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Arc deflection model and arc direction control for DC arc furnace

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Abstract: Based on the analysis of three-dimensional power conductor for DC arc furnace, the electric arc deflection model was set up and the control system of the arc direction was configured. According to the bus bar distribution at the bottom electrodes cooled by water, the arc direction control principle and its configuration were described. The simulation results show that the control system can restrain the electric arc deflection and control the arc direction.

Key words: DC arc furnace; electric arc deflection model; arc direction control

1 Introduction

The arc deflection phenomenon of the DC arc furnace depends on the distribution situation of the electromagnetic field in the furnace. During the operation of the DC arc furnace, the DC current of conductor bus bars around the furnace body is about 10-100 kA. The current forms an electromagnetic field in the furnace, and the field is affected by the circumstance situation around the arc furnace and the complex composition in the furnace. Since the electromagnetic field continually varies and the arc direction depends on the magnetic force, the variation of the electromagnetic field in the electric arc area will influence a little movement of arc deflection. And the amount of arc deflection will be varied stronger or weaker by the electromagnetic force. Due to the phenomenon of electric arc deflection the measures usually taken is reasonably to arrange the current bus distribution at the bottom of the furnace or the special reactor used for restricting arc deflection. But the measures are usually taken during the stage of constructing the furnace. After the arc furnace operation, the arrangement of the bus bars is already fixed. If we want to solve the problem thoroughly, it is necessary that the arc direction should be freely controlled during the DC arc furnace operation [1]. The control method is described in this paper, *i.e.* the arc direction can be controlled automatically with closed loop on the basis of four electrodes at the bottom of the furnace.

2 Establishment of an arc deflection model of the DC arc furnace

DC arc is a conductor easy to vary its waveform and very flexible freedom changed. The arc deflection will be affected by the DC arc shape and the distribution situation of the current density. We should first set up a model of the arc deflection on three-dimensional space in order to control the arc direction. The steady shape [2] of electric arc and the outline radius, R_z, of the steady arc is shown as

$$R_z = R_c\left[1+\sqrt{\frac{Z}{R_c}}\right] \tag{1}$$

where R_c is the radius of the spots on the cathode; Z the distance between the steel bath and the cathode. The current branch component (J_z) of the current density (J) for DC arc from shaft side will strongly affect the electromagnetic force of the arc column. The branch component (J_r) of the current density from radial direction plays an important role in making the arc column to be revolved. The J_z is much stronger than J_r, and J_z should appear in the distribution of the throw line:

$$J_z = \frac{2I}{\pi R_z^2}\left[1-\frac{r^2}{R_z^2}\right] \tag{2}$$

where I is the electric arc current; r the radius of the radial coordinate.

Set up the coordinate system shown in **figure 1**.

In the figure Z axis should be coincided with the

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centre line of the furnace body. The centre point of the furnace bottom is point O of the coodinate system. The circle plane S is a cross plane between the steel both plane C and the electric arc column. According to the law of Biot-Savart law [3], the direction of the magnetic induction strength B_p is produced by any position ($P_1(x_1, y_1, z_1,)$, $P_2(x_2, y_2, z_2,)$) of the conductors carried on the current I in the space. And any one spot, ($P(x, y, z)$) on the circle plane S is made up by the right hand law and its absolute value is

$$B_{\mathrm{p}} = \frac{k\mu_0 I}{4\pi r}(\cos\theta_1 + \cos\theta_2) \tag{3}$$

where k is a weak magnetic coefficient of the furnace shell, takes 0.5; μ_0 the vacuum magnetic conductivity; r, θ_1, and θ_2 are decided by the equation as follows:

$$r = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2}\sin\theta_1 \tag{4}$$

$$\theta_1 = \cos^{-1}\left\{\frac{(x - x_1)(x_2 - x_1) + (y - y_1)(y_2 - y_1) + (z - z_1)(z_2 - z_1)}{\sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2} \times \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}}\right\} \tag{5}$$

$$\theta_2 = \cos^{-1}\left\{\frac{(x - x_2)(x_1 - x_2) + (y - y_2)(y_1 - y_2) + (z - z_2)(z_1 - z_2)}{\sqrt{(x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2} \times \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}}\right\} \tag{6}$$

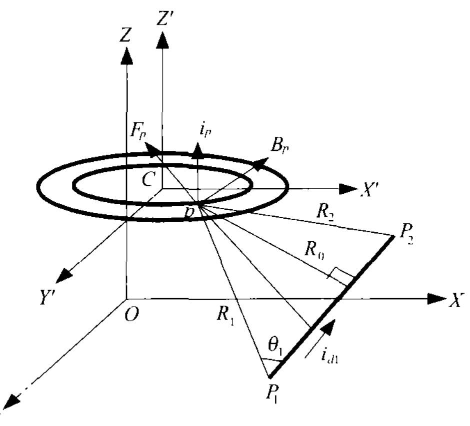

Figure 1 Magnetic force induced by current conductors.

For the current element ($i_p\Delta h$) passed spot P and vertical against surface S, the branch component B_{px} and B_{py} of magnetic induction strength B_p will induce the magnetic force parallel with plane S. The magnetic force applied on the current element of unit length ($\Delta h = 1$) is as following:

x direction:

$$f_x = -i_p \cdot B_p y = -j_z \cdot \mathrm{d}s \cdot B_{py} \tag{7}$$

y direction:

$$f_y = -i_p \cdot B_p y = j_z \cdot \mathrm{d}s \cdot B_{py} \tag{8}$$

The magnetic induction strength and magnetic force at spot P for the conductors carried on the current in the space can be derived on the basis of vector superposition theorem. The magnetic force, F_{m}, makes the deviation movement of arc column, *i.e.*

$$F_{\mathrm{m}} = \int_{z_t}^{z_l} \mathrm{d}z \iint_s j_z \cdot \sum_{k=1}^{N} B_p \mathrm{d}s \tag{9}$$

When the deviation movement of the arc column happens, the movement will be corrected by the restore force of the impulse acted from the plasma stream and its amount will be as follow:

$$F_{\mathrm{r}} = \frac{\mu_0 l}{4\pi} \cdot \frac{I_a}{R} \ln\left\{\frac{8R}{R_e}\tan\frac{\alpha}{2}\right\} \tag{10}$$

where l is the length of electric arc; I_a the arc current; R the curvature radius of the current loop in the graphic electrode; R_e the radius of the graphic electrode; α the deflection arc angle.

When the two forces (the magnetic force and the restore force) acted on the arc column reach balance, the arc column will stop a balance spot. When the magnetic field from the external force varies due to certain reason, the arc column will be deviated the spot and move to a new balance spot. The balance equation of the arc column is

$$F_{\mathrm{m}} + F_{\mathrm{r}} = 0 \tag{11}$$

After the conductor layout at the furnace bottom electrodes are fixed, the magnetic force of DC electric arc induced by the current bus distribution for each electrode can be calculated based on the model mentioned above. In accordance with the model the current bus distribution rule for the electrodes can be set up.

3 Principle and configuration of the arc direction control system

During the operation of DC arc furnace, the arc direction can not be measured directly, but it can be indirectly got through the varying temperature curve of the furnace wall, *i.e.* based on the analysis for the current curves and history curves the arc direction can be got. When the arc direction is deviated, the fire of DC arc will directly shoot into the furnace wall at a reflex angle and forms different hot spots and cold spots, which makes the the wall to appear different temperature distribution. The convective heat transfer of the arc fire is a dominant reason to form different temperatures for the furnace wall. The heat radiation transfer of the arc will play a little role, which analyses the dominant basis for the arc direction deflection. For the DC arc furnace, which has four bottom electrodes, there is an individual power supply loop for each electrode. When the total input power for the bottom electrodes is kept no change, the current through each bottom electrode can be controlled individually. The different current distribution control regulation could affect the electromagnetic field distribution in the furnace. Through the current control, the electromagnetic force of the DC arc column can be changed. So it can reach the goal of controlling the arc direction. The current distribution strategy relies on the arc position and the electromagnetic field induced by the different current bus bars. **Figure 2** shows the principle of the arc direction control.

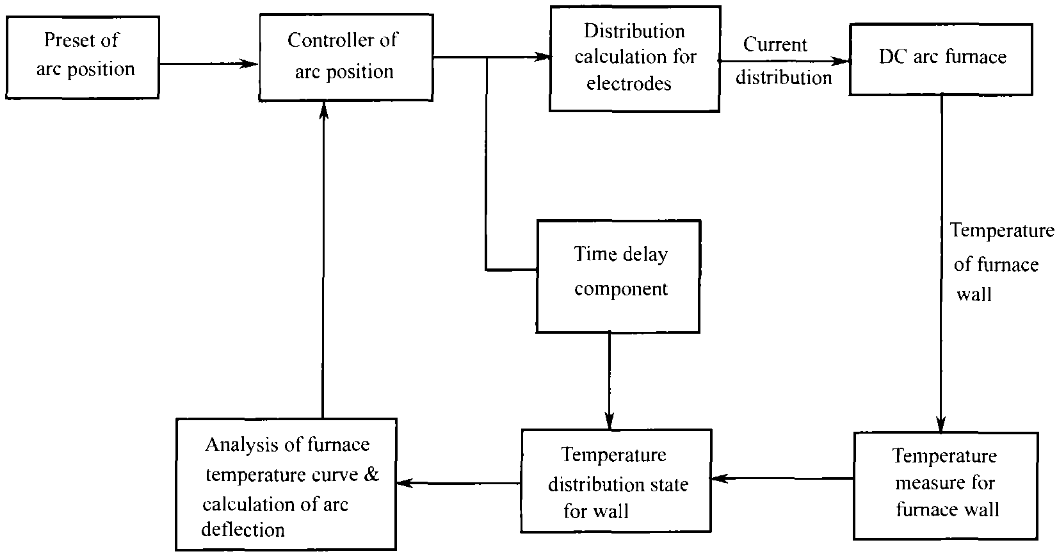

Figure 2 Principle of the arc direction control.

4 Result of the simulation

As shown in **figure 3**, we take the cross section of the furnace body as a circle, take the line from the dust hole to the electrical room as horizontal axis and the line from tap hole to the slag door as vertical, to set up a plane coordinate. If the spot (d) is the arc burning spot on the steel bath surface of liquid steel and α is defined as the arc deflection angle, its varying extent is $-180° \leq \alpha \leq 180°$; d, as the arc deflection amount, its change extent is $0 \leq d \leq 6.3$ m, where 6.3 m is the diameter inside of the furnace wall.

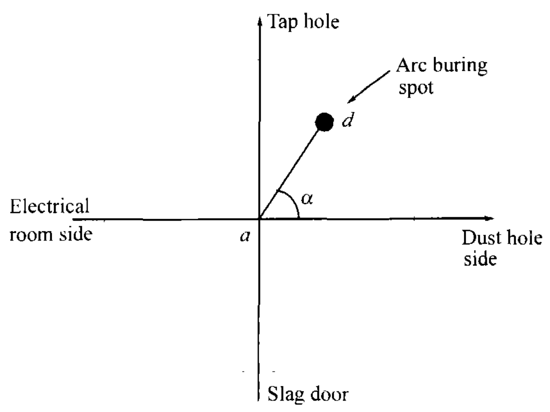

Figure 3 Co-ordinate system in the furnace.

The initial simulation for the temperature distribution curve is shown in **figure 4**.

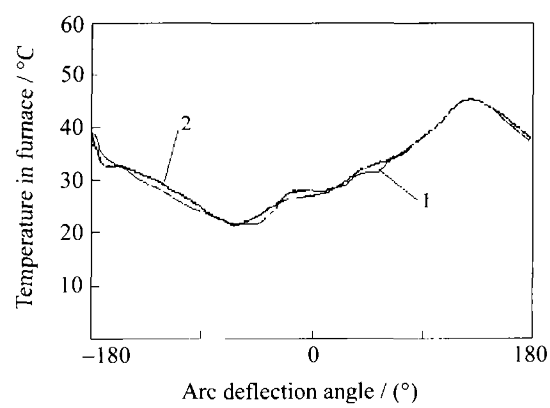

Figure 4 Temperature distribution curve of water cooling wall: 1—the actual measuring curve; 2— the simulation curve.

Figure 5 is the temperature distribution curve after 8 measure periods (about 4 min). **Figure 6** is the temperature distribution curve after 16 measuring periods (about 8 min), here the requirement of the temperature deviation has been met. During the control process for the arc position, the varying status of the arc deflection angle is shown in **figure 7**. The varying situation of the arc deflection amount is shown in **figure 8**. The current distribution situation is shown in **figure 9**.

The results of the simulation are as following. Initially the current of bottom electrode is average distribution, *i.e.* they are 25 kA. When the circumstance of the furnace and external condition are changed, the DC arc direction happens to be revolted. The angle of the arc deflection is 21.3° and the arc deflection amount was 181 mm, in which the total electromagnetic force withstanding the arc is 126 N. After redistributing the current of the bottom electrodes, the current of 4 bottom electrodes is individually 22.6, 26.4, 23.2 and 27.8 kA. At the same time the electromagnetic force withstanding the DC arc is nearly zero and the arc deflection is corrected very quickly. After the 16 measuring periods, the temperature deviation curve can meet the requirement of the temperature deviation index for the furnace wall. We can derive the conclusion from the simulation results, *i.e.* the system of arc direction control can change and adjust the current distribution of the bottom electrodes at short time and the arc deflection can be corrected very quickly. The arc direction can be corrected to reach the position controlled by the pre-set value from the control system. So the scheme can solve the problem of the arc deflection caused by the large capacity DC arc furnace.

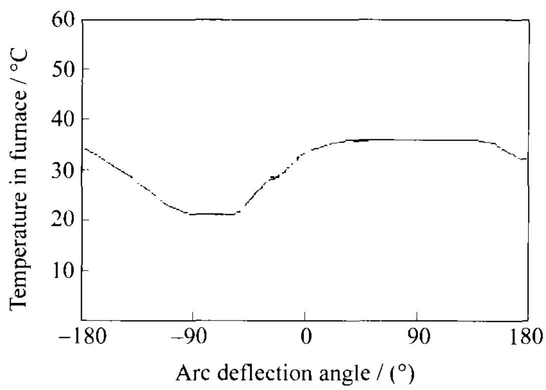

Figure 5 Temperature distribution curve after 4 min.

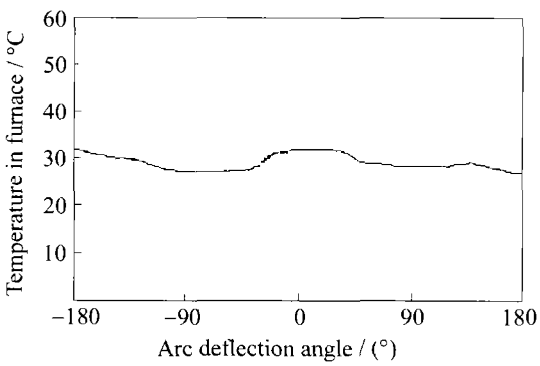

Figure 6 Temperature distribution curve after 8 min.

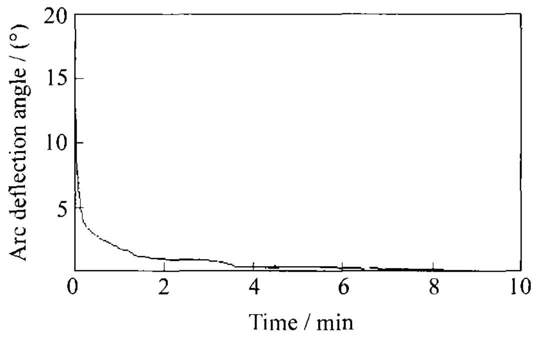

Figure 7 Changing status of the arc deflection angle.

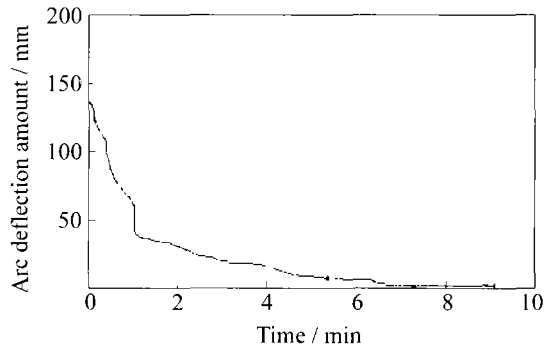

Figure 8 Changing status of the arc deflection amount.

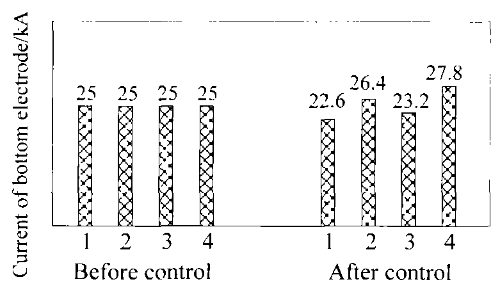

Figure 9 Changing status of arc deflection amount.

5 Conclusions

(1) In 3-D space, the actual conductor distribution is taken as its model and the situation withstanding the electromagnetic force about the arc in the electric arc region is analyzed. The arc deflection model is set up and the theoretical basis for arc direction control is provided.

(2) The idea, principle and algorithm of the arc direction control are presented. And based on the foundation the simulation was done by computer.

(3) The result shows that redistributing the current amount at the bottom electrodes, the electric arc direction can be corrected in accordance with the pre-set and the response time is short. The final results from theoretical and simulation is successful. It will be a great breakthrough if the method is successfully applied for large DC arc furnace and can get good results.

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