Heat Exchange in High-Power Arc Steel Furnace when the Height of the Slag Layer Changes

A N Makarov and A V Krupnov

Electric Supply and Electrical Engineering Faculty, Tver State Technical University, Tver, Russia

E-mail: AV.Krupnov@yandex.ru

Abstract. Calculation results and analysis of changes in thermal radiation density of arcs by wall height for hundred-ton arc furnaces at different slag layer height and at equal arc power are presented. It was found that with an increase in the height of the slag layer from 70 to 300 mm, that is, with an increase in the depth of the arcs in the slag, the density of thermal radiation flows of the arcs in the most heat-loaded part of the walls decreases by 2 times. The efficiency of arcs increases with the increase in the depth of arcs in the slag and increases by 1.61 times when fully buried.

1. Introduction
The influence of the height of the slag layer on the density of thermal radiation from electric arcs on the walls of an electric arc furnace (EAF) is a topical issue, despite the fact that the stability of the wall lining is affected by many factors [1–10]: melting modes, chemical composition and temperature of the slag, the quality of service of the lining, the materials used, and others. This is due to the fact that the main share in the thermal load of walls is from the thermal radiation of electric arcs.

Therefore, we performed calculations of the heat flux density for the height and perimeter of the walls for a hundred-ton DSP-100 furnace to determine the effect of the height of the slag layer. The power of the arcs in all calculations was assumed unchanged.

2. Method determination of densities of thermal radiation flows from three arcs
Determining the densities of thermal radiation flows from arcs on the wall surface is based on the method described in [11–13]. Figure 1 shows the necessary constructions in the AutoCAD program for calculations performed at scale in MS Excel.

Symbols used in Figure 1: $h_W$ – wall height of EAF, m; $d_E$ – diameter of the electrode, m; $h_T$, $h_M$, $h_S$ – the depth of the arc, respectively, the total, in the metal, in the slag, m; $D_{Bath}$, $d_{Dec}$ – accordingly, the diameter of the bath, the decay of the electrodes, m; $\gamma$ – the angle formed by the horizontal plane of the end of the electrode and the inclined plane that occurs on the electrode due to the electrodynamic movement of the arc from the axis of the electrode to its periphery, deg.; $0…5$ – calculation points on the walls of furnace; $l_{Arc}$ – arc length, m; $l_{Open}$ – length of the open part of the arc radiating heat flow to the calculated site, m; $r$ – beam, distance from the arc to the calculated point on the walls, m; $\alpha$ – the angle between the beam $r$ from the middle of the open part of the arc and the perpendicular $N1$ to the axis of the arc, drawn to the beginning of the beam $r$ on the arc, deg.; $\beta$ – the angle between the normal $N2$ to the wall surface at the calculated point and the beam $r$, deg.; $\theta$ – the angle of the electrodynamic deviation of the arc axis from the electrode axis is determined by the method presented in [11–13].
The density of the arc thermal radiation flux falling on the calculated site located on the walls of the EAF was determined by the expression [11]:

\[
q = \alpha_{\text{Arc}} \cdot P_{\text{Arc}} \cdot \cos \alpha \cdot \cos \beta \cdot l_{\text{open}} \cdot e^{-k \cdot r}, \text{ kW/m}^2,
\]

(1)

where \(\alpha_{\text{Arc}}\) – the percentage of arc power allocated in the arc pillar; \(P_{\text{Arc}}\) – arc power, kW; \(k\) – the coefficient of absorption of the gas atmosphere of the furnace, varies in the range of EAF from 0.1 to 1.3.

Figure 1. Diagrams of the mutual location of the arc, slag, walls (A); electrodes, metal bath, the scale is reduced (B); for calculating the fluxes of thermal radiation of arcs on the walls (C).

3. Initial parameters for calculations
The furnace atmosphere contains suspensions of solid and liquid particles, and the density of the dust-gas mixture varies from 5 to 50 g/m\(^3\) [14–19]. Therefore, for a complete picture, it is necessary to analyze not only the ray-transparent medium, but also the gas-polluted one. The gas content in the calculation is taken into account in (1) by the absorption coefficient of the furnace's dust and gas atmosphere, which can vary from 0 to 1.4 [11–13]. In calculations, we take the average value of the coefficient \(k = 0.7\).
The parameters of the DSP-100 furnace required for building the calculated model in AutoCAD (Figure 1,C) are shown in table 1[11].

Table 1. Parameters of the arc and furnace.

| Parameter | $D_{Bath}$ | $d_{Dec}$ | $h_{cm}$ | $d_{E}$ | $\gamma$ | $U_{Arc}$ | $I_{Arc}$ | $P_{Arc}$ | $l_{Arc}$ | $\alpha_{Arc}$ |
|-----------|------------|-----------|----------|---------|---------|-----------|-----------|----------|----------|-------------|
| m         | m          | m         | mm       | deg.    | V       | kA        | MW        | mm       | mm       | deg.        |
| Furnace DSP-100 | 5.4 | 1.4 | 2.5 | 600 | 35 | 260 | 69.2 | 18 | 300 | 0.92 |

Calculation of fluxes of thermal radiation from three arcs incident to the settlement site 0…5, which are located on the vertical wall surfaces (Figure 1, C) opposite arcs and between arcs by rotating the vertical plane crossing the electrode, the arc and the wall in front of the arc, at an angle of $60^\circ$ (Figure 1,B), performed by (1).

To determine the effect of the height of the slag layer on the density of thermal radiation flows on the walls of the DSP-100 furnace, the following values of the arc depth in the metal and slag are taken:

I – $h_T = 70$ mm – the arc is buried only in metal;

II – $h_T = 160$ mm – the arc is buried in metal and slag half its height;

III – $h_T = 300$ mm – the arc is buried at full height in the slag.

4. Result of calculation

At Figure 2 the obtained results of calculating the distribution of heat flux densities from three arcs to the sections of the furnace walls opposite one of the arcs in a dusty environment at $k = 0.7$ (Figure 2,a) and a ray-transparent atmosphere at $k = 0$ (Figure 2,b) are presented. Figure 3 shows similar calculation results, but only for the sections of the furnace walls between the arcs. And for simplicity of comparison of the received values, we will reduce them to table 2 [4].

The results of calculating the densities of thermal radiation flows of arcs on the walls of the DSP-100 furnace are confirmed by experimental data on the operation of water-cooled wall panels in the EAF [4].

In all the cases considered, the peak heat flux density of radiation observed on the height of the walls of 0.5–1.0 m. Maximum density of the heat flow, as seen from the results obtained in front of the arc at depth $h_T = 70$ mm at a height of 0.5–1.0 m and it is 600 kW/m² in a ray-transparent environment of the furnace. With an increase in the height of the slag layer, the maximum density of thermal radiation flows decreases by 1.3 times when the arc depth increases from 70 mm to 160 mm and by 2 times when the arc depth increases to 300 mm.

Figure 2. Distribution of heat radiation flux densities of arcs on the sections of walls located opposite the arc: when the arc depth is $h_T = 70$ mm (I), $h_T = 160$ mm (II), $h_T = 300$ mm (III) in the gas-filled atmosphere of the furnace (A), in the ray-transparent atmosphere of the furnace (B).
When the height of the slag layer increases, the density of heat fluxes of arc radiation is redistributed, at the height of the walls from 0 to 0.5 m it decreases, and at the height of 1.0–1.5 m it increases (see Figures 2, B and 3, B).

This phenomenon is due to the fact that the open part of the arc decreases (Figure 1, C). The density of thermal radiation flows of arcs along the height of the walls decreases by an average of 1.6 times with the increase in the depth of arcs in the slag.

As can be seen from Figure 2 (and table 2) in a dusty environment of the furnace, when the absorption coefficient $k = 0.7$, density heat flux radiation arcs decrease in 4–5 times in the area of the maximum is from 600 kW/m$^2$ to 132 kW/m$^2$, and up to 7–8 times at the height of the walls 1.5–2.0 m. These results correspond to the data given in [3], that in the case of a ray-transparent environment, the heat flow on the wall of the DSP-100 is 350-534 kW/m$^2$, with maximum dustiness it is reduced by 4–4.5 times to 80–115 kW/m$^2$.

The obtained results of calculating the densities of thermal radiation flows from three arcs to the wall sections located along the perimeter of the walls between the arcs (Figure 3), allow us to note that the densities of thermal radiation flows are 1.5–2 times less both in a ray-transparent environment (Figure 3, B) and in a dusty environment (Figure 3, A) compared to the densities of thermal radiation flows from arcs to the wall sections located opposite the arcs (Figure 2).

With an increase in the depth of arcs in the slag from 70 mm to 300 mm, the density of thermal radiation flows of arcs to the sections of walls located between the arcs decreases by 1.2–1.6 times in the height of the walls.

According to the method described in [11, 20], the efficiency of arcs was calculated depending on the height of the arc sinking into the slag and the following relations were obtained:

- when $h_T = 70$ mm ($h_T / l_{arc} = 70 / 300 = 0.23$) – $\eta_d = 0.46$
- when $h_T = 160$ mm ($h_T / l_{arc} = 160 / 300 = 0.53$) – $\eta_d = 0.53$
- when $h_T = 300$ mm ($h_T / l_{arc} = 300 / 300 = 1.0$) – $\eta_d = 0.74$

It can be seen that when the arcs are buried in the slag from 70 to 300 mm, that is, from $h_T / l_{arc} = 0.23$ to 1.0, the efficiency of the arcs increases by 1.61 times.

The experience of increasing the height of the slag layer on DSP-120 from 238 to 325 mm has shown that the efficiency also increases and the specific power consumption decreases by 22% [21].
Table 2. Values of heat flux densities of arc radiation along the wall height for the main points.

| Wall height | hT, mm | Heat flux density of radiation q, kW/m² |
|-------------|--------|----------------------------------------|
|              |        | in front of the arc                     |
|              |        | in a dusty environment | ray-transparent environment |
| 70 (I)       | 0.5    | 132 | 106 | 56 | 600 | 450 | 200 |
| 160 (II)     | 1      | 115 | 96  | 64 | 572 | 450 | 290 |
| 300 (III)    | 1.5    | 60  | 54  | 43 | 440 | 344 | 264 |
|              | 2      | 37  | 30  | 22 | 278 | 230 | 172 |
|              | between arcs | in a dusty environment | ray-transparent environment |
|              | 0.5    | 68  | 56  | 42 | 330 | 270 | 184 |
|              | 1      | 62  | 54  | 41 | 316 | 275 | 217 |
|              | 1.5    | 50  | 46  | 35 | 270 | 234 | 188 |
|              | 2      | 38  | 34  | 28 | 212 | 192 | 154 |

5. Conclusion

It was found that with an increase in the height of the slag layer and with an increase in the depth of the arcs of the DSP-100 furnace from 70 to 300 mm, the density of thermal radiation flows of the arcs decreases by an average of 1.6 times over the entire height of the furnace walls. With the growth of the slag layer, the share of thermal radiation of arcs on the walls decreases by 1.6 times. The densities of thermal radiation flows of arcs are unevenly distributed both along the height and along the perimeter of the walls.

Depending on the dustiness of the furnace atmosphere, the density of thermal radiation flows of arcs on the walls of the furnace DSP-100 may differ by 4–5 times from the maximum value of 600–650 kW/m² in a transparent environment to 130–160 kW/m² with a high dustiness of atmosphere of a furnace.

The height of the slag layer affects the efficiency of the arc, so increasing the height of the slag layer increases the efficiency and when the arc is completely buried in the slag reaches 74% for the DSP-100 furnace.

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