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Abstract: Recently, a magnetohydrodynamic modeling of a 3-phase plasma torch has been developed giving a fair correlation with experiment results. In this paper, parallels instead coplanar electrodes have been considered. Results show a different arc discharge behavior controlled by repulsive magnetic forces instead of hydrodynamic electrode jet forces. These forces give a particular arc discharge influenced by frequency, current and gas flow rate.

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

1. Introduction

3-phase AC power supplies with graphite electrodes have proven their durability and reliability for many years in steel industry for few MW [1]. Plasma technology based on this system, could overcome some problems of reliability and equipment/operating costs of DC arc plasma torches. Indeed, short lifetime of the electrodes [2] and sensitive electronics due to the rectifier part of the electrical signal give some limits to DC technology.

A solution developed for about 20 years at MINES-ParisTech is a 3-phase AC plasma technology with consumable graphite electrodes. By contrast with 3-phase arcs furnace, where the arcs transit via molten metal as star neutral point, there is not a neutral point which is ground connected in this developed system. Consequently, this technology is based on the generation of rotating arcs entrained in a gas flow generated at the tip of three electrodes. Thus, the 3-phase system is assimilated to a triangle configuration where generally only one arc can exist at one and two arcs can coexist only during a very short duration. Each electrode plays then alternatively two times by period the role of cathode and anode. One period is decomposed into the generation by rotation of 6 arcs. According to Fabry et al [3], this plasma system could be a solution to for the future development at industrial scale of the Waste-to-Energy gasification processes based on thermal plasma. However, very few studies have been dedicated to 3-phase AC plasma torches. Indeed, most of the industrial applications are based on DC plasma torches [4-5].

The 3-Phase plasma system was initially composed of three converging graphite electrodes located on three generating lines of a 15° revolution cone [6]. Recently, a new configuration with three radial electrodes being located in a plan perpendicular to the reactor axis has been developed. The arc behavior has been simulated by a MagnetoHydroDynamic (MHD) model [7]. This model automatically simulates the arcs ignition, extinction and produces a particular arc motion between the three electrode tips. Further, the analysis of the 3-phase plasma torch has been carried out using a 100 000 fps high speed video camera and oscilloscope [8]. Results show a fair correlation between MHD modelling and experiments, both regarding the arc behaviour and electrical waveforms [9]. In this paper, the results of MHD modelling with coplanar electrodes configuration are compared with parallel electrodes configuration and experimental images obtained with a high speed camera.

2. Description of the 3-Phase AC Plasma Torch

The parallel electrodes configuration grid mesh was created using the software Salome 6©. The computational domain refers to a slightly different geometry to the actual converging graphite electrodes located on three generating lines located on a 15° revolution cone. Due to meshing issue, we consider three parallel electrodes (**Fig.1**). Nevertheless, we can assume that this 15° has not a significant influence on the 3-phase arc discharge behavior compared to parallel electrodes. A functional fluid area of the arcs evolution has been considered. A non-uniform hexahedral mesh with approximately 800 000 nodes is used and is refined at the vicinity of the electrodes.

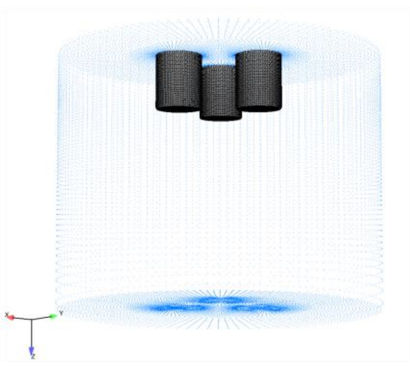

Fig.1 Computational domain used in this study composed of three parallel electrodes.

3. Assumptions and equations

The study was carried out for an arc discharge operating with nitrogen. The data of the properties have been taken from [10]. The 3-D model of the three phase system is based on the following main assumptions that are commonly used.

(1) The plasma is considered as a single continuous fluid (nitrogen) and at Local Thermodynamic Equilibrium (LTE).
(2) The gas is uncompressible.
(3) The gas flow is laminar and time dependent.
(4) Inductive currents are neglected.
(5) Gravitational effects and radiation are not taken into account.
(6) The voltage drop in the sheath is not considered in the model

Given the assumptions listed above, fluid equations can be written by normal conservation equations including the Lorentz force and the Joule effect, assuming the approximation of Ohm's law in its simplified form and the overall electrical neutrality [7].

3. Boundary Conditions

Boundary conditions are detailed and exposed on a cross section view on the **Fig.2** and **Table 1**. The boundary conditions could be separated into three different categories: (1) hydrodynamic conditions, (2) thermal conditions and (3) electromagnetic conditions. Regarding the hydrodynamic conditions, the central plasma gas injection is located in the AB, EF zones. The velocity is 0.1 m s^{-1}, giving a flow rate of 3.8 Nm^3 h^{-1}.

Current density and temperature assumptions on the boundary condition of the electrode are not suitable to well simulate the complex arc behavior in such system. The electrodes are then incorporate into the computational domain (zone BCDE). The objective is to characterize the magnetic interactions between the 3 graphite electrodes and arcs.

Regarding the electromagnetic conditions, a sinusoidal electrical potential of 680 Hz frequency is imposed on each electrode. This electrical potential is phase shifted by 2π/3 between the three electrodes and is adjusted by the model using a variable called ϕr, in order to control the measured current.

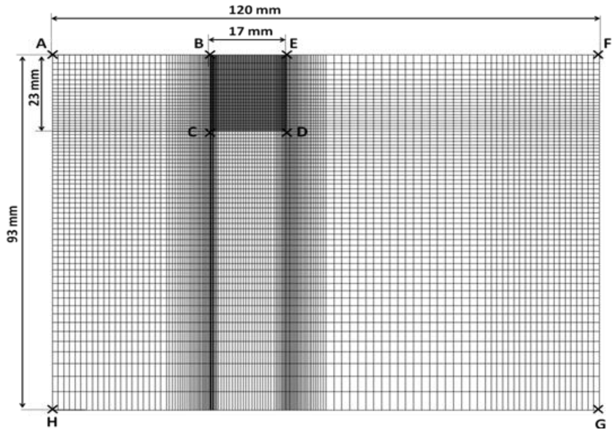

Fig.2 Grid mesh exposed on a cross section showing one electrode.

Table 1 Boundary conditions applied to a section of the computational domain, with f, t_{ref} and it the frequency, the times step and the iteration number respectively.

		Velocity ($m.s^{-1}$)	*Temperature (K)*	*Φr (V)*	*P (Pa)*	*A*
AB, EF	**Inlet**	0.01à 0.43	300	0	$\frac{\partial P}{\partial n}=0$	$\frac{\partial A}{\partial n}=0$
AH, FG	**Walls**	0	$\frac{\partial T}{\partial n}=0$	$\frac{\partial \phi r}{\partial n}=0$	$\frac{\partial P}{\partial n}=0$	$\frac{\partial A}{\partial n}=0$
BE	**Electrode condition**	0	$\frac{\partial T}{\partial n}=0$	$\phi_r \sin(2\pi f t_{ref} it - \frac{2k\pi}{3})$*	$\frac{\partial P}{\partial n}=0$	$\frac{\partial A}{\partial n}=0$
GH	**Outflow**	$\frac{\partial v}{\partial n}=0$	$\frac{\partial T}{\partial n}=0$	$\frac{\partial \phi r}{\partial n}=0$	1.013 10^5	0
BCDE	**Electrodes**	-	-	-	-	-

*k for the electrode number from 0 to 2.

3. Implementation of the Numerical Model on Code Saturne

The software Code_Saturne v. 2.0, electric arc module, was used for the 3D transient model of the three phase plasma torch. A 2 μs time-step has been used to give a reasonable computation time. The study is partitioned on eight processors (Intel Xeon 2.66 GHz). One iteration takes almost 1 min 20 s. To simulate one period (1.5 ms), we need about 750 iterations, i.e. 16 h of calculation. To ignite the first arcs at the first time-steps, a hot zone at 6,000 K is artificially implemented between the three electrodes and the peak current target is set during half of a period (0.75 ms) from 5 to 400 A.

As previously mentioned, the 3-phase system can be assimilated to a triangle configuration [6, 11] where two arcs can coexist just during a short time. We suppose that each new arc disturbs the previous by a repulsive magnetic effect, or the joule effect becomes insufficient to maintain two arcs in same time. Assuming this hypothesis, the theoretical current flowing in the arcs follows the maximum of the phase-to-phase voltage. We impose a constant value for the sum of the currents measured on the three planes between the 3 electrodes. This method shows results close to the experimental form. In the case of a phase delay or a lacking arc, this method gives also more degree of freedom to the model.

3. Results

In parallel and coplanar electrode configuration, MHD modeling has been successfully implemented and the model automatically simulates the arcs ignition, extinction and motion between the three electrodes tips.

Results show a different arc behavior in both case controlled by hydrodynamic electrode jet forces in coplanar electrode configuration instead of repulsive magnetic forces in parallel electrode configuration, as shown in **Fig.2**. This particular arc behavior has been already suggested and estimated by Ravary et al [6]. He demonstrated that, in such geometry, the interaction of the 3 line currents flowing in the electrodes and within the arcs induced strong rotating magnetic repulsive forces on the arc roots leading to a global centrifugal arc motion. Besides, this global arc motion in the centrifugal direction was also suggested and estimated in other papers [12]. Indeed, the 3-phase AC plasma torch has some similarities with electric arc furnaces.

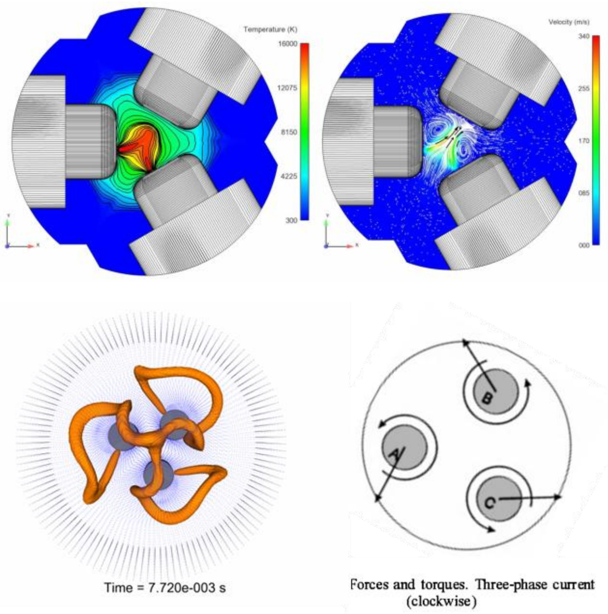

Fig.3 Arc behavior in coplanar electrode configuration (on the top) with temperature field (left) and velocity field with particule tracking (right) in a cross section located in a plan containing the 3 electrode axes. At the bottom, arc behavior in parallel electrode configuration correlated to theoretical arc shape in arc furnace system demonstrated by Bermudez et al. [12].

Moreover, from a parametric study, it appears that the imposed current will change the arc discharge behavior. By decreasing the current down to 50 A RMS, the arc stay within the inter electrode gap. Conversely, by increasing the current, arc roots move along the surface of the electrodes and finish on the extremity of the electrode tip (Fig.3). We can then notice that the Lorentz forces produced within the electrode have a strong influence on the arc behavior. A previous model, without the electrode incorporate into the computational domain, has shown that the arcs stay within the inter electrode gap like in coplanar electrodes configuration.

Consequently, by increasing the current above 150 A RMS, the arc motion increase strongly toward the outflow of the computational domain. The radial distance of this domain has also been increased in order to avoid that the arcs impact the torch walls. With the arc elongation, the mass flow emanating from the electrodes jets do not directly contribute to the new arcs ignition. The heat transmitted by this induced mass flow is directed outward to the inter electrode gap. The path of the arc produce a thermal channel, in which arc discharge operate. The increasing of the current raises the Lorentz forces. These forces give a motion to the thermal channel. By increasing the frequency, the motion of this thermal channel decrease and the 3-Phase arc discharge is more stable than previously. At 50 Hz, the 3-Phase system becomes unbalanced and only one arc remains after around 10 ms. Indeed, the temperature field in the others hot channel between the other others electrodes decreases below 5000 K. Arc discharge within this channel is avoided since the electrical conductivity is not enough. Consequently, the evolution of the hot channel is a key feature on the 3-Phase arc discharge stability. This evolution seems to be related to the imposed frequency, which influence the arc motion and then the 3-Phase arc discharge stability.

Regarding the electrical values, the power significantly increases with parallel electrode configuration compared to coplanar configuration. Indeed, heat transmitted by electrode jets in coplanar electrode configuration within the inter electrode gap stabilize the line voltage around 35 V. In fact, the increase of the current stabilizes the arcs within inter-electrode gap. Conversely, in parallel electrode configuration, the arcs are not stabilized within the inter electrode gap. The increase of the current raises the hot channel motion and the velocity of the arc column is faster than the plasma gas velocity injected. Arc elongation induces line voltage up to 100 V RMS. The power increases then significantly around 70-50 KW whereas it was around 8-20 KW in coplanar configuration.

3. Conclusion

A 3D MHD modeling of a 3-phase AC plasma torch with parallel graphite electrodes has been developed. Significant information that can hardly be achieved experimentally has been obtained with this modeling. Results show a different arc behavior than the previous developed model with coplanar electrode configuration. In this new MHD model, the arcs are mainly controlled by magnetic forces instead of hydrodynamic electrode jet forces. These forces give a particular arc behavior which has already been suggested and estimated by different studies. Results obtained with this model show that the arc motion is strongly influenced by the current, plasma gas flow rate and frequency. Frequency is then a key feature in electrical arc motion since it modifies the 3-phase discharge stability. This point, revealed by this study is interesting for mainly arc applications, as arc furnace systems and also other 3 phase plasma torches. Globally, arcs generated between three graphite electrodes induce a specific heat and mass transfer which tend to homogenize the plasma flow temperature. In other ISPC paper, results obtained with this model are compared to experimental results obtained with a high speed camera. Results show a fair correlation between MHD modeling and experiments, both regarding the arc motion and the dissipated power value.

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