Three-Dimensional Transient Modelling of a Well Type Cathode Torch with the Reversed Polarity Discharge

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In this study, a three dimensional (3D) unsteady magneto-hydrodynamic model is used to compare the plasma arc behaviour inside two hollow cathode torches with different vortex generator designs. Both studied torches work using the reversed polarity discharge. Cold flow analysis is applied to estimate the erosion area on the anode wall and the cathode spot is fixed at a point near the entrance of the torch. In the initial design, the chamber has two columns of holes generating the vortex in different directions. The results obtained from this design showed that the arc attaches at the entrance of the anode and cathode parts and there is no arc entering the anode part. In the other word, the torch does not work properly and comparing the numerical results with the arc attachment spots obtained from the experiment, showed a good agreement. The second design is chosen between several designs for the vortex chamber based on the minimum erosion areas on the anode wall. The comparison illustrated the second design works well for the torch with the reversed polarity discharge where it can be used to treat the radiative wastes including the combustible and non-combustible materials.

Keywords: 3D numerical modelling, Electro-magnetic fields, Hollow electrode torch, Reversed polarity discharge

1. Introduction

For many years, direct current (DC) plasma torches are extensively used in waste-to-energy processes, materials processing and thermal spray coating processes. In a DC plasma torch where an arc is struck between a cathode and an anode nozzle, cold gases introduced into the torch are heated to high temperatures by the arc where the electric energy is converted to the thermal energy. Based on the cathode shape, DC plasma torches are divided into the rode type cathode (RTC) (Fig. 1) and well type cathode (WTC) (Fig. 2) torches. RTC plasma torches are mostly used for thermal spray process or waste treatment while WTC torches used in material processing including the hazardous treatment (Ref 1).

The way of the plasma gas injection into the RTC and the WTC plasma torches is different. In the RTCs, the cold gas is injected around the cathode part while in the WTCs, it is injected through a vortex chamber between the two concentric cylindrical electrodes generating a swirling plasma flow. Generally, WTC plasma torches are more complex than RTCs to analyse. In RTCs plasma torches, the cathode spot is fixed on the cathode tip and so the location of the cathode erosion is known (see Fig. 1). However, in the WTCs, the cathode spots are moving because of the vortex flow. Therefore, the erosion area on the cathode wall (cathodic arc attachment) is difficult to predict.

A conventional hollow cathode torch (see Fig. 2a) combines of two concentric cylindrical electrodes where the cathode is located at the end of the torch and the anode part is connected to the outlet (Ref 2- 4). Figure 2b shows a schematic of a reversed polarity in which the cathode has two ends open. One of the advantages of using the hollow cathode torches with the reversed polarity discharge is that by increasing the voltage, the arc column can be transferred to the targeted materials. The transferred arc causes higher thermal efficiency and so can be used in the radioactive waste treatments containing of the combustible and non-combustible materials (Ref 5, 8).

The aim of this study is comparing two different cases to find a proper design for the vortex chamber. In the initial design, vortex chamber generates the rotation in different directions (clockwise and counterclockwise) using the two columns of holes. In the next step to find the proper design for the vortex chamber, four different geometries are studied, and the results compared to the initial design.

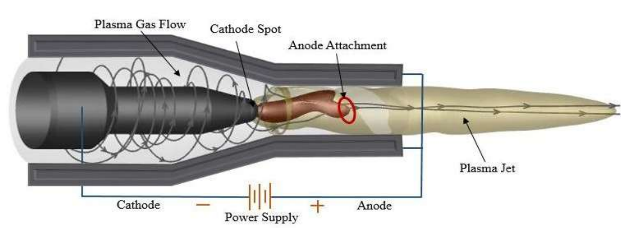

Fig. 1 Typical of a RTC plasma torch

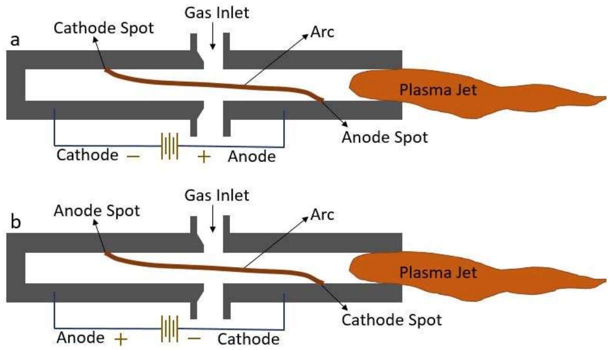

Fig. 2 Schematics of plasma torches with hollow electrodes a) conventional and b) reversed polarity discharges

2. Geometry and Operating Conditions

WTCs have three main parts, the anode, cathode, and vortex generator, which should be considered in the simulation. Vortex chamber which generates the plasma swirling flow should be well designed due to their effect on the flow behaviour and arc attachments spots. Figure 3 shows the cross-sectional view and the computational domain for the initial design where the chamber generates two vortexes in different directions (clockwise and counterclockwise). A cathode with the length of 100 mm and the diameter of 5.5 mm and an anode with the length of 107 mm and the diameter of 4.5 mm are considering in the model. The opening between the cathode and anode parts is 5 mm. the plasma working gas is air with the mass flow rate of 150 slpm and the current of 200 A. The computational domain contains of about 1,000,000 unstructured cells in which the cell sizes are locally refined near the electrodes and in the vortex generator region to capture the large plasma temperature and velocity gradients. Four new designs for the vortex chamber generating the clockwise swirl are illustrated in Fig. 4.

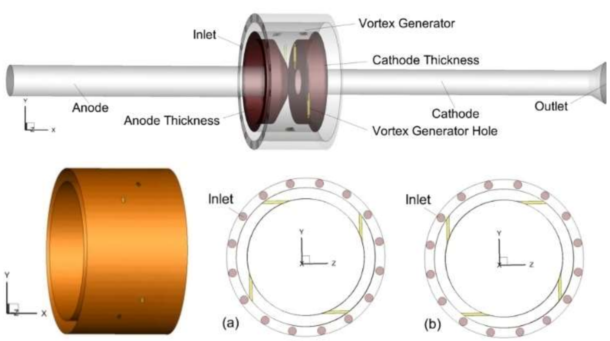

Fig. 3 Cross-sectional view and computational domain of the study- initial design

3. Mathematical Modelling

A 3D unsteady magneto-hydrodynamic model is used to simulate the plasma arc behaviour inside the torch comparing two different designs. The used assumptions are: The plasma is in the local thermodynamic equilibrium (LTE). Temperature-based thermo dynamic and transport properties of air are used. Radiation losses using the net emission coefficient is added to the model. K-epsilon turbulence model is used to model the turbulent plasma flow.

Considering the above assumptions in 3D time-dependent modelling, thermal plasmas are generally defined by 5 variables $(P, \vec{u}, T, \emptyset, and\ \vec{A})$ and 9 components, where, P, $\vec{u}$, T, $\emptyset$, and $\vec{A}$ are the pressure, velocity vector, temperature, electrical potential, and magnetic vector potential, respectively. The general form of the scalar transport equation is defined as (Ref 11):

$$\frac{\partial \rho \Phi}{\partial t} + \nabla.(\rho u \Phi) = \nabla.(\Gamma \nabla \Phi) + S_{\Phi} \qquad (1)$$

where, the first and second term in the left-hand side are the unsteady and convection terms, respectively, and the terms in the right-hand side are diffusion and source terms, respectively. Applying five mentioned independent variables in equation (1), conservation of mass, momentum, energy, conservation of electrical current, and magnetic induction equations are defined and used in the model. A code is written and compiled to the system to solve the electric and magnetic fields and couple them with the fluid flow.

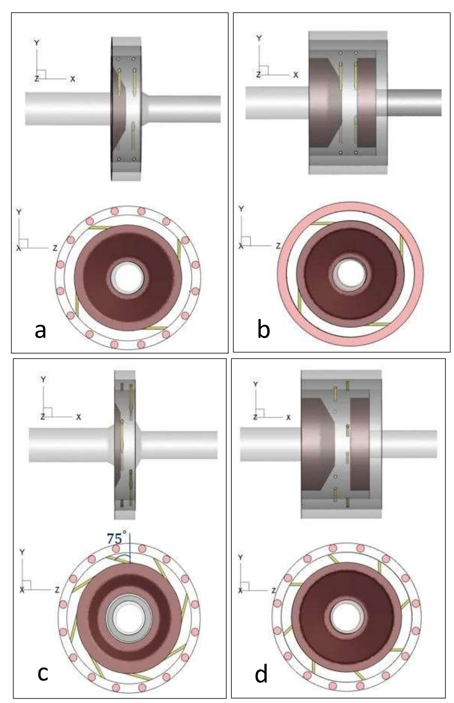

Fig. 4 Geometry of the different vortex generators

The mass flow inlet and the pressure outlet are used for the inlet and outlet boundary conditions. A constant temperature of 3000 K is imposed at the anode and the cathode arc root spots and 2000 K everywhere else. A parabolic current density profile is used on the cathode spot (Ref 1),

$$J(r) = J_{max}\left(1 - \left(\frac{r}{r_c}\right)^2\right) \quad (2)$$

where r is the radial distance from the torch axis, r_c and $J_{\max}$ define the profile shape. r_c is obtained from equation 17 (Ref 1),

$$I = 2\pi \int_0^{r_c} J(r).r.dr \quad (3)$$

where I is the current intensity. The value of J_{max} generally varies between 9×10^7 and $1.2 \times 10^8\ A/m^2$.

In the numerical modelling, the cathode spot position in which the arc starts from there is necessary to consider. As mentioned, the cathode root moves freely on the cathode wall and so, this spot is difficult to predict. This position can be estimated from the cold flow analysis in the conventional WTC. The cathode spot for the WTCs with the reversed polarity discharge, is more difficult to predict. One way to estimate the cathode spot position, is using the erosion areas captured from the experiments. Another way is to fix one attachment point on the cathode surface which provide the landing of the arc spot. Park et. al. (Ref. 10) suggested a second step close to the torch exit on the cathode part in their design in which the arc starts from that point. In the current study, the cathode spot is fixed at a location near the torch inlet.

4. Results and Discussions

4.1. Estimating the Erosion Areas

One approach to estimate the cathode and anode spot positions in the conventional WTC and the reversed polarity discharge torches, respectively, is the cold flow analysis. Hur and Hong (Ref. 2-4) by applying the cold flow analysis suggested by Brillhac et al., (Ref. 8), predicted the cathode spot position in their numerical model. They claimed that the erosion area on the cathode wall can be estimated by a limited axial velocity of the cold gas at a distance close to the cathode wall (0.5 mm from the wall). Kim et al., (Ref. 9) did not applied the cold flow analysis in their study and instead used the cathode spot position determined based on the erosion traces on the cathode wall observed in the experiment.

In the current study, to analyse the flow behaviour inside the torch (Fig. 3) and to predict the erosion area on the anode wall, air at room temperature with the mass flow rate of 150 slpm is used as the injected gas flow. Figures 5 represents the limited axial velocity of the gas at three moments. It is observed that almost no gas enters the anode part. In other word, it can be concluded that the erosion happens between the cathode and the anode parts.

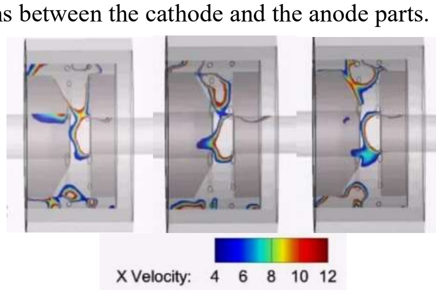

Fig. 5 Limited axial velocity of the gas

The limited axial velocity on the anode entrance at three instants as well as the erosion of the anode entrance captured from the experiments are illustrated in Fig. 6. Comparing the results shows a good agreement between the numerical and experimental results.

The results up to this point show that the vortex chamber with the two columns of holes generating the swirl in two different directions is not suitable for the torch operation. Therefore, to find the proper design for the vortex chamber, four different geometry are chosen and studied (see Fig. 4). All vortex chambers include two columns of holes generating the swirling gas flow in one direction. Among different designs for the vortex chamber, case b in figure 4 is selected as a result of the smaller erosion area on the anode wall. The rest of the results will be for the arc behaviour inside the torch with the chosen vortex generator.

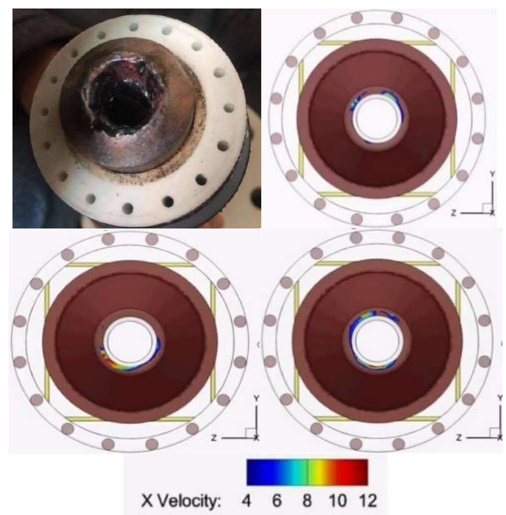

Fig. 6 Limited axial velocity of the gas (numerical) and the image of erosion (experimental) on the entrance of the anode

4.2. Plasma Gas Temperature Distribution

Instantaneous plasma gas temperature distribution is shown in Fig. 7. Temperature distribution represents a plasma arc starting from the cathode spot where the arc current density and temperature are in their maximum values.

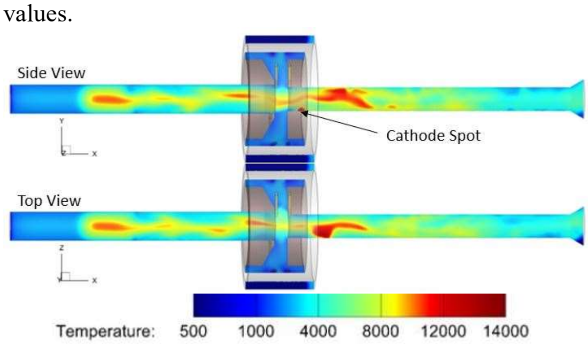

Fig. 7 Instant temperature distribution inside

4.3. Arc Shape Inside the Torch

To observe the 3D nature of the plasma arc inside the torch, the temperature distribution is illustrated using three moments with the iso-surfaces of 7 and 10 kK (Fig. 8). The results show that the higher temperatures occur in the arc spots. It is also shown that the plasma arc and attachment spots are moving and rotating due to the swirling plasma flow.

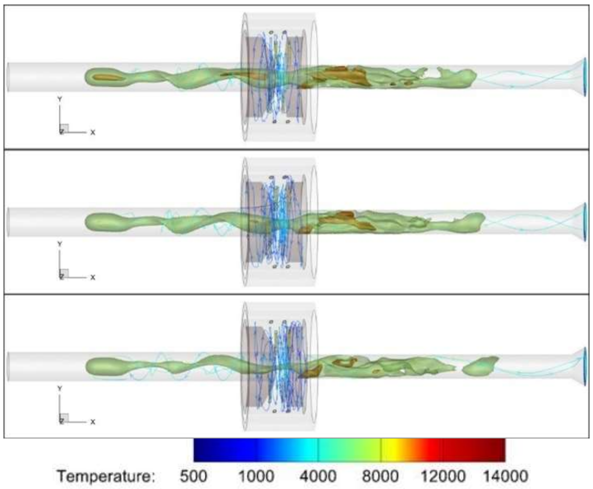

Fig. 8 Arc shape inside the torch using the iso-surfaces of 7 and 10 kK

4.4. Gas Temperature Distribution at the Torch Exit

Figure 9 represents the plasma gas temperature distribution at the torch exit at four moments. It is observed that the temperature varies with time as the result of the arc voltage fluctuations and swirling flow.

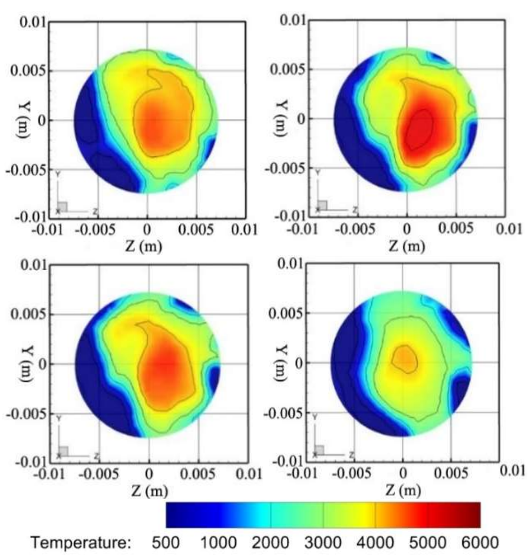

Fig. 9 Plasma gas temperature distribution at the torch exit

5. Conclusion

In this study, a 3D unsteady magneto-hydrodynamic model was used to simulate the plasma arc behaviour inside a WTC torch. The cathodic arc attachment spot (erosion area) is important in the numerical modelling. The cold flow analysis was done to observe and analyse the flow behaviour inside the torch and estimate the anode spot locations. It was shown that using a vortex chamber having two columns of holes generating the swirl in two different directions is not appropriate for the torch operation. Air was used as the gas flow and it was shown that there is no flow enters the anode part and arc attaches the anode and the cathode parts at their entrances. In other words, the erosion happens between the entrances of the cathode and the anode parts. This erosion area obtained from the numerical model was compared with the experimental image and showed a good agreement.

Then, among different vortex chambers studied applying the cold flow analysis, one was selected to use in this part. Air was used as the plasma working gas. The results showed a swirling plasma arc starting from the cathode spot and temperature oscillations due to the arc fluctuations.

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