

To determine the reasons for the significant difference in the characters of the VCC at *x* less than 100 mm and at *x* > 100, the dependence of arc voltage on the arc length was established (Fig 4). It was found, that the short arc burns in a laminar mode, while it looks like a rod and burns noiselessly. For example, at *I* = 400 A, the laminar arc reaches the distance of *x* = 170 mm. At *x* > 170 mm the noise and crackling appears, a part of the arc starts to operate at turbulent mode and becomes as multifilament as visible in Fig 1b. The turbulent regime is characterized also by higher values of arc voltage.

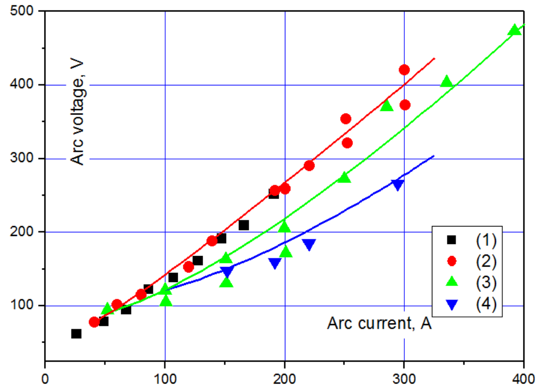

Fig 4. Dependence of arc voltage on arc current at different distances from anode emitter (*x*): 1 – 70, 2 – 300, 3 – 400, 4 – 500 mm. Anode is melted

Same experiments were carried out with graphite anode (Fig 5). In this case, it was found that arc voltage is higher than in the case of melt anode. When the melted anode is used, arc voltage falls due to the presence of melted material vapors in the arc. However, the length of the laminar part of the arc is almost the same in both cases.

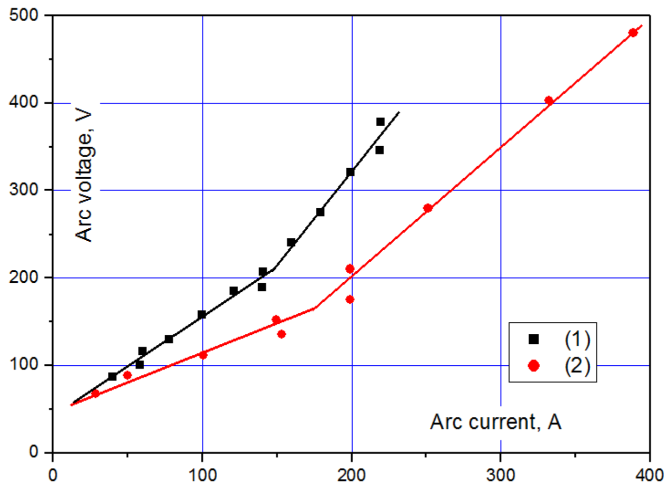

Fig 5. Dependence of arc voltage *U* on the distance *x* at arc current *I* = 400 A. Anode: 1 – graphite, 2 – melt

Analyzing the results provided in Fig 4 it may be noted that the behavior of the VCC (Fig. 2) in the distance up to *x* = 100 mm does not depend on the electric current, or depends insignificantly – the arc burns in a laminar mode. When *x* exceed 200 mm, the VCC greatly depend on the electric current – part of the arc burns in turbulent mode, however the length of the laminar part of the arc increases and arc voltage decreases increasing arc current. According to the

dependencies given in Fig 4 and Fig 5, the voltage for the laminar part of the arc column was established. The experimentally determined dependence of arc voltage at I > 100 A as constant and equal to 1000 V/m. When graphite anode was used, the voltage in laminar part of the arc was about 1000 V/m. In general cases, for arc current (I = 500–2000 A) the arc voltage is about 200 V/m in *Ar* atmosphere [9]. So, for the same value of arc current and length it is possible to obtain several times higher arc power in *N*, than in *Ar*.
From the experimental results of VCC, it can be seen that it is very simple to establish the dependence of free arc power on arc current and length in *N* (Fig. 6). It was found, that the power of the laminar arc increases with increasing arc current and/or arc length only in the case when a part of the arc burns in a turbulent regime (x = 290 mm). In this case appears the region where arc power is inversely proportional to arc current. The reason of such phenomena is the increment of arc current which causes the elongation of laminar part of arc and sudden drop of arc voltage.

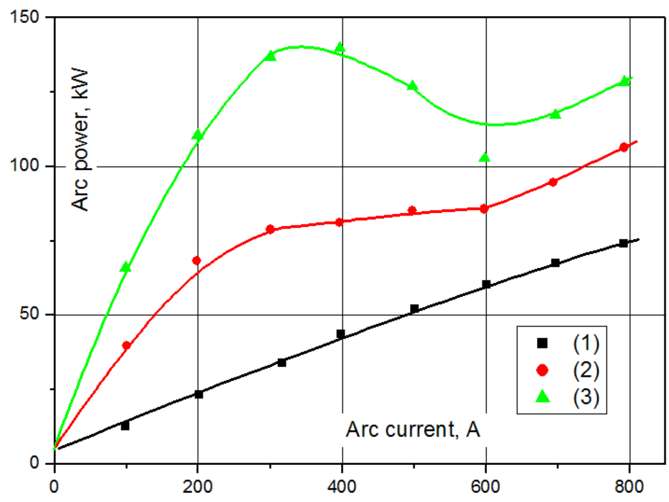

Fig 6. Dependence of arc power on arc current at different length of x (mm): 1 – 100, 2 – 220, 3 – 290.

The heat loses with the cooling water of the PT was also analyzed in the work. The heat loss by the cooling PT was relatively low: at I = 500 A, P = 90 kW and x = 200 mm, the value of P_w was only 1.97 kW, that makes about 2.2% of the total PT power. Such small values of heat losses were due to the presence PT inside PChR the walls of which protected it by relatively cold refractory material.

3.3. Anode energy balance.

In the areas, where the arc contacts with PT electrodes, the heat flux achieves high values through the arc spot. Local heating in this area is very intensive and for conventional PT only rapidly moving arc spot may protect the electrode from the melting. When electric arc is used for material processing, very intensive heat flushes are used for material melting. The transfer of energy to the PT anode occurs by following modes:
– By transmission of thermal and kinetic energies of electrons,

$$Q_1 = I\left(2.5\frac{kT_e}{e} + V_a\right). \quad (1)$$

– By energy transfer from electron (proportional to φ_e),

$$Q_2 = I\varphi_e. \quad (2)$$

– By radiation heat transfer (Q_R) from the arc;
– Convective heat transfer (Q_c) from plasma through the boundary layer.
In our experiments, the total heat transfer (Q_a) was measured. So, there was necessary to consider separately each mode of energy transfer to the anode. Heat transfer by electrons Q_e computed from Eq. (1) and (2):

$$Q_e = Q_1 + Q_2 = I\left(2.5\,\frac{k\,T_e}{e} + V_a + \varphi_e\right). \quad (3)$$

In Eq. (1-3): k is Bolzmann constant, J/K, T_e is the electron temperature, K, e is electron charge, C, V_a is anode potential, V, and φ_e is electron work function, V.
At I > 10 A in presence of atmospheric pressure, equilibrium is established in the arc, i.e., T_e and temperature of heavy particles are very similar. Consequently, in formula (3) we can admit Te equal to T_0 which was calculated out from the spectroscopic analysis (Fig 7).

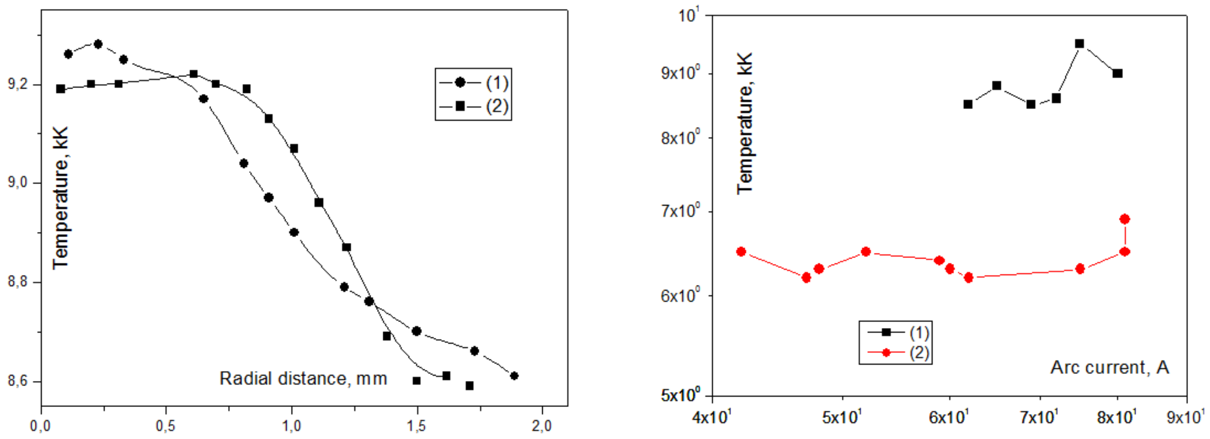

Fig 7. Temperature distribution across of the nitrogen arc (a), dependence of the axial arc temperature on arc current in nitrogen atmosphere (b). 1 – I = 62 A, 2 – I = 73 A

The voltage drop in anode surface V_a can be expressed [10] as

$$V_a = V_{a1} + V_{a2} \ . \tag{4}$$

Here V_{a1} and V_{a2} are potential drops in the regions of space charge and contraction at the anode.
It is important to notice that part of the energy V_a is transmitted by electrons to heavy particles ($I \cdot V_{a2}$) and is included in the convective heat flux Q_k. The other part of the energy ($I \cdot V_{a1}$) remains in the electrons. According data [17], for the arc in nitrogen atmosphere at I = 100 A, V_{a1} = 4 ± 2 V, φ_e = 5.2 V [0 13]. Substituting the corresponding values in (3), we obtain

$$Q_e = 11.4I \ . \tag{5}$$

In the former research of the authors [18] the heat loss distribution in the sections of the PT and power of the air arc along the length of the channel were measured. After recalculation of heat loses for the case of nitrogen arc at I = 72.3 A, the gas flow rate has been found G = 0.47 g/s. Using this data and the values of Q_e, found from (5), the dependence of Q_e/Q_a on arc length was established and placed in Fig 8. Fig. 8 shows that for a short arc (l = 10 mm) the bulk of the energy (up to 80%) is transferred by electrons.

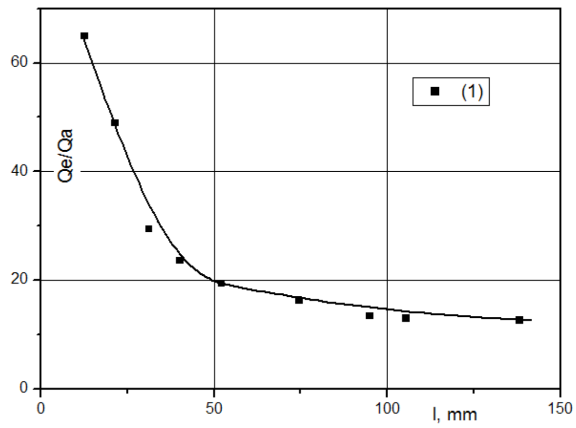

Fig 8. Dependence of the relative part of the heat flux transferred by electrons to the anode, from arc length

The radiation heat transfer Q_R for I <100 A, according to our experiments is negligible. According to our experimental data, heat transfer in the nitrogen arc in the range of I = 40–80 A varies within the range of 2–6 %. The part of convective Q_c heat flux in the energy balance at the anode side depends on the arc length. Our experiments show that at arc length exceeding 50 mm the bulk of the energy is transferred by convection as it is visible from Fig 8.

3.4. The influence of nitrogen flow rate and arc current on the heat transfer in the anode.

The experiments were carried out for various nitrogen flow rates (*G*) and strength of arc current (*I*) (Fig 9). With increasing *G*, the arc power increased, and Q_a decreased. For the explanation of an apparent contradiction it is necessary at first to consider the gas dynamics in a laminar arc.

The electric arc during the passage of the current is compressed by radial directed electromagnetic forces. In the arc of variable cross–section (for example, near the cathode) under the action of electromagnetic forces the longitudinal pressure gradient arises, which increases the generation of a plasma streams from the sites of constricted area. In present case, a plasma jet flows from the cathode towards the anode.

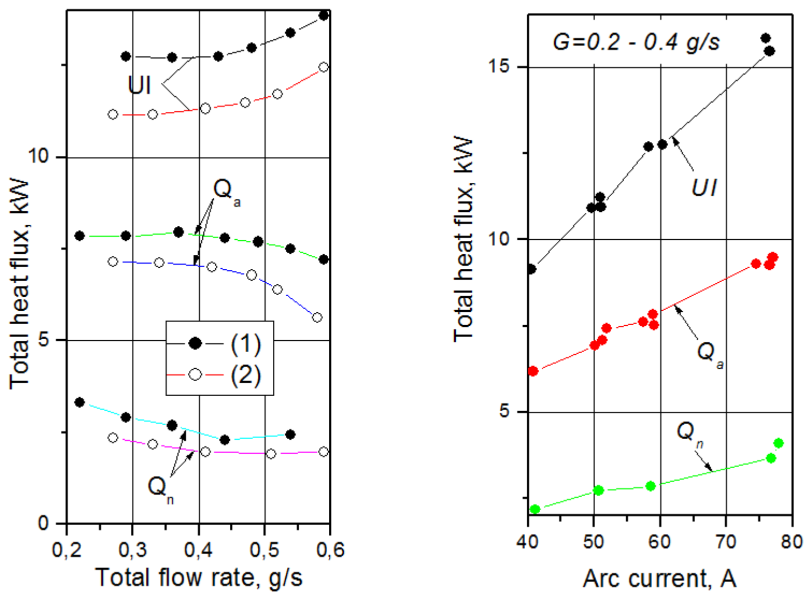

Fig 9. The dependence of arc power and heat loss from gas flow rate at different arc current strength. 1 – *I* = 51 A, 2 – *I* = 58 A

Thus, the arc (for given current *I* and length *l*) pumps "through itself" a certain definite rate of gas *G*. If a feeding gas flow rate exceed the necessary gas flow rate defined from the condition of electromagnetic compression, a part of the gas not injected into the arc and its surrounding is squeezing from the walls of the plasma torch reducing the heat losses in PT sections (that means it works like a gas curtain). This effect can explain the decrease of heat losses in the plasma torch with the growth of gas flow rate *G* (Fig. 9). In exhaust of PT nozzle, this extra gas *G* does not reach the anode and dissipates a part of the arc power by convection into the surrounding space. Therefore, as gas rate increases, Q_a decreases, although PT power also increases (Fig. 9).

3.5. Convective heat transfer on a flat anode (local, medium and at the critical point)

When the anode was moved across the arc, the sensor measured the distribution of specific heat flux (*q*) along the arc heating spot (Fig 10). The sensor measured the convective component of heat flux (*Q*) since it was electrically isolated from the anode (as mentioned heat transfer by the arc radiation was insignificant). We performed experiments (Fig. 10, points 1, 2) when the anode moved in different directions. The obtained data were generalized in dimensionless coordinates. In Fig 10: r_1 is the distance from the arc axis to the point where *q* is twice less than its maximum value. The *q* distribution along the heating spot of the arc can be approximately described by the law of the normal distribution of energy.

Our data for a laminar arc for Re <500 can be generalized by the following dependence:

$$q = q_0 \exp\ [-0{,}69\,(r/r_1)^{\,2}]. \qquad (6)$$

As the Prandtl number (Pr) for nitrogen at *T* < 10000 K varies insignificantly [0 the data on the average convective heat transfer was generalized according to the equation

$$Nu_f = C\, Re_f^m. \qquad (7)$$

The generalized results on convective heat transfer at the critical point of the anode are presented in Fig 11. They can be described by following equation:

$$Nu_O = 0{,}8\, Re_0^{0{,}5}. \qquad (8)$$

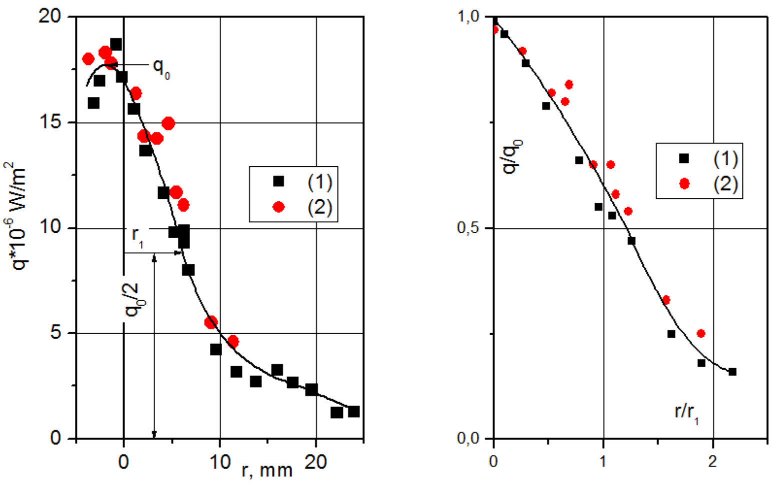

Fig 10. Distribution of the density of the heat flux of the nitrogen arc in a flat anode. I = 52 A, l = 114 mm, q_0 = 17,5 · 10^6 W/m^2, r_1 = 7.5 mm. Data: 1– anode was moved in horizontal direction, 2 – in vertical direction

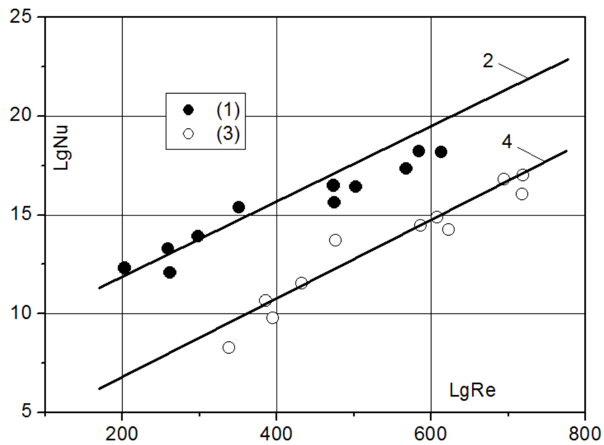

Fig 11. Overage convective heat transfer and heat transfer at the critical point between the nitrogen arc and the flat anode. Data: 1, 3 – our experiment, 2, 4 – [18].

The average convective heat transfer on the anode side were described by equation

$$Nu_f = 0{,}57\, Re_f^{0{,}5}. \tag{9}$$

The results were compared with the classical expressions and experimental data for heat transfer between the high–temperature impinging axisymmetric air jet and the perpendicular obstacle [18]. Results were also compared with the theoretical dependence of heat transfer at the critical point (Fig 11, dependence 2) [18]. The comparison showed that our experimental data of convective heat transfer between the arc and the flat anode is in good agreement with the results of others work on the heat transfer of the gas flow with the obstacle.

Conclusions

The behavior of free arc burning in plasma chemical reactor with nitrogen ambient is very confused and complicated. In the range of arc current I = 100–600 A and at different free arc length the voltage-current characteristics in nitrogen were measured. It was found that the VCC strongly depends on arc burning regime (laminar or turbulent).

The power of laminar arc increases with increasing arc current or its length. With increasing length of the arc the part of turbulent burning regime appears, and there exist range of arc current where the arc power is inversely proportional to the arc current.

Dependency of the length of laminar part of free burning arc in nitrogen atmosphere and arc current were determined. The relative parts of heat fluxes transferred by electrons or forced convection in the energy balance at the anode depend on arc length. At the arc length over 100 mm and arc current less than100 A, the major part of the energy (up to 88%) is transferred by convection.

The heat flux (*q*) distribution on the anode arc spot was generalized by the dependence (6). The generalized data of the convective heat transfer of the nitrogen arc in the anode area are in satisfactory agreement with the results of other work on heat transfer between the high temperature gas flow and the obstacle.

Acknowledgement

This research is funding by the European Regional Development Fund according to the supported activity 'Research Projects Implemented by World-class Researcher Groups' under Measure No. 01.2.2-LMT-K-718.

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