Refereed Article

High-speed photography and modelling of direct-current plasma arcs

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Abstract

Direct current (DC) plasma arc furnace technology has been used in industrial pyrometallurgical processes for many years, for applications including scrap steel remelting as well as the smelting of various metallurgical products such as ferrochrome, ferronickel, cobalt, ilmenite, magnesium, and platinum group metals. Central to the operation of the DC arc furnace is the direct current plasma arc: a high-temperature, high-velocity jet of ionised gas sustained and driven by interactions between the electric, magnetic, and temperature fields within the furnace. At industrial scale, the arc jet can operate at temperatures in excess of 20 000 K and reach supersonic velocities. In this work, the qualitative nature of the dynamic behaviour of DC plasma arcs at typical pilot-plant-scale current levels (500 – 2 000 A) was studied using both theoretical and experimental approaches. Previous work in this area has made use of consumer-class photographic equipment, and, due to the extremely short time scales characteristic of plasma arc motion (< 1 ms), much of the detail in the dynamics of the arc motion remained unobserved. In this case, however, an Olympus iSpeed 3 high-speed digital video camera was used to capture images of the arc column at between 5 000 and 30 000 frames per second in order to resolve the dynamic behaviour sufficiently. The results of these tests were then compared with the output from an advanced computational model of the plasma arc, with a number of novel phenomena and transition effects being observed in both sets of results. Helical motion and arc length transition effects, anode arcs, transitions between chaotic and pseudo-steady arc behaviour, and arc extinguishment were studied.

Keywords: high-speed photography, DC plasma arc, furnace, pyrometallurgy

1. Introduction

A direct current (DC) arc furnace typically comprises a refractory-lined cylindrical steel shell in which the power is supplied by an electric arc that is generated in the open space between a vertical graphite cathode and the molten material that is in contact with an anode connection at the base of the vessel.

DC furnaces have been in existence for a very long time, and were used for the bulk melting of metals as early as 1878 (by Sir William Siemens in Europe). Since the 1980s, the application of DC arc furnaces has been extended to smelting processes, where significant chemical reactions are involved. Mintek has contributed to the industrial-scale commercialisation of this technology for the smelting of fine chromite ore to produce ferrochromium, the smelting of ilmenite to produce titania slag and pig iron, and the recovery of metals from non-ferrous smelting slags. Other applications, such as for ferronickel and platinum group metals, are on the brink of commercialisation.

The principal energy source in the furnace is a direct-current plasma arc, which is struck between the end of the graphite electrode and the surface of the electrically conductive molten bath. The plasma arc functions by raising the temperature of the gas between the electrode and the molten bath via ohmic heating. Once the temperature of the gas is sufficiently high, its constituent molecules and atoms begin to ionise into positively charged ions and negatively charged electrons, giving a neutral but very strongly-conductive plasma gas. This conducting material permits electrical current to pass from the furnace electrode through to the furnace bath and complete the circuit. Energy escapes from the arc via a multitude of mechanisms, most importantly thermal radiation from the hot plasma gas, and convection to the molten bath surface. As much of this energy is delivered to a localised area directly beneath the arc, it is a very efficient way of heating the process material.

This present work builds on previous photographic and modelling work[1-5] by using high-speed photography to study the behaviour of arcs. The effects studied were helical motion and arc length transition effects, anode arcs, transitions between chaotic and pseudo-steady arc behaviour, and arc extinguishment. A better understanding of these phenomena could improve the control and operation of furnaces.

2. Experimental equipment

The equipment used was an Olympus iSpeed 3 camera, which is able to capture images at up to 2 000 frames per second at a resolution of 1280 by 1024, and up to 150 000 frames per second at reduced resolution. The camera can use shutter speeds as short as 1 µs, which are necessary in the case of filming arcs without filters, as the high temperature plasma emits extremely intense visible light and is more than capable of providing its own illumination even at very high frame rates. A Tokina 80-200 mm telephoto lens was used, set at 200 mm and an aperture of f/22.

The test facility for generating arcs included a graphite electrode of 100 mm diameter attached to a movable hoist, and a large graphite block connected as the anode. Arc length was measured as the distance from the tip of the electrode to the surface onto which the arc impinged. The arc was struck in open air. A 3 MW direct current power supply based on pulse-width modulation rectification using IGBT transistors was used to provide an approximately constant current for each of the tests.

3. Helical motion and arc length transition effects

Arcs are often represented as steady cylindrical columns of plasma. More detailed investigation shows that, in fact, arcs are highly dynamic phenomena and exhibit rapid changes on very short time scales, of the order of 1 ms or less. The nature of the arc behaviour changes with various process factors including arc length and current.

The simplest form of dynamic motion observed is a regular precession of the arc jet around its attachment point on the electrode. This results in the arc column taking on a helical shape. As the arc length increases beyond a certain transition point, the movement of the arc becomes more chaotic and irregular.

Figures 1(a)-(d) show the behaviour of an arc of length 5 cm. Regular helical oscillations of the arc column can be seen, repeating roughly every four frames. The second sequence, shown in Figures 2(a)-(d), show an arc of length 10 cm exhibiting more chaotic, irregular behaviour.

(a) Frame 107 (b) Frame 108 (c) Frame 109 (d) Frame 110

Fig. 1. Successive frames from a high-speed video sequence showing an arc at 1000A and 5cm length, 5000 frames/s, shutter 4µs

(a) Frame 332 (b) Frame 333 (c) Frame 334 (d) Frame 335

Fig. 2. Successive frames from a high-speed video sequence showing an arc at 1000A and 10cm length, 5000 frames/s, shutter 4µs

The photographic sequences shown here are consistent with results from an advanced dynamic computational model of the arc[5]. Figure 3 shows that regular oscillations give way to more erratic motion as the arc length is increased at constant current.

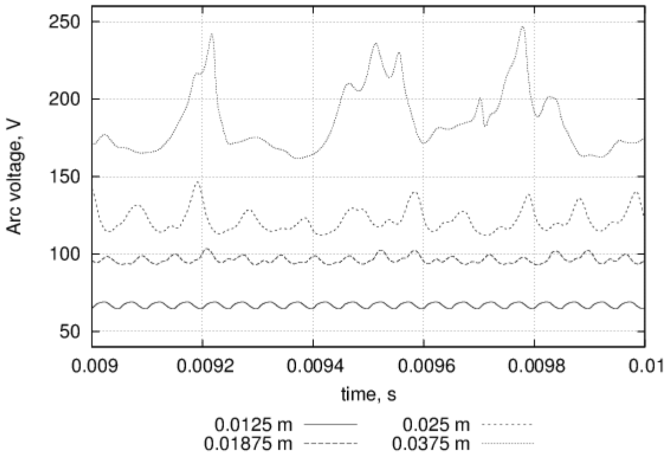
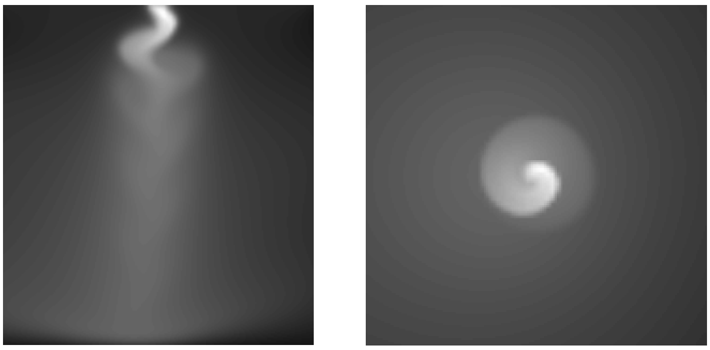


Fig. 3. Variation of arc voltage behaviour at arc lengths between 1.25cm (bottom curve) and 3.75cm (top curve) at 500A in 2D computational model

Figures 4(a) and (b) show side and plan views of a temperature profile arising from three-dimensional models of the plasma arc, in which the helical shape is spontaneously formed as the root of the arc jet precesses around the cathode attachment spot. Good agreement is seen between the model results and the high-speed photographs.



(a) Side view (b) Top view

Fig. 4. Views of temperature field from 3D arc model at 250A and 5cm arc length, scale 2000K (black) to 15000K (white)

4. Anode arcs

Formation of spontaneous, transient arcs at the anode surface was a surprising phenomenon first observed in results from the computational arc model. This qualitative phenomenon was subsequently confirmed by high-speed video data. A plausible explanation for this behaviour is the self-reinforcing response of a localised hot-spot on the anode surface being amplified by resistive heating due to the increased electric current that flows through the conductive high-temperature spot. The formation and decay of an anode arc can be seen on the lower right of the successive high-speed video frames shown in Figures 5(a)-(d). Figures 6 and 7 show the striking resemblance between photographed and modelled anode arcs.

(a) Frame 365 (b) Frame 366 (c) Frame 367 (d) Frame 368

Fig. 5. Successive frames from a high-speed video sequence showing anode arc formation at 1000A and 10cm length, 5000 frames/s, shutter 4 µs

Fig. 6. Image of arc at 1000A and 10cm arc length, 5000 frames/s, shutter 4 ms, anode arc at lower right

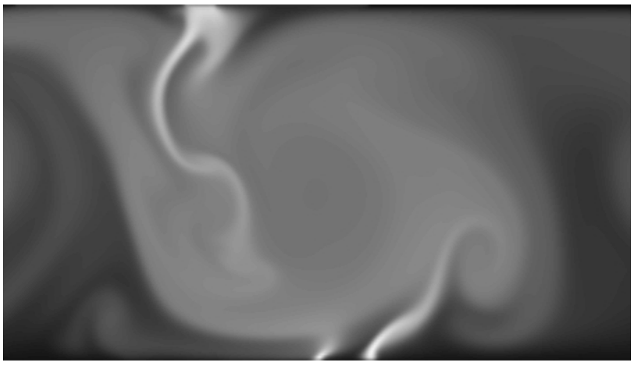


Fig. 7. Temperature field from 2D arc model at 500A and 5cm arc length, scale 2000 (black) to 15000K, anode arc at lower right

5. Transitions between chaotic and pseudo-steady arc behaviour

Even while in regimes of chaotic unstable motion, the plasma arc is occasionally seen to enter short periods of pseudo-stability during which the arc jet takes on a columnar shape and remains located in one position. Very high frame rates are required in order to properly capture this phenomenon visually and observe all of the intermediate states that occur during the transition.

As seen in Figures 8(a)-(f) (representing a duration of approximately 2ms), the transition from chaotic unstable motion to a temporary steady state occurs as a result of the formation of a strong, dominant plasma jet that forms at the electrode tip. This strong jet abruptly draws the current flow away from outlying structures in the arc and maintains the columnar shape for a short period of time.

(a) Frame 212 (b) Frame 216 (c) Frame 239

(d) Frame 251 (e) Frame 266 (f) Frame 275

Fig. 8. Frames from a high-speed video sequence of an arc at 1000A and 10cm length, showing a temporary transition from irregular dynamics to a pseudo-stable arc column, 30 000 frames/s, shutter 4 µs

6. Arc extinguishment behaviour

For economic reasons, it is highly desirable for an industrial furnace to operate without interruption. For this reason, the system behaviour immediately prior to catastrophic failure of the self-sustaining plasma arc is of particular interest. To date, only very limited testing of this phenomenon has been conducted, results of which are presented here.

It would appear that the mode of arc failure varies considerably with the current level. At lower currents, instabilities near to the anode surface trigger the extinguishment of the arc. These include the formation of strongly dynamic anode arcs and clouds of vapour ablated off the anode surface, which interfere with the conducting path between the cathode and anode. One such sequence is shown in Figures 9(a)-(f).

(a) Frame 1 (b) Frame 607 (c) Frame 681 (d) Frame 698 (e) Frame 876 (f) Frame 909

Fig. 9. Frames from a high-speed video sequence of an arc at 500A and 45cm length showing failure of the arc at lower current, 5000 frames/s, shutter 4 µs

At higher currents, the arc is extinguished by a different mechanism. The sequence in Figures 10(a)-(d) and 11(a)-(d) shows the arc undergoing a transition from chaotic, irregular motion (typical at higher currents and arc lengths) to a regime of pseudo-stability. As the pseudo-stable arc attempts to resume chaotic unstable motion, electrical contact between the cathode and anode is broken for too long and the arc is extinguished.

(a) Frame 147 (b) Frame 162 (c) Frame 177 (d) Frame 196

Fig. 10. Frames from a high-speed video sequence of an arc at 1000A and 35cm length showing the establishment of a pseudo-stable state prior to failure, 5000 frames/s, shutter 4 µs

(a) Frame 804 (b) Frame 811 (c) Frame 828 (d) Frame 890

Fig. 11. Frames from a high-speed video sequence of an arc at 1000A and 35cm length
showing failure of the arc as the pseudo-stable state breaks down, 5000 frames/s, shutter 4 µs

7. Conclusions

Because of the extremely rapid motion of the DC plasma arc, high-speed photography is required for the successful study of arc dynamics. Many arc-related phenomena have been elucidated using a combination of this technique and computational modelling. This work has shown that arcs exhibit helical motion, with a transition to more irregular chaotic movement as arc length increases. The unexpected modelling results predicting the existence of anode arcs were confirmed by high-speed imaging. Details of the transition between chaotic and pseudo-steady arc behaviour were observed using very high frame rates. Different modes of arc extinguishment were observed at different current levels. Arc extinguishment warrants further study because of its importance in maintaining steady operation of industrial furnaces.

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