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Experimental analysis of arcs behavior in a 3-Phase AC arc plasma torch with hot graphite electrodes: comparison with MHD modeling results.

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Abstract: Arcs behavior in 3-Phase plasma systems remains poorly studied. In this paper, arc behavior observed with a high speed camera has been compared to some typical results obtained by a MHD modeling. Numerical results highlights the origin of some typical arc shape obtained experimentally.

Keywords: electric arc motion, 3-phase AC plasma torch, MHD modeling.

1. Introduction

For about 20 years, a 3-phase AC plasma technology with high temperature consumable graphite electrodes is under development at MINES-ParisTech [1]. As displayed in **Fig.1**, this system was initially composed of three converging graphite electrodes located on three generating lines of a 15° revolution cone [2]. Recently, a new configuration with three radial electrodes being located in a plan perpendicular to the reactor axis has been developed. The arc behaviour in such system has been simulated by a MHD model [3]. As illustrated in **Fig.2**, the analysis of the 3-phase plasma torch using a 100 000 fps high speed video camera [4] has shown a fair correlation between MHD modelling and experiments, both regarding the arc behaviour and the current waveform [5].

This MHD model was faintly modified and adapted for the simulation of the 15° angular electrode configuration. Due to meshing issue, we have simulated this 3-Phase system with parallel electrodes configuration. We assume that this 15° angle has not a significant influence on the arc behaviour compared to the parallel electrode configuration. Besides, the graphite electrodes are now considering into the computational domain as mentioned in other IPSC paper.

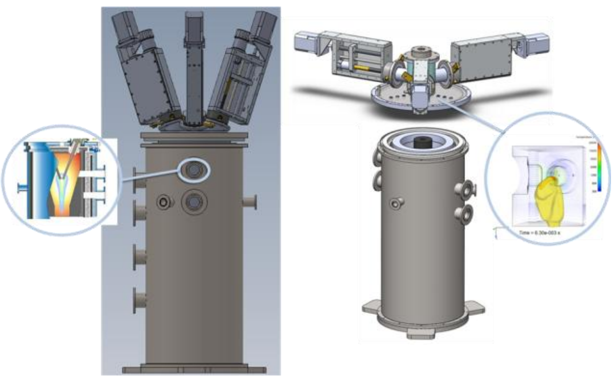

Fig.1 3-phase plasma torch systems developed at PERSEE Mines-ParisTech with coplanar electrode configuration (right) and angular electrode configuration (left).

In this paper, the numerical results are compared with experimental images obtained with a high speed camera. First, the main characteristics of the experimental setup are described. Then, the comparison between experimental and some numerical results are presented.

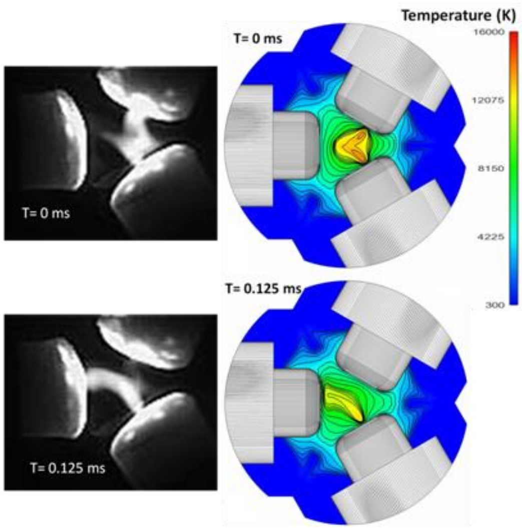

Fig.2 Comparison of the temperature fields in a cross section located in a plan containing the 3 electrode axes (left) with the arc video sequence (right).

2. 3-Phase AC Plasma Torch Set Up

The studied 3-phase plasma system is composed of three graphite electrodes (Ø 17 mm) located on three generating lines located on a 15° revolution cone, as represented in **Fig. 1**. This system has no ground connected neutral point and is assimilated to a triangle configuration. Generally, only one arc can exist at time and arc discharge follows the maximal electric gap potential. Each electrode plays alternatively two times the role of cathode and anode by period and one period is decomposed into the generation by rotation of 6 arcs. The frequency was set to 680 Hz by a 263 KW 3-Phase converter (rectifier-chopper-inverter). Video camera analysis was carried out using a high-speed video camera Olympus FS with a 50,000 fps shooting rate, 20 µs exposure time and 180x132 pixels on the raw images recorded with the camera. This camera is located at around 2 m optical distance from the electrodes tips. Experiments were realized for 200A phase current, 3.82 $Nm^3.h^{-1}$ nitrogen plasma gas flow rate. Various optical filters were used in order to adjust the image brightness.

3. Comparison between experimental results and MHD modelling

Video sequences obtained with the high speed camera show that the 3-phase discharge is mainly erratic. The chronological 6 arcs formation in each period is almost verified and the 3-Phase system is sometimes unbalanced. This arc discharge behaviour could not be perfectly reproduced by the simulation since the arc discharge is mainly chaotic. However, this behaviour is partially simulated with the model and it is then analysed with the MHD model in order to improve the understanding of such discharge. Besides, arc motions are observed by a bottom view of the inter electrode gap. The numerical results show the same arc shape with an entire 3D view.

Experimental arcs can have different geometries that can be classified into numerous shapes. Five main classical shapes already reported in the literature for different plasma systems: I, V, U, W or S [6-9] are observed. It is commonly accepted that these shapes are mainly influenced by the electrode jet velocity and magnetic repulsive forces induced by the electric current. Consequently, the arc root position on the electrode has a significant influence on these particularly arc shapes.

The comparison of the results obtained with the high speed camera and the results obtained with MHD model is exposed in **Fig.3**. This figure shows the decomposition, in a cross projection view under the inter electrode gap of the arc shapes. The images have been correlated with the numerical results. Numerical results were obtained with a sinusoidal voltage waveform and a 400 A imposed peak current, which gives almost 200 A RMS current value. In the experimental setup, a 150-200 A RMS current is used and the voltage waveform has a non sinusoidal waveform (3-Phase chopper-inverter output waveform). However, it has been demonstrated in a previous article that the voltage waveform shape has a negligible influence on the current waveform [5].

To initialize the simulation, a hot zone at 6,000 K is artificially implemented between the three electrodes and the current target is set during 0.75 ms from 5 to 400 A. With the increasing of the imposed current, the hot zone moves toward the torch outlet. Indeed, the hot zone moves faster than the velocity of the surrounding gas flow. The temperature in this hot zone remains above 5,000 K, which is a privileged area for the arc discharge. Once the arc root and the hot zone reach the bottom of the electrodes, the arc curvature increases; partly induced by the magnetic arc repulsion and the electrode jets. Thus give a centrifugal arc motion, as shown in **Fig. 3** (t= 1.46 ms). This arc shape is almost reached in 1-1.5 ms, which correspond to the end of the current increment or one period. Arc shape is mainly influenced by the magnetic forces rather than the plasma gas aerodynamics forces.

Later on, on image t = 1.98 ms, one observe that the arcs are characterized by a particular arc shape with two electrode vapour jets. The mass flow emanating from each electrode vapour jet is almost entirely directed along the normal of its associated electrode tip and the arc has almost a U shape. With the arc column motion toward the torch outlet, the phase voltage increases. Therefore an arc column ignites between the two electrode jets which decreases the phase voltage, as shown at t= 2.02 ms and in **Fig.4**.

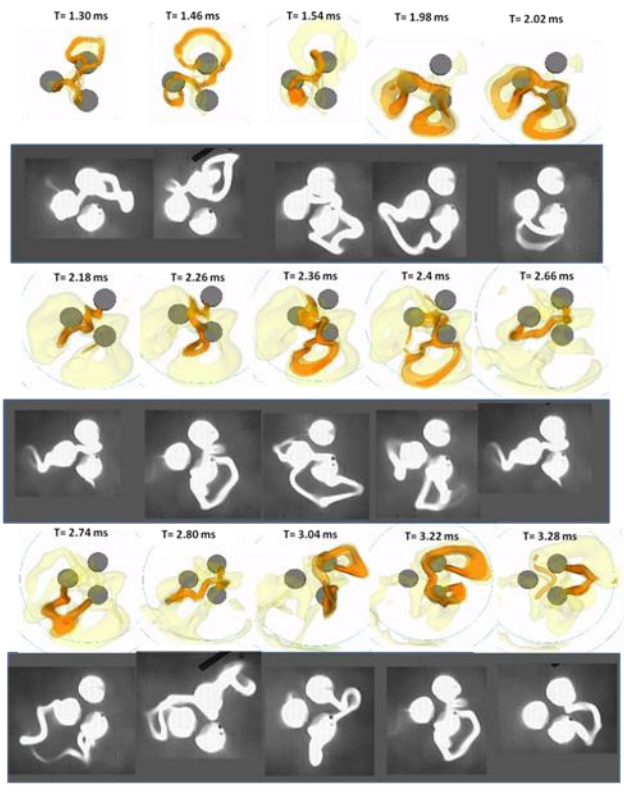

Fig.3 Comparison of the arc shapes, displayed by a 10 000 K isosurface temperature and hot channels displayed by a 5 000 K isosurface temperature, with the arc video sequence by a bottom view of the inter electrode gap.

With the rotation of the electrical potential difference on the electrodes, the phase voltage increases to maintain the arc. Thus, an arc column ignites with the other electrode in a previous arc column where the gradient of the electrical potential is high. As represented in **Fig.4**, the arc shaped by a front view, one part of the initial arc column switches off and the arc discharge remains mainly in the other part of the previous hot channel. Nevertheless, we can observe that the arc does not follow the maximal phase to phase voltage. Concerning the arc shapes, the position of the new arc root will change this shape. Different shapes have been observed, as shown in **Fig.3** and **Fig.4**. These shapes modify the position of the hot channels which contributes to the erratic arcs discharge.

Later on, a part of the heat contained in the arc column cross an old hot channel and the arcs ignite on this channel. Voltage between arc column and electrode is a key parameter on the 3-phase arc discharge behaviour. Besides, the arc motion around the inactive electrode enhanced the 3-Phase arc discharge. Results of the MHD modelling highlight this behaviour. This mechanism is well reproduced by the simulation and occurs three times per period. The arc rotates by passing from a pair of electrodes to another one with a frequency which is twice that of the power supply.

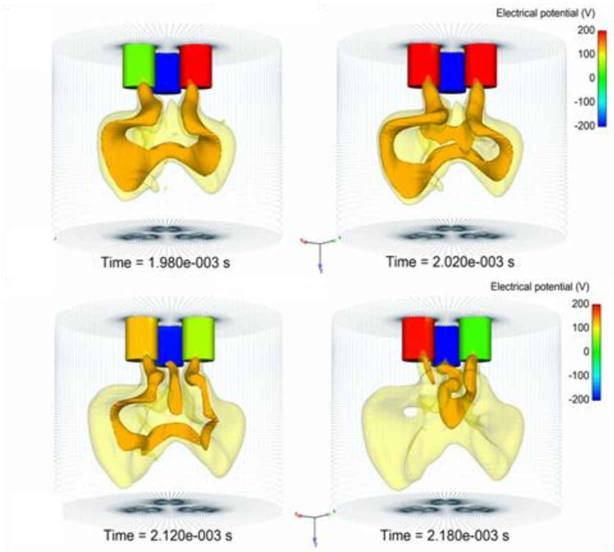

Fig.4 Arc shapes obtained with the MHD modeling, displayed on a front view by a 8 000 K isosurface temperature and the hot channels are displayed by a 5 000 K isosurface temperature. Electrodes are colored by the electrical potential value.

Besides, unbalanced 3-phase behaviour was sometimes observed with the high speed video camera. In this case, the arc column does not cross the periphery of the inactive electrode zone. With the MHD modelling, this behaviour was also observed. However, the calculations diverge with this discharge. As shown on image at t= 3.28 ms or on **Fig.5**, the arc is directed toward the torch walls. The temperature within the inter electrode gap decreases and the electrical conductivity becomes insufficient to ignite a new arc with the other electrode. This point highlights the key feature of the hot channels motion near to the inter-electrode gap for the 3-Phase arc discharge stability. Indeed, it has been highlighted that decreasing the frequency down to 50 Hz, the arc elongation increases which produces an unbalanced 3-phase arc discharge.

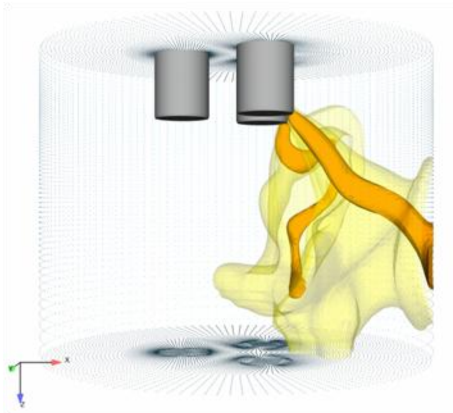

Fig.5 Arc shapes when the 3 phase system is unbalanced, arc is represented by a 8 000 K isosurface temperature and hot channels are represented by a 5 000 K isosurface temperature,.

3. Conclusion

In order to understand the 3 phase arc discharge behaviour with angular electrode configuration (15°), a MHD model has been developed. This model is based on a previous one, developed for coplanar electrode configuration. The model has been modified by considering parallel electrode configuration. Experimental results obtained with a high speed camera show a fair correlation between the experimental and numerical arc behaviours and arc shapes. These results highlighted the strong influence of the arc motions and the hot channels positions on the 3-phase plasma system operation. The heat contained on the hot channels near the inter-electrode gap contributes to ignite new arc roots by increasing the gradient of the electrical potential in the zone near the inactive electrode. Arc ignition is therefore mainly related to the evolution of the hot channels which is related to the arc motion. This arc motion is mostly influenced by the electrode jet forces (Maecker effect) and Lorentz forces. These forces modify the heat exchanged in the system and are mainly influenced by the current, plasma gas and electrodes configuration. In other ISPC paper, the influence of such parameter on the 3 phase discharge behaviour is discussed.

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