Experimental and computational study of arc discharges in powerful alternate arc heater

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Abstract. The paper deals with the results of computational and experimental research on the formation process of electric arc discharges in a three-phase Zvezda-type alternating current arc heater. A flow modelling in the arc heater, as well as an experiment on providing a visual control for the location and the shape of arc discharges were conducted. A device of a visual control system is presented. The analysis of the results obtained from experimental research is carried out.

1. Introduction
Alternate current arc heaters are a fairly versatile tool for conducting various high-temperature tests. For example, the oil and gas sector are highly interested in the field of plasma application for recycling, waste disposal and hydrocarbon treatment in order to obtain non-hazardous substances in the output [1]. At the same time, certain types of unstable operation of arc heaters are quite often manifested in experiments, which is largely due to the behavior of electric arcs and the effect of shunting.

For the effective use of plasma torches, one of the key factors is service life (the overhaul period). A shunting process, the interaction between an electric arc and elements of a gas path not provided by design or by operating mode, has a great influence on service life. The shunting process is a rather negative factor because current and voltage characteristics of the electric arc heater and a gas heat rate change due to shunting occurrence. Apart from that, purity of an outgoing flow of a working fluid can be disrupted, and the erosion of metallic electrodes rises significantly.

The objective of this paper is a study of specific features on the formation of arc discharges and their shunting in the plasmatron of unique design Zvezda developed and used in the Keldysh Research Center [2].

2. Shunting process
The most distinctive process, namely a shunting of an arc, cannot remain unnoticed when studying electric and physical processes occurring in a gas path of the plasmatron. One can say that a shunting process is a specific case of electric breakdown. It was investigated in works of many authors, for example, in the reference [3]. There are several types of shunting. In fact, they can be divided into a large-scale shunting process and a small-scale one. The scheme of shunting processes is shown in Figure 1.
If a large-scale shunting process, electric breakdown (2) occurs between the arc (1) located on the electrode axis and its wall. A new arc section appears and it is moved by a working fluid flow towards the output section of the heater. The shunted section of a discharge gradually fades. The described process is periodic. A large-scale shunting process regulates an average length of arc column and an average drop of the potential on it, a destroyed zone of a wall surface of the electrode-chamber (zone A), pulse or other characteristics of the arc and of the flow.

A small-scale shunting process (3) between arc-electrode occurring in gas layers that are close to chamber walls mainly determines a specific erosion of the material of an electrode. Electric breakdown (4) between arc–arc happens if a small-scale shunting process. It occurs in a hinge of the arc and it indirectly affects the rate of erosion of an electrode. The reason for this is that while shunting between arc-arc, a spot of the arc does not move, warming under it the surface of an electrode-chamber (zone B).

This paper deals with interactions between arc discharge and design elements such as a mixing chamber and confusers, which is a small-scale shunting process within the frames of the accepted classification.

3. Special features of the Zvezda-type arc heater

A scheme of the Zvezda-type alternating current electric arc heater [2, 4] is shown in Figure 2.
The arc heater consists of 3 identical arc chambers arranged under the $2\pi/3$ angle to each other and a common mixing (damper) chamber (1). An arc chamber consists of a backplate (2), an electrode-chamber (3) and a compression channel (confuser) (4) in which the intensification of gas heating is performed by means of a gas dynamic compression of the arc due to the radial velocity component. To increase erosion resistance of electrodes, the rotation of arc spots interacting with the surface of the electric arc chamber is used. For this reason, each electrode is equipped with magnetic coils (5) each of which is included into the circuit of one of phases. These coils provide coincidence by current phase in an arc and by magnetic field strength. The phases of supply network (A, B and C) are connected to electrodes. The induction coil ($L_1-L_3$) is included in each phase in sequence with the arc; moreover, it is possible to change a value of induction with the help of switching in order to ensure stable burning of each arc and to have opportunity in changing a value of the arc current. Figure 2 illustrates measuring current transformers ($TA_1- TA_3$) with the help of which a control for arc currents is performed. Electrode-chambers are separated from a conical compression channel by an electric insulator (a vortex generator) each of which is equipped with small nozzles through which the tangential feed of the working gas is realized. The main working gas flow rate $G_{main}$ is supplied between a confuser and an electrode-chamber via insulators. The remaining part of gas flow rate $G_{add}$ (10-30%) is supplied from a backplate side. A mixing chamber (1) has an output nozzle whose axis is perpendicular to the plane of the figure.

Arcs’ ignition process in the investigated electric arc heater is initiated by electric potential difference between an electric arc chamber and a compression channel. At that moment, the arcs interact according to the Zvezda (star) scheme with a zero point on the metal because compression channels are electrically connected between each other. Consequently, both electric arc chambers and confusers are eroded. After passing through compression channels, the arcs are pulled to the mixing chamber and they converge in a zero point in the plasma.

4. Calculations using engineering methods

In accordance with the objective set before the experiment, an operating mode of the plasmatron was calculated. The determination of operating parameters was conducted using engineering methods based on empirical dependence that showed its reliability and satisfactory accuracy on the Zvezda-type arc heater operating on air as a working fluid. The following parameters were determined:

1. Working fluid mass flow rate and pressure were calculated by the formula (in accordance with the reference [5]):

   \[ G = \dot{m} = \frac{p_w F_c r A(k)}{\sqrt{R T}} \]  

   where \( A(k) = \left( k \left( \frac{2}{k+1} \right)^{k+1} \right)^{k-1} \), \( \dot{m} \) is air mass flow rate, \( p_w \) is stagnation pressure at the nozzle, \( F_c r \) is a nozzle throat area, \( k \) is a ratio of specific heat, \( R \) and \( T \) are gas constant and gas temperature.

2. Gas temperature in output section (in accordance with the reference [2]):

   \[ T = 2.6 \cdot 10^3 \cdot \left( \frac{I^2 p \dot{d}_{avr}}{G_1^2} \right)^{0.095} \]  

   where \( G_1 \) is a mass flow rate via an electrode \( G_1 = G/3 \), \( \dot{d}_{avr} \) is an average value between the diameter of an electrode and the diameter of a confuser’s output section, \( I \) is arc current. The value \( \dot{d}_{avr} = 4.13 \text{ cm} \) for the Zvezda-type arc heater considered in this paper.
Table 1 illustrates the calculated gas dynamic parameters of the chosen mode in accordance with the above formulas.

**Table 1.** Calculated gas dynamic parameters.

| $G$ [kg/s] | $p$ [MPa] | $I$ [A] | $T$ [K] | $k$ | $A(k)$ | $v$ [g/mol] | $R$ [J/K·kg] |
|------------|-----------|---------|---------|-----|--------|-------------|-------------|
| 0.21       | 1.14      | 280     | 3919.74 | 1.21| 0.65   | 27.03       | 307.56      |

It is necessary to determine the shape and the location of arc discharges relative to a gas path of the arc heater in order to implement a numerical modelling of the plasmatron. Some assumptions were taken to simplify calculations, namely arc discharges were presented as a static one-piece construction in the shape of needles, which are converged at one point laying in the central plane of electrodes and in the geometric center of the mixing chamber. The tip of a needle in these assumptions determines the location of an anchor spot of arc discharge. Therefore, it is necessary to determine physical parameters of needles for setting up a problem in a Flow Simulation Solver of Solid Works Software. The diameter of an arc channel was determined by a method described in the reference [2]:

$$
d = 0.08 \frac{I^{0.6}}{H^{0.2} p^{0.2}} \tag{3}
$$

where $I$ is current force, $H$ is magnetic field strength and $p$ is pressure, $H = \frac{I \times w}{L}$, where $w$ is a number of turns in a coil, $L$ is a coil length. The diameter of an arc channel was so equal to 0.28 cm.

It is necessary to determine the location of anchor spots of an arc in order to identify the geometry of arc discharges. The length of arc discharges was estimated on the base of reports for the detection of defects of the plasmatron that present data about an average location of the anchor spot of the arc while working with operating modes similar to the calculation mode. Therefore, the final length of arc discharge was 461.9 mm.

Thermal power of AC arc was estimated by the following formula:

$$
P = I \cdot U \cdot \cos \phi \tag{4}
$$

where $U$ is voltage in arc discharges (according to the reference [2]): $U = 1.84 \times 10^3 \cdot \left(\frac{q_1 \cdot p \cdot d \cdot \varphi}{I}\right)^{1/3}$, $\varphi$ is an angle of phases shift. The values of radiative and convective heat flux were deducted from the obtained value of a thermal power to a cooling jacket of the arc heater, which were separately calculated under the conditions of a thermal balance.

5. **Experimental research**

The achievement of the task set in the part of experimental research is related to the necessity of visual observation of special features of the formation of electric arc discharges in a chamber, as well as the analysis of compliance of the special features to classical conceptions. To ensure opportunity for observation, the Žvezda-type plasmatron was modified in terms of construction from the backplate side of the mixing chamber. A pressure measuring node has undergone changes, which was redesigned to a compartment for a video camera. The scheme of the node is shown in Figure 3.
The Air Pro 3 HD Sports video camera (1) is a basis core of a visual observation system. It has the following characteristics: 12 MP resolution matrix, 120-Hz frame frequency at the resolution of 1280x720, aperture is f/2.8, observation angle is 160°. The video camera is located in such a way that its axis coincides with the axis of the mixing chamber of the arc heater (3) and that its axis traverses a geometrical point of connection of axes of three electrodes. Quartz glass (2) protects the Air Pro camera against pressure and high temperatures. An optical light filter protects the camera against electromagnetic radiation from electric arc discharges. Arc discharges (5) passing through compression channels (4) are connected in the mixing chamber. Cooling jackets (6) ensure the operational performance of the system. The video camera (1) showed a good stability at all operating modes of the plasmatron under the conditions of strong electromagnetic fields.

6. Results obtained and their analysis

The processing and the analysis of experimentally obtained data showed that a theoretical calculation with the use of engineering methods was correctly fulfilled. The difference in calculated and measured values is in the orders of error. The analysis of a video record showed that this mode does not ensure a stable nominal operation of the plasmatron because the pictures of convergence of arcs to each other are periodically replaced by the pictures of divergence of arc discharges in the mixing chamber by the angles from 10,75 ° up to 45,17 ° (Fig. 4). The angle of an average deviation of core flows with arc discharges was equal to 33,85 °. The developed method showed with a high accuracy (within the range of error) the coincidence of calculated values of gas dynamic processes that occur in the Zvezda-type electric arc heater with experimental parameters. Consequently, one can say that the developed method and calculations performed with it describes processes occurring in the arc heater with sufficient accuracy. Additionally, one can make a conclusion about the correct approach to a computer modelling of the flow.
7. Conclusion
In conclusion, it is worth organizing the results obtained within the framework of conducted research, which concerns one of the most important characteristics (in terms of industrial use) of the electric arc heater in question, namely service life (the overhaul period). Service life in its turn depends on peculiarities of the interaction between an arc discharge and elements of the plasmatron design. The presence and intensity of such interaction in the mixing chamber zone and the exit of compression channels (confusers) were investigated in the present paper. A successful attempt to organize a visual observation system over a process of the formation and of the existence of arc discharges was made. Based on the results of the work done, the following conclusions were made:

1. A method for calculating main gas dynamic parameters of a gas path of the arc heater was developed on the base of a commercial software complex.

2. The view and the location of arc discharges differ from the classical conception of the presence of straight-lined cores that are converged at one point of the geometric center of intersection of the electrodes and the mixing chamber axes.

3. The picture illustrating shapes and the location of arc discharges is not stationary, but periodic. The period time is about 12-30 Hz. This fact seems to be related to gas dynamic special features of a flow formation in the gas path.

4. The shapes of arc discharges coming out of the compression channels are straight linear segments, nevertheless they are not converged at one point in the geometric center, and they deviate by an average value of 33,85° at the exit of confusers, in the width range from 10,75° up to 45,17°. This fact is due to gas dynamic special features of a flow formation in gas path. The deviation of arc discharges causes their interaction with side faces of the compression channels of an adjacent phase and their intensive destruction because of high temperatures.

5. The calculations made in the Solid Works FlowSimulation software complex indicate that the direction of trajectories of a gas velocity flowing out from a compression channel has a deviation from the axis of an electrode. This fact is well consistent with the observed deviation of arc discharges from the axis of an electrode in the experiment, it indicates the influence of gas-dynamic effects on the shape, and the location of the arc discharges.

Thus, increasing service life of the Zvezda plasmatron considered scheme is closely related to the organization of the flow in the gas path.

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