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THE GASDYNAMIC AND ELECTROMAGNETIC FACTORS AFFECTING THE POSITION OF ARC ROOTS IN A TUBULAR ARC HEATER*

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ABSTRACT: The gasdynamic and electromagnetic factors affecting the position of arc roots in a tubular arc heater are analyzed. Magnitudes of the various factors are estimated through numerical modelling, and the overall action on the arc assessed. It is found that the actions on the arc in the rear electrode can be balanced in a stable manner and the arc root can be stabilized at a certain axial position. In the front electrode, the various factors cannot be balanced, and the arc root can only stay within the electrode through the mechanism of recurrent shunting. These conclusions agree with experimental observations.

KEY WORDS: arc heater, arc stabilization, arc position

I. INTRODUCTION

The tubular arc heater is commonly used in industry for its high power, low electrode loss and long service life with a wide variety of reducing, neutral and oxidizing working gases. In order to improve the performance and facilitate the design of arc heaters, it is necessary to have better understanding of the basic processes occurring inside, especially those related to arc configuration and arc motion. Since the processes involve gaseous discharge, electromagnetics, flow with large temperature gradients and often covering both the laminar and turbulent regimes, it is difficult to make comprehensive and detailed studies of the phenomena inside the arc heater. Very few works have been published on the factors affecting the position of arc roots in a tubular arc heater[1,2], which is important to arc characteristics and electrode erosion. In this paper, various factors affecting arc motion, namely the gasdynamic, magnetic, electric and thermal actions, are analyzed, and their overall effect on the motion and stability of the arc root assessed. This work may help to elucidate the mechanism of arc positioning inside the tubular arc heater, and also to shed light on the factors affecting arc motion in general.

II. ARC MOTION AND "FORCE"

Arc is one form of gaseous discharge. Under normal pressures, the central region of the arc is characterized by temperatures of about $(1\sim3)\times10^4$ K, and is surrounded by cooler gases. The temperature varies continuously, and thus the determination of the position and shape of the arc is somewhat arbitrary. It is common to define the arc as the electrically conducting region, and describe the motion of the arc by the motion of this region. For instance, the point of maximum conductivity can be regarded as the center of the arc, and the point where the conductivity drops to 1/2 of the maximum value is the arc boundary. Motion of the arc is the motion of the line of maximum electric conductivity within the arc column. From the above discussion, it can be seen that electric arc is described by "fields" (current, conductivity or temperature), and arc motion is the motion of these fields. Arc column is the chief characterizing portion of these fields.

When the arc moves, the physical particles inside the arc may or may not move

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synchronously with the arc. In certain cases, they may even move in a direction opposite to that of the arc. However, the current or conductivity fields exist because of the state of particles inside the arc. The state and motion of these particles at one instant will determine where the electrically conducting region will be at the next instant, thus determining the direction and velocity of arc motion. Therefore, the motion of the arc can be analyzed through the study of the state and motion of the particles within the arc.

For a physical body, motion is always related to forces acting on it. But an electric arc does not necessarily move as a physical body. There are many factors which will cause the change in the position of the conducting region. In order to be able to compare the magnitudes of various factors causing the motion of the arc, a unified basis of comparison must be adopted. Here we try to name the various factors as "forces", and use the dimension of force to describe the magnitude of these actions.

Sometimes, such an action can indeed be identified directly with a force. For instance, at high densities where collision of particles is frequent, action of gas blowing and magnetic field across the arc can be described quite well by forces on the arc column. In Ref.[3], experiments are described in which arc in cross flow is balanced by the action of a cross magnetic field in a perpendicular direction. The forces here are the usual gasdynamic force and the Lorentz force. However, under other circumstances, the concept may not be so simple, and each factor must be analyzed in more detail.

On the whole, the motion of the arc is affected by the electrodynamic, external magnetic, gasdynamic and thermophysical factors, and also can be affected by the material of the electrodes and the process of electric breakdown in gas. These will be analyzed in the following sections.

III. THE ELECTRODYNAMIC ACTION

The electrodynamic action mentioned here refers to the electromagnetic action acting on the arc without external electric or magnetic field being present. We found that there are two parts in this action: one is due to the interaction of the arc current with the magnetic field it produces, and the other is due to the uneven Joule heating in the arc. The latter may be caused by uneven electric field strength over an arc cross section, and may cause the arc motion through the nonsymmetrical temperature distribution in the arc. This will be discussed later together with the thermophysical factor. Here only the self-magnetic field of the arc current will be discussed.

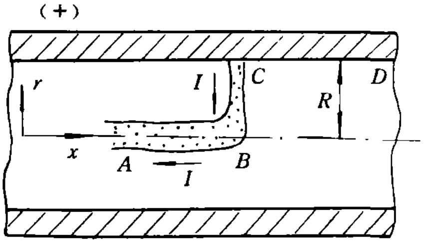


Fig. 1 Assumed shape of arc in the tubular arc heater
$\overline{AB}=L_a$ $\overline{CD}=L_d$

The magnetic field at a point in space produced by a current carrying conductor can be calculated by the Biot-Savart law. In a tubular arc heater, the arc can be seen as having a shape as shown in Fig.1. Attention is focused on the radial portion of the arc.

At a point on BC at radius r, the magnetic field is

$$\boldsymbol{B}=\boldsymbol{B}_a+\boldsymbol{B}_d=\frac{\mu_0 I}{4\pi r}\ \frac{L_a}{(r^2+L_a^2)^{1/2}}\cdot(-\boldsymbol{e}_z)+\boldsymbol{B}_d$$

where $\boldsymbol{B}_a$ is magnetic field due to the current in the arc column, $\boldsymbol{B}_d$ is magnetic field due to current in the electrode, and μ_0 is the permeability constant $(4\times10^{-7}\ \mathrm{WbA^{-1}m^{-1}})$. The magnitude of $\boldsymbol{B}_d$ depends on the current distribution in the electrode, and can be expressed by

$$\boldsymbol{B}_d=\frac{\mu_0 I}{4\pi(R-r)}\cdot\frac{L_d}{[(R-r)^2+L_d^2]^{1/2}}\cdot(\boldsymbol{e}_z)\cdot k_B$$

where k_B is a factor less than 1. Then the expression for $\boldsymbol{B}$ becomes

$$\boldsymbol{B}=\frac{\mu_0 I}{4\pi}\left\{\frac{k_B}{(R-r)}\cdot\frac{L_d}{[(R-r)^2+L_d^2]^{1/2}}-\frac{L_a}{r[r^2+L_a^2]^{1/2}}\right\}\cdot(\boldsymbol{e}_z)$$

The force acting on a section dr of the radial portion of the arc is

$$d\boldsymbol{F}_c = -I d\boldsymbol{r}\times \boldsymbol{B} = d\boldsymbol{F}_a + d\boldsymbol{F}_d = \frac{\mu_0 I^2}{4\pi}\left\{\frac{L_a}{r(r^2+L_a^2)^{1/2}} - \frac{k_B}{(R-r)}\cdot\frac{L_d}{[(R-r)^2+L_d^2]^{1/2}}\right\}\cdot \boldsymbol{e}_x(dr)$$

The two parts are the forces due to the arc column and the current in the electrode respectively. Consider a small section near the arc root. Since $R>>\Delta r$, $r\doteq R$, $L_d>>\Delta r$, $L_a>>R$, we have

$$\Delta \boldsymbol{F}_c = \frac{\mu_0 I^2}{4\pi}\left[\frac{\Delta r}{R} - k_B\right]\boldsymbol{e}_x$$

This is the axial force on the arc near its root due to the self-magnetic field of the arc current.

IV. ACTION DUE TO EXTERNAL MAGNETIC FIELD

External magnetic fields are often employed in the tubular arc heaters to rotate the arc so that the arc root moves rapidly over the electrode surface, thus reducing the erosion rate. In the past, interaction of magnetic field with the arc has been studied mainly with the assumption that the arc behaves like a current-carrying conductor. Such methods may explain the arc rotation, but cannot explain the axial action on the arc due to the magnetic field. Since the magnetic field acts on the arc through its interaction with the charged particles in the arc, the detailed action must be analyzed by studying the motion of the charged particles in the magnetic field.

1. Motion of Charged Particles in External Magnetic Field

The charged particle is acted upon by the electric field in the arc with a force $\boldsymbol{F}_E = q\boldsymbol{E}$, where q is the charge of the particle and $\boldsymbol{E}$ the electric field strength. Immediately after a collision, if the particle has velocity $\boldsymbol{V}_0$, then the velocity it reaches just before the next collision, $\boldsymbol{V}_c$, will be

$$\boldsymbol{V}_c = \boldsymbol{V}_0 + \frac{q}{m}\cdot\frac{1}{\nu_c}\cdot \boldsymbol{E}$$

where m is the particle mass and ν_c the collision frequency. For electrons in an arc column at atmospheric pressure, if $\nu_c = 2\times 10^{10}$/s, $E = (10^3 \sim 10^4)$ V/m, then the directional velocity acquired by the electron will be $\frac{qE}{m_e \nu_c} \doteq 8.84E = 8.84\,(10^3\sim 10^4)$m/s. The average thermal velocity of the electron is (taking $T_e = 10^4$K)

$$V_{te} = \left(\frac{3kT_e}{m_e}\right)^{1/2} = 6.74\times 10^5\,\text{m/s}$$

Thus the thermal velocity of the electron is much higher than the directional velocity along the electric field.

The equation of motion of the charged particle is

$$\boldsymbol{F} = m\boldsymbol{a} = m\frac{d\boldsymbol{V}}{dt} = q(\boldsymbol{E} + \boldsymbol{V}\times\boldsymbol{B}) \qquad \boldsymbol{V} = \boldsymbol{V}_0 + \boldsymbol{V}_p$$

where $\boldsymbol{V}_p$ is the additional velocity acquired by the particle through the action of the electric and magnetic fields. Writing

$$\boldsymbol{V}_p = u\boldsymbol{e}_x + v\boldsymbol{e}_r + w\boldsymbol{e}_\theta \qquad \boldsymbol{B} = B_x\boldsymbol{e}_x + B_r\boldsymbol{e}_r + B_\theta\boldsymbol{e}_\theta$$

we have

$$\frac{d\boldsymbol{V}_p}{dt} = \frac{q}{m}[\boldsymbol{V}_0\times\boldsymbol{B} + \boldsymbol{V}_p\times\boldsymbol{B} + \boldsymbol{E}] = \frac{q}{m}(\boldsymbol{V}_0\times\boldsymbol{B} + \boldsymbol{E}) + \frac{q}{m}\begin{vmatrix} \boldsymbol{e}_x & \boldsymbol{e}_r & \boldsymbol{e}_\theta \\ u & v & w \\ B_x & B_r & B_\theta \end{vmatrix}$$

Along the radial portion of the arc, we have $E=Ee_r$, and $B_\theta=0$ due to the usual field configuration. Writing

$$a=a_x e_x+a_r e_r+a_\theta e_\theta=\frac{q}{m}\ V_0\times B$$

the equations of motion become

$$\frac{du}{dt}=a_x-q\,w\,B_r/m$$

$$\frac{dv}{dt}=a_r+q\,E/m+q\,w\,B_x/m$$

$$\frac{dw}{dt}=a_\theta+q\,(u\,B_r-vB_x)/m$$

In a tubular arc heater, we have $E\sim 10^4\,\mathrm{V/m}$, $w\sim 10^2\,\mathrm{m/s}$, $B_x\sim 0.1\mathrm{T}$, $B_x\sim B_r$, $v>>u$, so approximately $qE>>qwB_x$, $vB_x>>uB_r$. With these approximations, the equations can be integrated to give

$$v=a_r t+\frac{qE}{m}\ t$$

$$w=a_\theta t-\left(a_r+\frac{qE}{m}\right)\frac{qB_x}{2m}\ t^2$$

$$u=a_x t-\frac{qB_r}{2m}\,a_\theta t^2+\frac{q^2B_rB_x}{6m^2}\left(a_r+\frac{Eq}{m}\right)t^3$$

2. Force in Axial Direction on the Radial Portion of the Arc due to the External Magnetic Field

From the above equations, the total increase in momentum of all the charged particles in a portion of the arc during a time interval between collisions can be calculated, from which the "force" acting on the arc can be found. Considering the particle velocities are distributed according to a distribution function $f(v)$, the total increase in momentum per unit volume of the arc would be given by

$$M=M_e+M_i=m_e\int_{v_e} n_e f(v_e)u_e\,dv_e+m_i\int_{v_i} n_i f(v_i)u_i\,dv_i$$

where n is number density, and subscripts e and i refer to electrons and ions respectively.

By definition,

$$\int_v a f(v)\,dv=\frac{q}{m}\int_v (V_0\times B)f(v)dv=\frac{q}{m}\left[\int_v V_0\,f(v)dv\right]\times B$$

The integral within the bracket is the average velocity of all the particles at the initial instant,

$$\int_v V_0 f(v)dv=\overline{V}_0=\overline{u}_0\,e_x+\overline{v}_0\,e_r+\overline{w}_0\,e_\theta$$

When there is no external electric or magnetic field, the average velocity of the charged particle is zero. When electric and / or magnetic field are present, $\overline{V}_0$ represent the overall drift velocity of the electron as a group. Thus,

$$\int_v a_x f(v)dv=-\frac{q}{m}\cdot\overline{w}_0\,B_r$$

$$\int_v a_r f(v)\,dv=\frac{q}{m}\cdot\overline{w}_0\,B_x$$

$$\int_v a_\theta f(v)dv=\frac{q}{m}\left(\overline{u}_0\,B_r-\overline{v}_0B_x\right)$$

The momentum increase acquired by the electrons is

$$M_e=n_e m_e t_e\left\{-\frac{q_e}{m_e}\overline{w}_{0e}B_r+\frac{q_e^2 t_e}{2m_e^2}(\overline{v}_{0e}B_x-\overline{u}_{0e}B_r)+\frac{q_e^2 B_x B_r t_e^2}{6m_e^2}(\overline{w}_{0e}B_x+E)\frac{q_e}{m_e}\right\}$$

In arc plasmas under atmospheric pressure,

$$n_i\doteq n_e=n \qquad t_i\doteq t_e=\frac{1}{\nu_c} \qquad q_i=-q_e=e \qquad m_i>>m_e$$

Therefore $M_e>>M_i$ and $M=M_i+M_e\doteq M_e$. Furthermore, since the average drift velocities $\overline{u_0}$, $\overline{v}_0$, $\overline{w}_0$ are much smaller than the velocity produced by the electric field, qEt_c/m_e, the main terms in the above expression are those involving E. Thus, after neglecting the minor terms, the momentum increase in the axial direction is

$$M=-\frac{1}{6}\,\frac{ne^3}{\nu_c^3 m_e^2}\,B_x B_r E$$

If the cross sectional area of the arc is A, then the axial force per unit arc length is

$$F_m=-\frac{1}{6}\,Ane^3 B_x B_r E/(\nu_c^2 m_e^2)$$

From definition of the current

$$I=-Ane\overline{v}_e=Ane\left(\frac{eE}{m_e}\cdot\frac{t_c}{2}\right)=Ane^2\left(\frac{E}{2\nu_c m_e}\right)$$

we finally have

$$F_m=-\frac{1}{3}\,I\,\frac{e}{\nu_c m_e}\,B_x B_r=-\alpha I B_x B_r$$

where $\alpha=\frac{e}{3\nu_c m_e}$. Current I has different signs at the two electrodes. It takes negative sign at the anode, and positive sign at the cathode.

3. Action of External Magnetic Field on the Arc in a Tubular Arc Heater

In an arc configuration as shown in Fig. 2, the following cases may be discussed:

For the anode, we have

at $x<x_0$ $B_x>0$ $B_r<0$

at $x=x_0$ $B_x>0$ $B_r=0$

at $x>x_0$ $B_x>0$ $B_r>0$

With $I<0$ and from the expression of F_m, we see that the action of the magnetic field always tends to push the arc away from the center ($x=x_0$) of the magnetic field. For the cathode, $I>0$, we see that the magnetic field always tends to draw the arc toward the center of the field. If the direction of the field coil is reversed, the direction of the force will still be the same. These conclusions agree well with experimental observations.

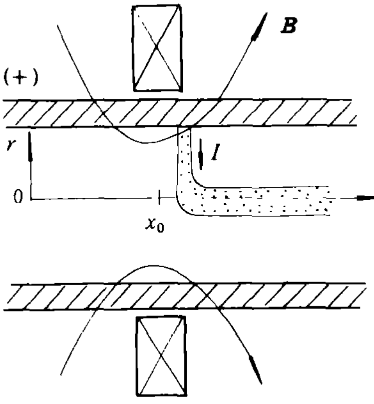


Fig. 2 Configuration of the arc and the magnetic field in the arc heater

V. THE EXTERNAL ELECTRIC FIELD

There is a voltage gradient within the arc column which is the driving force of the electron motion that forms the arc current. The electric field in space cannot penetrate into the arc column because the slightest charge separation within the arc plasma will cancel the external electric field so that there is no net field in the arc except that causing the current flow. Therefore the effect of external electric field on arc motion can be neglected. However, there are complicated phenomena in the cathode and anode sheath regions which are beyond the scope of this work.

VI. THE GASDYNAMIC ACTION

Under atmospheric pressure, the collision frequency among particles is high. The action of gas flow on the arc is mainly the collision among the gas particles with particles in the arc, which causes them to move in the direction of the gas flow. Many investigations have shown that under atmospheric or high pressure, the action of gas flow on the arc motion can be approximated by gas blowing on a solid cylinder. Of course, the arc is not a solid body, so the similarity exists in form only. The aerodynamic force acting on unit length of arc can be expressed as [3]

$$\boldsymbol{F}_g = \frac{1}{2} C_D \rho |\boldsymbol{u}_g| \cdot \boldsymbol{u}_g \cdot d$$

where C_D is drag coefficient, ρ is gas density, d is effective arc diameter, and $\boldsymbol{u}_g$ is the relative velocity between the gas and the arc. C_D and d are experimentally determined values, and empirical formulas exist for these parameters, respectively. Usually C_D lies between 0.6 and 1.2[5]. Since the determination of d is somewhat arbitrary, the absolute value of C_D is also not a rigorously determined one.

VII. THE THERMOPHYSICAL ACTION

The electric arc is a phenomenon combining electrical factor with thermal factor. Any thermophysical effects produced by the environment on the arc, such as heat conduction, convection and radiation or other forms of heat addition, will affect the state of the arc and its motion. From the literature[6], if there is uneven heating or cooling on the two sides of the arc, it will move towards the side where the temperature is higher. The velocity of arc motion can be expressed by

$$V_{am} = \frac{\frac{1}{\rho C_p}\left[\sigma \frac{\partial E^2}{\partial x} - \lambda \frac{\partial^3 T}{\partial x^3} - \frac{\partial e_{\mathrm{net}}}{\partial x}\right]}{-\left(\frac{\partial^2 T}{\partial x^2}\right)}$$

where the parameters are evaluated at the point of maximum temperature. The denominator is always positive since the point in question is a temperature maximum. In the numerator, the first term represents the effect of unevenness of Joule heating (caused by uneven electric field distribution). The second and third terms represent the effects of unevenness in conductive and radiative heat transfer respectively.

As we mentioned earlier, we try to express the action causing the motion of the arc in terms of a "force". We name the action connected with thermophysical factors the "thermophysical force", written as F_t. Let us assume that if there are equal and opposite gasdynamic and thermophysical effects on the arc motion such that the arc is stationary, then the velocity of arc motion which would have been produced by the thermophysical effect would be exactly the same in magnitude as the relative velocity between the arc and the gas stream. Thus the thermophysical "force" can be expressed as

$$\boldsymbol{F}_t = -\boldsymbol{F}_g = \frac{1}{2} C_D \rho | V_{am} | \cdot V_{am} \cdot d$$

VIII. CALCULATION OF THE FLOWFIELD PARAMETERS IN THE TUBULAR ARC HEATER

To estimate the various actions on the arc, it is necessary to know the velocity and temperature fields in the arc heater. In practical arc heaters, the flowfield is usually turbulent with a vortex stabilized arc in it. Experimental measurement is very difficult, and numerical computation seems to be a simpler way of getting some idea on the parameter distribution inside the heater. One particular model used to calculate the flowfield is briefly described below[4,7]:

With the usual assumptions, the basic equations of two-dimensional, axi-symmetric turbulent flow inside the heater with the K-ε turbulence model can be written as

$$\frac{1}{r}\left[\frac{\partial}{\partial x}(\rho u r\varphi)+\frac{\partial}{\partial r}(\rho v r\varphi)-\frac{\partial}{\partial x}\left(r\Gamma_\varphi\frac{\partial\varphi}{\partial x}\right)-\frac{\partial}{\partial r}\left(r\Gamma_\varphi\frac{\partial\varphi}{\partial r}\right)\right]=S_\varphi$$

Equation	φ	Γ_φ	S_φ
Continuity	1	0	0
Axial momentum	u	μ	$\frac{\partial p}{\partial x}+S_u$
Radial momentum	v	μ	$-\frac{\partial p}{\partial r}+\frac{\rho w^2}{r}-\frac{2uv}{r^2}+S_r$
Tangential momentum	w	μ	$-\frac{\rho v w}{r}-\frac{w}{r^2}-\frac{\partial(r\mu)}{\partial r}$
Turbulent energy	K	μ/σ_k	$G-\rho\varepsilon$
Turbulent energy dissipation	ε	μ/σ_ε	$(C_1\varepsilon G-C_2\varepsilon^2\rho)/K$
Energy	h	λ/C_p	$j^2/\sigma-e_{net}$

where h is enthalpy, C_p is specific heat at constant pressure, σ is electric conductivity, j is current density, e_{net} is net radiative heat flux, λ and μ are effective thermal conductivity and viscosity respectively,

$$\mu=\mu_l+\mu_t=\mu_l+C_\mu\rho K^2/\varepsilon$$

$$\lambda=\lambda_l+\lambda_t=\lambda_l+C_p\mu_t/\sigma_k$$

where μ_l and λ_l are the viscosity and thermal conductivity of the gas.

$$S_u=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial v}{\partial x}\right)$$

$$S_v=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial v}{\partial r}\right)$$

$$G=\mu\left[2\left\{\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial r}\right)^2+\left(\frac{v}{r}\right)^2\right\}+\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial w}{\partial x}\right)^2+\left\{r\frac{\partial\left(\frac{w}{r}\right)}{\partial r}\right\}^2\right]$$

The constants are $C_1=1.44$, $C_2=1.92$, $C_\mu=0.09$, $\sigma_k=\sigma_\varepsilon=\sigma_h=0.9$

The boundary conditions are:

at the entrance	$\varphi=\varphi_0$	
at the exit	$v=0$	$\partial\varphi/\partial x=0$
on the axis	$v=0$	$\partial\varphi/\partial r=0$
at the wall	$\varphi=0$	$q_w=\alpha(h-h_w)/C_p$

The electric current conservation condition is

$$I=\int_0^{R_c}\sigma E 2\pi r\,dr$$

$$j=\sigma E$$

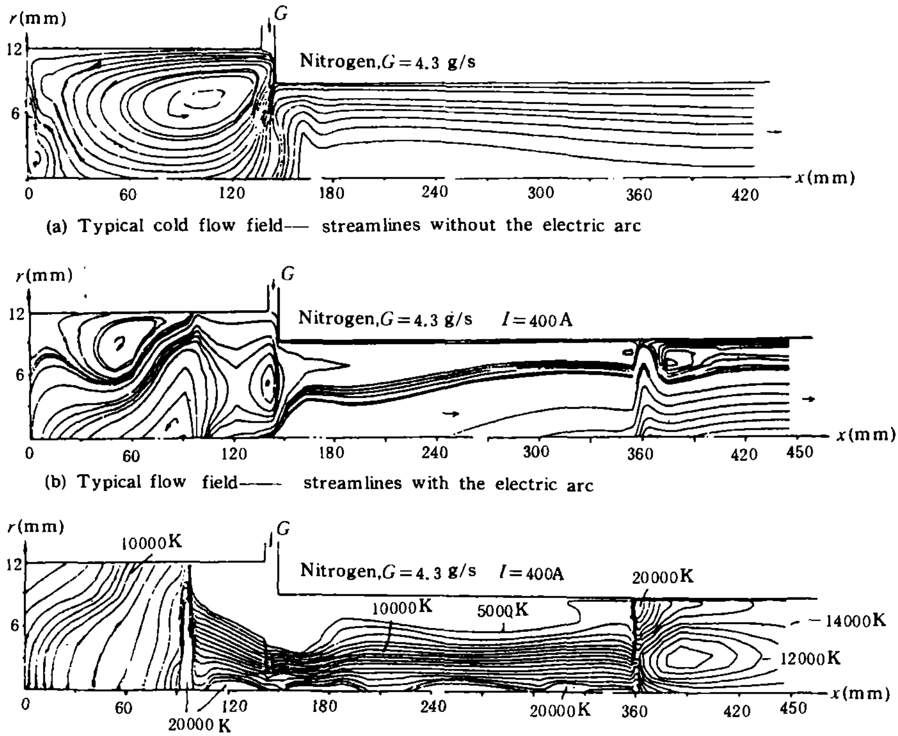
R_c is the radius of the arc column (characteristic radius of the electrically conducting region).

Due to difficulty in determining the position of the arc roots by computation, this is taken from the experiments. The radial portion of the arc is assumed to be axi-symmetrical (a disk) to facilitate computation. This assumption is a poor one, but we have to take it for the present.

With the above assumptions and system of equations, using known thermophysical properties of gases, the velocity and temperature fields in the arc heater can be calculated. Fig.3

shows one example of calculated results for one particular set of conditions.

Once the flowfield parameters are calculated, the magnitude of various factors affecting the motion of the arc can be estimated from the formulas given in the sections above.



(a) Typical cold flow field— streamlines without the electric arc

(b) Typical flow field—— streamlines with the electric arc

(c) Typical temerature field

Fig. 3 Example of computed velocity and temperature fields in a tubular arc heater

IX. EFFECT OF SHUNTING ON ARC MOTION

One important phenomenon which affects arc configuration and motion is shunting. During the operation of the arc heater, electric breakdown may occur between the arc column and the electrode wall, or between various portions of the arc column (See Fig. 4). The potential along the arc column varies from the cathode potential to the anode potential. But the electrode is an equipotential surface with its potential at that of one of the arc roots. Thus there exist potential differences between the electrode and various parts of the arc column. If this potential difference ΔU at any point exceeds the breakdown voltage for the gas layer needed at that point ΔU^*, then an electric breakdown will occur at that point and form a new current path. The arc will be "shunted" at this point and the arc motion will start anew from this configuration. The shunting phenomenon has been studied by many investigators before[8]. The value of ΔU^* depends on the gas temperature and flow structure, where high temperature, high turbulence and thin gas layer facilitate breakdown. The arc motion will be repeated in cycles, and this is one way by which the arc root stays within the tubular electrode of the heater.

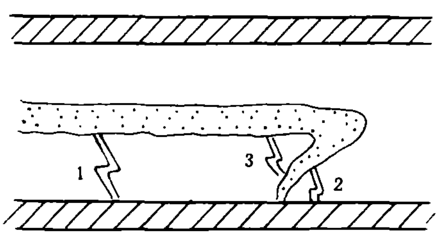


Fig. 4 Possible positions of electric breakdown in the arc heater

X. CRITERIA OF ARC STABILITY IN A LINEAR ARC HEATER

Here stability of the arc means that the arc can be operated steadily and continuously in the heater so that a basically steady stream of heated gas can be produced. It does not necessarily mean that the arc is stationary. In a linear arc heater with tubular electrodes, if the arc roots move within certain limited range along the axial direction or make oscillatory motion of certain frequency along the electrode without going beyond the exit of the heater, the arc is said to be stable.

For stable arc operation, the load characteristics of the power supply must be matched to the $U-I$ characteristics of the arc by satisfying the following relation:

$$-\left(\frac{\partial U}{\partial I}\right)_s > -\left(\frac{\partial U}{\partial I}\right)_a$$

where subscripts s and a refer to power supply and arc, respectively.

There are two ways in which the arc root can be stabilized in the electrodes of the tubular arc heater: The first type of arc stabilization occurs when the "forces" on the radial portion of the arc can be balanced in a stable manner. The overall action on the radial portion of the arc in the axial direction is $\boldsymbol{F}_x$, where

$$\boldsymbol{F}_x = \boldsymbol{F}_g + \boldsymbol{F}_m + \boldsymbol{F}_c + \boldsymbol{F}_t$$

If the arc root is located at $x = x_1$, then the arc would be stable in the x direction if in the neighborhood of x_1, $F_x = 0$ when $x = x_1$, and $F_x > 0$ when $(x_1 - \varepsilon) < x < x_1$ and $F_x < 0$ when $x_1 < x < (x_1 + \varepsilon)$. This means that the various actions on the arc are balanced in the x direction, and the arc will return to its original position if it is disturbed from that equilibrium position. Such conditions are the stability criterion of the first type.

Sometimes in a linear arc heater, stable operation is possible even when the action on the arc root cannot be balanced, but "shunting" occurs in such a way that the arc root oscillates within a limited range. If we define $\Delta U^*_{x,L}$ as the minimum breakdown voltage between the arc column and the electrode wall with the arc root located at the exit of the electrode, $x = L$, and ΔU_x as the actual voltage difference between the arc column and the electrode wall, then the arc heater can be stably operated if $F_x > 0$ and if at any point along the arc, $\Delta U_x > \Delta U^*_{x,L}$. This is a stability criterion of the second type.

XI. MECHANISM OF ARC STABILIZATION IN THE TUBULAR ARC HEATER

For a given arc heater under given operating conditions, the actions on the arc roots can be estimated from the formulas given above. From the axial distribution of the "forces", it can be analyzed as to whether conditions for stability of the first type exist. If not, then the possibility of stability of the second type will be investigated. An example of calculations for a typical operating condition of a tubular arc heater is shown in Fig. 5. The various actions and their sums are plotted along the axial direction. It can be seen that in the rear electrode, there is a point A where the stability criterion of the first type is satisfied. Thus, the rotating arc root may be stabilized at position A. It is interesting to note that point A appears in front of the center of the magnetic coil. This is exactly the case in experiments, where observation is made of the burning mark by the arc root inside the electrode.

In the front electrode, the "forces" cannot be balanced, as the gasdynamic effect is overwhelming. Here we have $F_x > 0$, so stable operation can only be achieved through the mechanism of shunting. In experiments, the burning mark left by the arc root is spread over a rather wide range axially. This is a typical case when shunting is present.

When the rear electrode is the cathode, experiments have shown that the arc roots move to the center of the magnetic field, and a narrow burning mark is left by the rotating arc. This also agrees very well with the analysis made above.

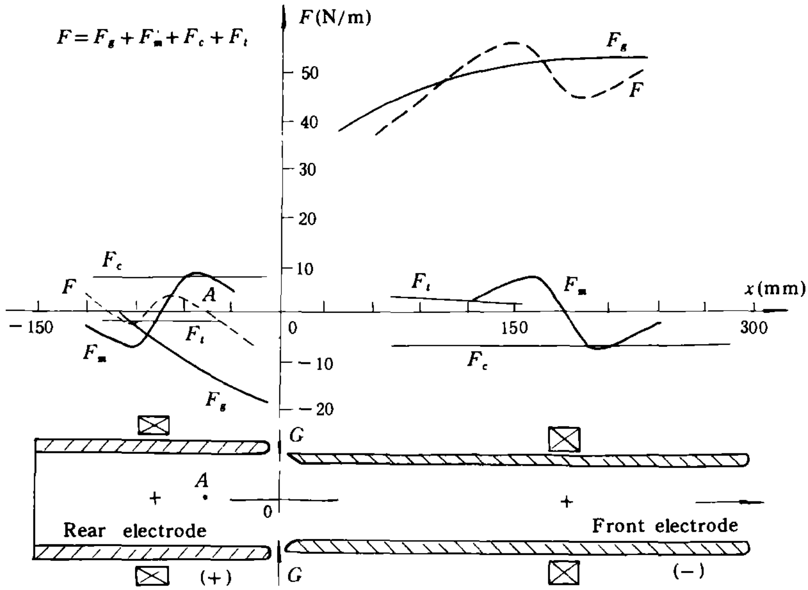


Fig. 5 Approximate magnitudes of various "forces" acting on the arc near the roots in a tubular arc heater $I=400\mathrm{A}$, $G=3\mathrm{g/s}$, N_2, $D=24\mathrm{mm}$, $d=18\mathrm{mm}$

XII. CONCLUSIONS

1. The motion of the electric arc in a tubular arc heater is mainly affected by the gasdynamic, external magnetic, electrodynamic and thermophysical factors, and also by the phenomenon of shunting. The magnitudes of these factors can be expressed as "forces".
2. The axial and radial components of the external magnetic field cause the rotation and axial motion of the radial portion of the arc column. At the cathode, the action of the magnetic field tends to move the arc to the center of the magnetic field. At the anode, the action is opposite, tending to move the arc away from the center of the magnetic field.
3. There are two possible types of stable operation of the arc. One occurs when the actions on the arc column is balanced in a stable manner. The other occurs when the actions cannot be balanced, but conditions are such that recurrent shunting can happen within the electrode.
4. In the present tubular arc heater, it is analyzed that in the rear electrode, the arc is stabilized by the first mechanism, that of balanced "forces", and in the front electrode, the arc can only be stabilized through the second mechanism, that of shunting. These agree well with experimental observations.

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