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Impacts of External Magnetic Fields Applied to High-Pressure Electric Arc Heaters

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Acceptable behavior of electrical arc discharges inside high-power arc heaters usually requires the introduction of externally applied magnetic fields near the arc terminations. The strength and spatial distribution of these fields are discussed for a typical configuration. The effects of the Lorentz force produced by these fields on the arc discharge near the electrodes are evaluated in terms of azimuthal, axial, and radial components of the force. In general, there are only two possible states of the Lorentz force interaction with the arc, one of which enhances the gas swirl and the arc attachment, the other opposes the gas swirl and the arc attachment. Simple rules are given for ensuring the proper polarity of the magnetic field to obtain the desired result. An analysis of the proper scaling of the magnetic field strength in conjunction with geometric scaling of the arc heater shows that the magnetic field strength is only weakly dependent on scale.

Nomenclature

B = magnetic field strength, G
D = diameter, cm
D^* = throat diameter, cm
F = force, N
H = enthalpy, MJ/kg
I = current, A
i = unit vector
J = current density, A/cm^2
L = characteristic length, cm
P = pressure, MPa
r = radial coordinate, radius, cm
s = general length coordinate, cm
t = time, s
z = axial coordinate, cm
β = scaling factor
θ = azimuthal coordinate, rad
μ = gas viscosity, kg/m/s
ρ = gas density, kg/m^3
σ = electrical conductivity, mho/m
v = gas velocity, cm/s

Subscripts
a = arc
B = bulk or mass average
b = bore
L = Lorentz
r = radial component
z = axial component
0 = reservoir or stagnation value
θ = azimuthal component

Introduction

ELECTRIC arc heaters have been used for aerospace applications since the late 1950s, when the need for testing thermal protective materials for re-entry bodies became important. The earlier heaters were of the Huels type,[1] consisting of two coaxial tubular electrodes separated by a swirl chamber, as shown in Fig. 1a. The Huels-type heaters are characterized by simplicity, durability, reliability, and operational maturity, but have limited performance. The segmented arc heater,[2] developed later, has many electrically isolated segments separating the anode (upstream end) from the cathode (nozzle end), as shown in Fig. 1b. The segmented arc heater offers higher performance at all pressure levels and also much less contamination from electrode erosion, since it operates at higher voltage and lower current. A typical operating condition for a segmented heater is a voltage of 20 kV, a current of 1200 A at a chamber pressure of 10 MPa, which produces a flowfield bulk (mass-averaged) enthalpy of approximately 7 MJ/kg. For the same pressure, the Huels-type heater typically operates at lower enthalpy (5–6 MJ/kg) than the segmented arc heater, but is easier to operate and maintain because of the simpler construction.

The typical high-pressure segmented arc heater utilizes a strong gasdynamic swirl flow to stabilize the electric discharge near the heater axis (Fig. 2a), by generating a positive radial pressure gradient. The gas swirl also produces rotation of the arc attachment point on the surface of the electrode rings, thereby reducing the possibility of burn-through at the arc at-

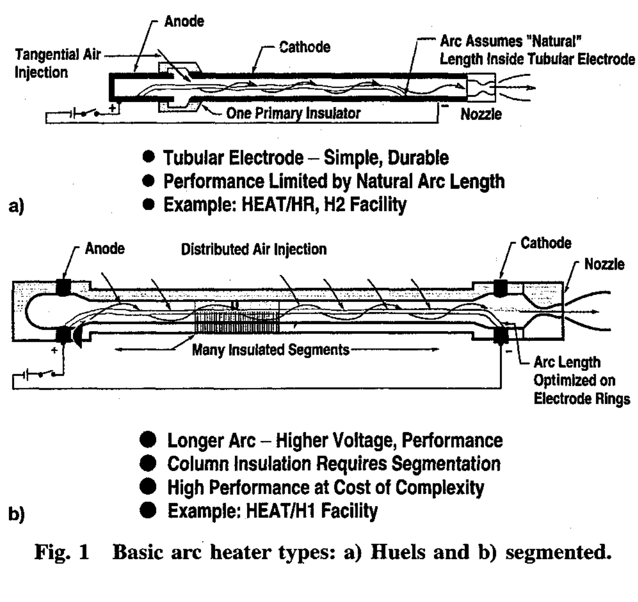

Fig. 1 Basic arc heater types: a) Huels and b) segmented.

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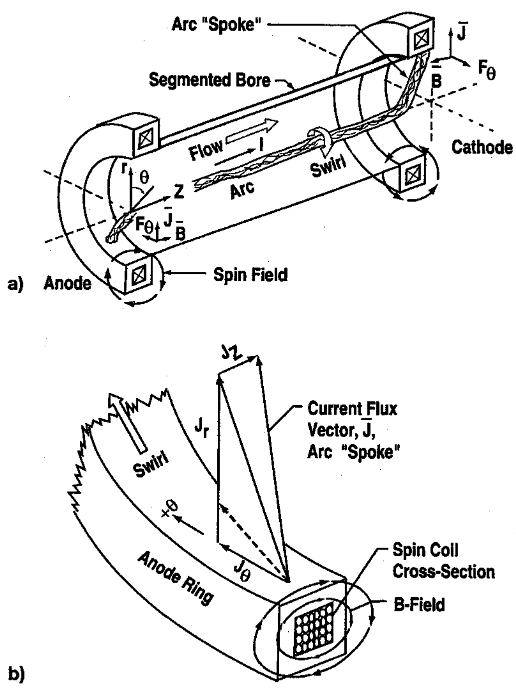

Fig. 2 Arc heater and spin coils: a) overall schematic and b) current flux, *B* field, gas swirl at anode ring.

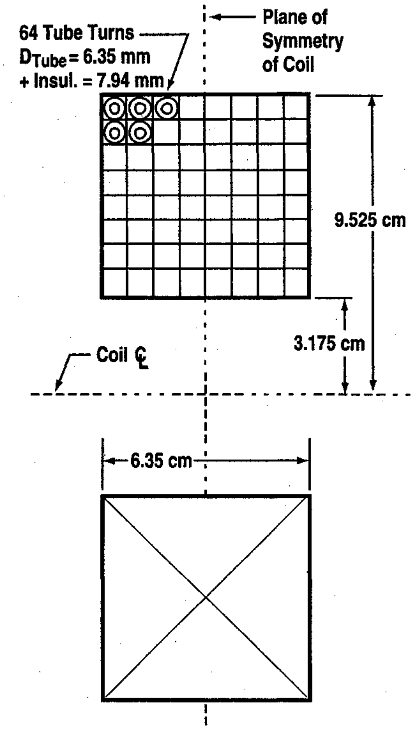

Fig. 3 Coil cross section for configuration of Ref. 3.

tachment spots. However, the gas swirl force is small near the base of the boundary layer on the electrode wall and is also generally small during the initial startup pressurization of the arc heater. To provide a positive rotation force on the base of the arc spoke at all times, magnetic spin coils are usually located in close proximity to the electrode rings. The arc spoke is that part of the arc that lies between the attachment spot on an electrode and the central arc column lying on or near the heater axis. It is shown in idealized form, normal to the electrode surface, in Fig. 2a. In actual operation, however, the arc spoke is inclined at some angle to the surface (Fig. 2b). The magnitude and direction of the localized magnetic field produced by the coil is critical to the development of the necessary Lorentz force on the arc spoke. The objective of this article is to document the rationale for determining the magnitude and direction of these fields and to demonstrate how the applied magnetic field enters into geometric scaling.

Characteristics of the Magnetic Field Produced by Spin Coils

The spin coils are typically formed from water-cooled copper tubes, wires, or ribbons located inside the water-cooled electrode ring assembly[1-3] (see Figs. 2 and 3). The coils are usually connected in series with the main arc discharge; however, excitation by an independent power supply is an alternative. There are relatively few conductor loops in a typical coil, and frequently the total coil may be subdivided into three or four subsets so that the coil can be reconfigured easily.

A right-hand cylindrical coordinate system (r, θ, z) is established with its origin on the heater axis somewhere near the upstream electrode, with the z axis on the heater axis and directed in the downstream direction (Fig. 2a). The coordinate θ is positive in a clockwise direction looking downstream along the z axis. The radial coordinate is measured positive outward from the z axis. In Fig. 2a, the upstream electrode is shown as the anode (positive electrode).

Magnetic field strength measurements are available in Ref. 3 for the specific coil geometry shown in Fig. 3. The 64-turn coil carried 200 A of current during the experiment. The calculated B_z is shown vertically in Fig. 4a as a function of radial position within 6.35-cm-diam of the coil bore and as a function of axial position over ± 15 cm distance from the coil plane of symmetry. The axial component is, of course, strongest at the coil midplane and shows a modest increase as the coil surface is approached. This increase is not more pronounced because the coil is large compared to the size of the aperture. The localized nature of the field is demonstrated by the fact that B_z at the edges of the coil width is only 65% of the midplane value, 30% at one additional coil width, and 14% at two additional coil widths.

The component B_r is shown in Fig. 4b for the same axial and radial locations as in Fig. 4a. The radial component is seen to be considerably smaller in magnitude than the axial component. The peak value, which occurs just past the edges of the coil width, is only 22% of the peak value of B_z. The radial component is zero on the heater centerline and maximum at the coil surface. It changes sign at the coil midplane, forming two lobes of different direction on either side of the plane of symmetry, a point that will be discussed later.

Effects of an Externally Applied Field on an Arc Spoke

The Lorentz force (per unit volume) on an element of current density in the presence of a magnetic field can be written in the previously specified coordinate system as

$$\bar{F}_L = \bar{J} \times \bar{B} = (J_\theta B_z - JzB_\theta)\bar{i}_r + (J_z B_r - J_r B_z)\bar{i}_\theta + (J_r B_\theta - J_\theta B_r)\bar{i}_z \tag{1}$$

For nearly all arc heaters, the coils used to produce the external magnetic field are of the classical short-solenoid type, discussed in the previous section. As noted, the coils are generally mounted coaxially with the arc heater axis, providing a strong axial magnetic field near the center of the coil and a weaker radial field off the axis. The component B_θ is negligible, thus the Lorentz force vector components developed on the arc spoke inside the spin field are reduced to four terms:

$$F_r = J_\theta B_z \tag{2}$$

$$F_\theta = J_z B_r - J_r B_z \tag{3}$$

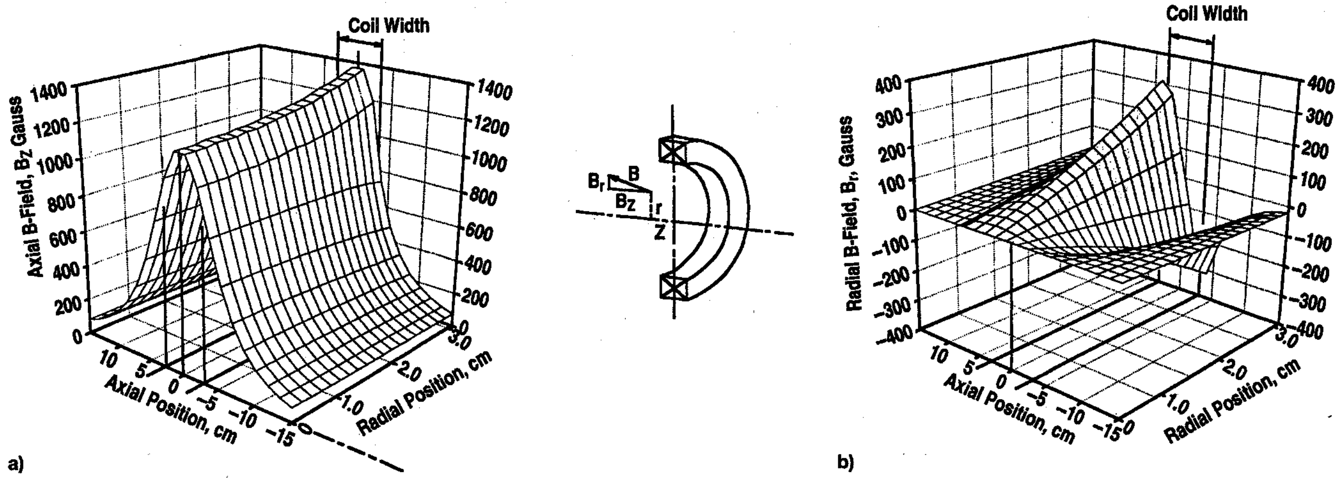

Fig. 4 Distribution for coil of Fig. 2, 200 A: a) axial and b) radial B fields.

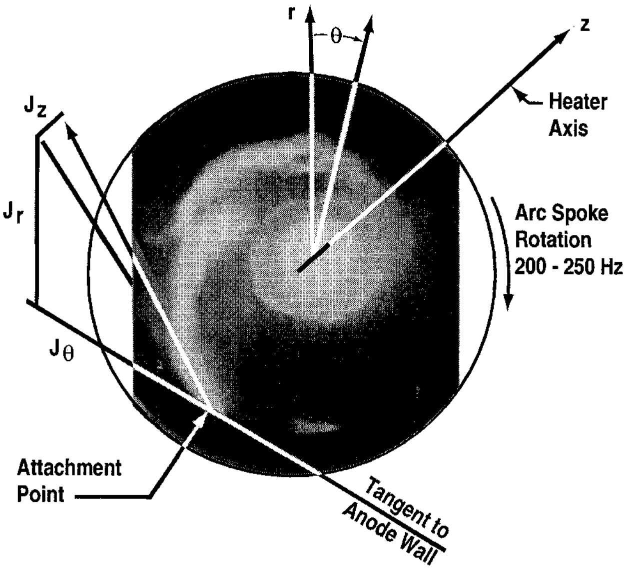

Fig. 5 Photograph of arc spoke rotating on anode surface.

$$F_{ez} = -J_\theta B_r \tag{4}$$

The current density components depend on the angular orientation of the arc spoke. The arc spoke shown normal to the electrode surface in Fig. 2a is highly idealized. High-speed motion photographs taken of the inside of the anode section of an arc heater[4] have shown the arc foot to be strongly inclined in the direction of the gas swirl (Fig. 5). The largest component of current is usually the component J_θ in the direction of gas swirl. Both upstream and downstream inclinations of the arc foot have also been observed, so that both ± values of J_z occur, depending on the circumstances. The component J_r is negative at the anode and positive at the cathode.

Polarity of the Spin Fields

Since the purpose of the magnetic fields is primarily to produce a tangential or azimuthal Lorentz force component in a desired ± direction (usually the swirl direction), the polarity of these fields must be selected appropriately. The direction of the azimuthal component of Lorentz force can be assessed by evaluating only the second term on the right side of Eq. (3), $F_\theta \sim -J_r B_z$, since B_z is much larger than B_r for typical spin coil fields (Figs. 4a and 4b). Since J_r is negative at the anode and positive at the cathode, B_z must also be of a different sign at the anode and cathode for the F_θ to be of the same sign at the two electrodes. In particular, a positive F_θ requires a positive B_z at the anode and a negative B_z at the cathode, or likewise a negative F_θ requires a negative B_z at the anode and a positive B_z at the cathode. These requirements are independent of the electrode polarity on the arc heater.

The magnetic field polarity of a coil is determined solely by the direction of current flow through the coil, and the familiar right-hand rule establishes that a positive B_z is produced by a clockwise current (looking downstream) in the coil, and vice versa for a negative B_z. By combining these concepts, the simple rule is established that a positive F_θ is produced by establishing anode coil current flow in the same positive θ direction and by reversing the current flow at the cathode.

Characteristics of the Lorentz Force Components

Azimuthal Force

The total F_θ is the sum of two factors [Eq. (3)]. Assessment of high-speed motion pictures of the arc spoke in the anode region indicates the spoke angular orientation and the axial location are such that the two components of F_θ are usually additive. Examples of how the tangential force components $J_z B_r$ and $-J_r B_z$ combine are shown in Figs. 6a and 7a. In both figures, the upstream electrode shown is the anode and the externally applied magnetic field direction is downstream relative to the electrode axis. This polarity produces a radially inward (negative) magnetic field component at the electrode wall upstream of the coil centerline and a radially outward (positive) field at the wall downstream of the coil centerline. The arc does not attach to the wall at exactly the coil centerline. If the natural arc column length is longer than the interelectrode distance (Fig. 6), the attachment spot on the upstream electrode is upstream of the coil midplane (and downstream of the midplane at the downstream electrode). The arc path will first turn upstream from the wall, then reverse direction downstream through the center of the coil near the electrode axis. If the arc column is shorter than the interelectrode distance (Fig. 7), the attachment point on the upstream electrode is downstream of the coil midplane (and upstream of the midplane at the downstream electrode). The arc path will immediately turn downstream from the wall as it approaches the arc heater centerline. For the two examples shown, both tangential Lorentz force components, $J_z B_r$ and $-J_r B_z$, on the arc spoke add, and both are clockwise looking downstream. The tangential force augments rotation of the foot of the arc spoke on the electrode if the tangential force is oriented in the same direction as the gas swirl, and it is the primary reason that most arc heaters utilize an externally applied magnetic field. In addition to axial and radial components of current, the arc spoke that attaches to the electrode has been observed to have a large azimuthal current component. This azimuthal component of the arc current occurs because the strong gas swirl dominates

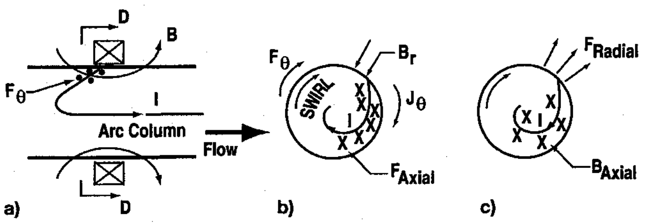

Fig. 6 Vector relations at anode, arc length longer than optimum: a) anode/coil cross section; b) view *D–D*, axial force toward coil; and c) view *D–D*, radial force outward.

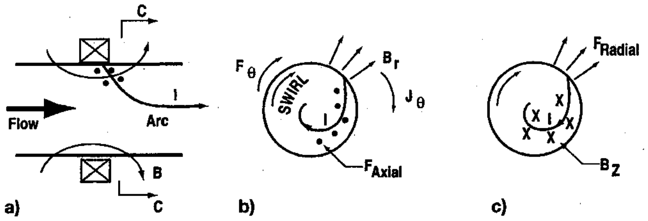

Fig. 7 Vector relations at anode, arc length shorter than optimum: a) anode/coil cross section; b) view *C–C*, axial force toward coil; and c) view *C–C*, radial force outward.

the shape of the arc spoke in the electrode region. The gas swirl pushes the arc column into a helical spiral as shown in Figs. 6b and 7b. The component J_θ produces both axial and radial Lorentz force components [Eqs. (2) and (4)].

Axial Force

The gas swirl and F_θ are oriented in the same direction in the examples of Figs. 6 and 7 (clockwise looking downstream), but the direction of the axial force component produced, $F_z = -J_\theta B_r$, depends upon the axial location of the arc foot relative to the coil plane of symmetry. If the arc attachment point is upstream of the coil midplane (Fig. 6), the radial component of the magnetic field is directed inward, and the resultant axial force is directed downstream toward the coil centerline. Conversely, if the arc attachment point is downstream of the coil midplane (Fig. 7), the radial component of the magnetic field is directed outward, and the resultant axial force is directed upstream toward the coil centerline. Thus, the direction of the axial force is such as to push the arc foot toward the plane of symmetry of the coil from either side. Attachment on the electrode does not generally occur at the coil midplane ($F_z = 0$), because the aerodynamic forces on the arc spoke can only be balanced at a location where the Lorentz force is nonzero.

Equation (4) demonstrates that, except for the gradual reduction in J_θ away from the electrode wall, the axial Lorentz force should be distributed spatially very similarly to the two-lobe distribution of B_r in Fig. 3b. From this figure it is inferred that the axial force is maximum at the electrode wall and near the edges of the coil width, falling off in all directions from this peak, i.e., both toward and away from the coil plane of symmetry and toward the axis, $r = 0$. Thus, for a given electrode coil, there are two semitoroidal zones of strong axial force, indicated in Fig. 8. There is a tendency for the arc foot to be trapped at some location between these two zones near the wall. Only when a disturbing aerodynamic force exceeds the peak F_z near the wall will the arc spot and foot of the spoke move away from the coil past the peak, qualitatively similar to escape from a potential well. Once past this point, however, the arc spot is free to move to the limit of the electrode conducting surface (Fig. 8). At inner radii, the axial Lorentz forces are smaller and the arc foot fairly easily moves out of the peak F_z zone. (The foregoing is true for all cases in which the Lorentz force reinforces the gas swirl. There are exceptional cases in which axial Lorentz forces are purposely directed away from the plane of coil symmetry, and are thus destabilizing to the arc spot.)

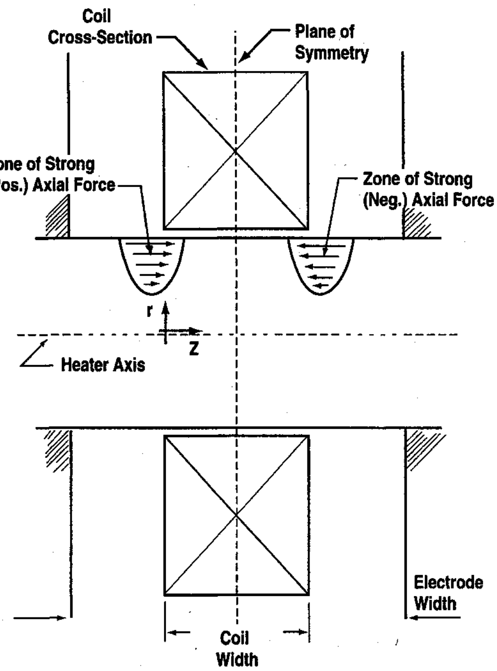

Fig. 8 Axial Lorentz force on arc foot.

Radial Force

Finally, the radial force, $F_r = J_\theta B_z$, is directed outward toward the wall, regardless of the axial position of the arc attachment point (see Figs. 6c and 7c), as long as the gas swirl and tangential Lorentz force are in the same direction. This radial force toward the wall is reinforced by the gas swirl and the resulting helical spiral of the arc, which produces a self-induced magnetic field in the axial direction having the same sense as the externally applied magnetic field. The inclination of the arc spoke relative to the electrode surface has been observed to fluctuate substantially during operation. Resulting changes in J_θ produce associated fluctuations in both F_z and F_r, which contribute to the instability of the arc attachment location.

Lorentz Force Effects Resulting from the Spin Coil Field

The direction of the component Lorentz forces produced by spin coils may be determined for any configuration by using diagrams similar to those shown in Figs. 6 and 7. The electrode may be either an anode or a cathode, and the direction of the externally applied axial magnetic field may be downstream (positive) or upstream (negative). The gas swirl may be positive (in the clockwise, positive θ, direction) or negative (in the counterclockwise, negative θ, direction). The arc heater polarity may be straight (cathode upstream) or reverse (anode upstream).

General Observations of Directional Relationships

The following observations can be made for various configurations:

1) For the case in which aerodynamic swirl forces dominate the Lorentz forces (vortex-stabilized arc heaters), the arc spoke is always inclined in the direction of gas swirl, with the arc spot on the electrode trailing the arc spoke. In this case, the Lorentz force/swirl relationship has two possible and different states:

Enhanced

This occurs when the triple product (±electrode) (±B field) (±swirl) is positive. For this case 1) azimuthal Lorentz force and gas swirl are in the same direction, 2) axial Lorentz force is directed toward the symmetry plane of the coil, and 3) radial Lorentz force is toward the wall (positive r direction).

Opposed

This occurs when the (±electrode) (±B field) (±swirl) product is negative. In this case 1) azimuthal Lorentz force and gas swirl are in opposite directions, 2) axial Lorentz force is directed away from the center of the coil, and 3) radial Lorentz force is directed away from the wall (negative r direction).

2) If any two of the parameters in the previous triple product change sign, the Lorentz force/swirl state remains unchanged. But if only one (or all three) of the parameters changes sign, the Lorentz force/swirl state is reversed, enhanced-to-opposed, or vice versa.

3) Although it is not the usual situation, it is possible for the gas swirl to be diminished to the point that the Lorentz force dominates. In such a case, the arc spot on the electrode will lead the arc column in the direction of the tangential or azimuthal Lorentz force. When this occurs, both enhanced and opposed states as determined in observation 1 are still possible, but only with respect to the tangential Lorentz force. The axial and radial Lorentz force directions are always characteristic of the opposed state, i.e., both the coil and the electrode wall appear to repel the arc.

4) The arc heater polarity (straight or reverse) does not seem to affect the previous conclusions, although the axial location of the arc foot relative to the electrode/coil centerline may be affected by the axial gas flow velocity and direction.

Benefits Derived from Application of Spin Coil Fields

There are a number of beneficial effects resulting from the application of an external magnetic field at or near the electrodes.

Augmentation of Arc Rotation on the Electrode Wall

Rotation of the arc attachment point on the electrode is necessary to prevent burnout and minimize the erosion rate. To improve rotation of the arc, the coil magnetic field direction is oriented to produce a tangential Lorentz force in the same direction as the gas swirl. For arc heaters using a vacuum-starting technique, the externally applied magnetic field induces arc rotation before gas is introduced into the arc heater.

Axial Positioning of the Arc on the Electrode Wall

If the Lorentz force augments the gas swirl, the arc foot is attracted to the coil. This axial Lorentz force is weak compared to the rotational (tangential) force, because the radial component of the magnetic field is weak compared to the axial component. The radial Lorentz force may also have a relatively strong impact on the axial positioning of the arc. A radially outward force on the arc will push it to the wall, and has the same effect as the coil repelling the arc axially. The radial force may be relatively strong because of the strong axial component of the magnetic field. This effect, coupled with the tangential force of the gas swirl and the self-induced axial magnetic field produced by the helical arc path as it approaches the electrode wall, all enhance the tendency to drive the arc toward the wall and away from the coil centerline. This action can be detrimental if the electrode width is short, thereby allowing the arc to attach to components adjacent to the electrode where the arc cannot be tolerated.

Prevention of Blown Arc

In Huels-type arc heaters, long, continuous tubular elements perform the functions of both electrodes and heater bore.[1] The arc does not have a fixed length, but seeks an equilibrium length resulting from the combined aerodynamic and electromagnetic forces. In such arc heaters there is a tendency at high pressure for the arc to be blown past the downstream electrode and through the nozzle throat, finally attaching to the downstream nozzle face. To reduce this tendency, a solenoid coil is often positioned near the downstream end of the electrode. If the magnetic field direction is configured to produce an azimuthal Lorentz force that opposes the gas swirl, the arc rotation rate is reduced and the coil repels the arc axially. This technique has been used successfully in several arc heater installations to reduce blowing of the arc.

Scaling of the Magnetic Field with Heater Size

A proposed change in the size of an arc heater raises the issue of the proper scaling of the magnetic field strength of the spin coils. A proper behavior of the arc foot involves not only the rate of rotation of the arc spot, but also the axial positioning and angular orientation. The detailed interaction of the Lorentz force and rotating fluid flow is so complicated that securing a satisfactory operating state of the arc foot is as much art as science. In scaling to a different size at the same operating condition, the Lorentz force need only remain the same relative to other forces in the flow. The scale is defined by a β-fold change in all linear dimensions (i.e., $\beta = L_2/L_1$, D_{b2}/D_{b1}, or D_2^*/D_1^*), and the operating condition is defined by a constant reservoir pressure and enthalpy at all scales. With the scaling so defined, both the mass flow and gas thermal power will vary directly as β^2.

Forces on the Arc Spoke

The balance of forces at any point in a fluid flow is expressed by the vector differential equation of momentum:

$$\rho \frac{D\bar{v}}{Dt} = -\nabla P + \mu\Delta^2\bar{u} + \bar{J} \times \bar{B}$$

The forces represented by the various terms are expressed in the following word equation. The dependence of the terms on β is noted below each term:

$$\underset{(1/\beta)}{\text{inertia force}} = -\underset{(1/\beta)}{\text{pressure force}} + \underset{(1/\beta^2)}{\text{viscous force}} + \underset{[J(\beta)\times B(\beta)]}{\text{Lorentz force}} \quad (5)$$

The inertia force is the kinematic response of the fluid element at a given point to the vector sum of the three forces on the right, all per unit volume. The viscous force is negligible outside the boundary layer, the Lorentz force is zero outside the arc column, but some component of the pressure force is present everywhere.

Excluding the boundary layer, a plausible expression of Lorentz force similarity in scaled flows is that the Lorentz force at any point inside the arc retain the same relation to the inertia force at a neighboring point just outside the discharge for all values of β. Since the forces are not generally aligned, the constraint must be expressed in terms of absolute magnitudes of the vectors:

$$JB \bigg/ \rho \frac{Dv}{Dt} = JB \bigg/ \rho v \frac{dv}{ds} = \text{const} \quad (6)$$

A geometric scaling will be considered so that the arc heater total pressure and enthalpy are held constant. This determines that ρ, ν, and $d\nu$ are constant at corresponding points in the scaled flows, so that the inertia force will vary inversely with the scale, as indicated in Eq. (5). The Lorentz force must also be adjusted to vary inversely with scale, i.e., $JB \sim 1/\beta$, or

$$JBL = \text{const} \quad (7)$$

J is neither controlled nor directly measured in any arc heater operation, however, its dependence on scale can be inferred in the following manner. Data correlation and scaling relations have recently been reported for high-performance, segmented arc heaters.[5] These correlations were developed using the principles of dimensional analysis. To adequately develop the nondimensional variables, a simple slug model for the arc was assumed. This model consists of an imaginary cylinder representing D_a (less than D_b) and temperature T_{arc} (greater than the average gas temperature) through which the current is assumed to flow. Integrations are performed over the bore cross section to ensure that the conservation of energy and mass are satisfied.[5] While this model may not predict the true absolute value of the current density, it should predict the dependence of current density on scale.

The correlation equations developed in Ref. 5 were used to predict operating conditions for arc heaters of three different characteristic length scales (β = 1, 2, and 3). Selected results, referenced to the β = 1 scale, are shown in Table 1. The correlations were developed from experimental data from β = 1 and 2 scale heaters and compared with initial data from a β = 3 heater.[5] The following are observed:

1) The current increases with scale at approximately the $\beta^{0.9}$ rate.

2) The diameter of the arc slug increases nearly linearly with scale.

3) T_{arc} decreases with scale so that the electrical conductivity varies inversely with scale. These results are used to compute J (shown in the last line of Table 1), which is found to vary as $\beta^{-1.1}$. When this scaling dependence for J is applied to Eq. (7), along with the fact that the scaling of $L = \beta$, it follows that B must be varied like $\beta^{0.1}$ for the Lorentz force to be the same at different scales. Therefore,

$$B_2/B_1 \sim \beta^{0.1} \tag{8}$$

This analysis indicates that the applied magnetic field is nearly independent of scale.

Required Magnitude of the Magnetic Field

An attempt was made to estimate the minimum external B field that could influence the electrode arc attachment. The SWIRLARC code[6] was used to make this estimate. It was reasoned that the Lorentz force on the arc spoke, obtained from an applied external B field and the arc current, had to be of the same order of magnitude as the dominant fluid dynamic terms in the axial and radial momentum equations obtained from the SWIRLARC code, specifically, the pressure gradient terms. The code was run at conditions typical of an arc heater with a 5-cm-diam bore operating at a nominal 1000 A with a pressure of 10 MPa and an enthalpy of 5.8 MJ/kg. The θ component of current was assumed to vary from 35 to 100% of the total. Within the framework of these assumptions, values of the external B-field components were calculated: B_z = 250 G and B_r = 75 G. These values represent the lower threshold of influence of the magnetic field on the arc attachment. The actual values required are usually determined by operating experience.

Table 1 Segmented arc heater scaling for β = 1, 2, and 3

β	1	2	3	Reference value, $\beta = 1$
L/L_{ref}	1	2	3	81.28 cm
$D_b/D_{b\,ref}$	1	2	3	2.54 cm
D^*/D^*_{ref}	1	2	3	1.143 cm
I/I_{ref}	1	1.88	2.61	701 A
R/R_{ref}	1	0.96	1.007	15.1 Ω
D_a/D_b	0.983	0.986	0.988	——
T_{arc}/T_{ref}	1	0.922	0.874	6953 K
σ_{av}/σ_{ref}	1	0.519	0.33	106 $(\Omega\ \mathrm{m})^{-1}$
J/J_{ref}	1	0.467	0.287	——

Summary

A rationale for predicting the effect of an externally applied magnetic field at the electrodes of electric arc heaters is presented. High-speed motion pictures taken in the electrode region of arc heaters have shown the arc spokes are strongly inclined in the direction of the gas swirl used to stabilize the arc near the central axis of the heater. Thus, the current vector has a significant azimuthal component in the vicinity of the electrodes and this fact has a strong bearing on the Lorentz force/arc spoke interactions.

In swirl-dominated arc heaters, there are only two possible states of the Lorentz force/arc spoke interaction at an electrode. The interaction state is determined by a combination of three properties: 1) type of electrode (anode or cathode), 2) polarity of the B field, and 3) direction of the gas swirl. A preferred, or enhanced state in which the azimuthal component of Lorentz force is in the same direction as gas spin, is always accompanied by an axial Lorentz force toward the planes of symmetry of the spin coil from each direction, and a radial force that is directed outward toward the electrode surface. A generally undesirable, or opposed, state in which the azimuthal Lorentz force is opposite the direction of gas swirl is always accompanied by an axial force directed away from the coil plane of symmetry in each direction, and a radial force in the inward direction away from electrode surface.

It is further observed that the polarity of the arc heater itself (anode upstream or downstream) has no effect on the Lorentz force/arc spoke interaction state. Benefits accruing from the spin coils are both the enhanced spin rate of the arc spot and the axial stabilization of the arc spoke. Analysis of the Lorentz and inertia force terms in the momentum equation has shown that the magnetic field strength of the spin coils is only weakly dependent on scale.

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