Influence of capacity, distance from arcs to walls on the efficiency of arcs and electricity consumption in arc steel-making furnaces

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Abstract. The influence of the distance from the arc to the walls in the entire range of arc steel-making furnaces with a capacity from 0.5 to 120 tons on the efficiency of arcs and specific power consumption in the furnaces was investigated. In low-tonnage arc steel-making furnaces, the arcs are close to the walls and the efficiency of the arcs is small and amounts to 30-35%, and the specific power consumption for melting is 650 kWh/t. In heavy-duty steel-arc furnaces, the arcs are located far from the walls, the efficiency of the arcs is 46-49% in the absence of a slag layer, and the specific energy consumption for melting is 375-385 kWh/t.

1. Introduction

In [1], the results of the calculation and analysis of heat transfer in electric arc furnaces (EAF) of small and large capacity are presented, however, there is no explanation for the significantly large specific energy consumption in EAF of small capacity compared to EAF of large capacity. It is necessary to investigate the effect of the distance from the arcs to the walls in the entire range of arc steel-making furnaces from 0.5 to 120 t on the efficiency of arcs and specific power consumption in arc steel-making furnaces, as well as establish a proportional relationship between the efficiency of arcs and specific electricity consumption by furnaces.

2. Heat transfer and efficiency of arcs in EAF

Electric arcs are the main sources of thermal energy in electric arc furnaces, they account for 55-65% of the thermal energy supplied to a modern high-power EAF [2]. From gas-oxygen burners, exothermic reactions of oxidation of iron and other elements of the charge with oxygen, reactions of oxidation of coke and electrodes, 35-45% of energy is supplied to EAF [1-2]. All electrical energy in the arcs of the chipboard is converted into heat energy, heat flux. According to the results of numerous experimental studies, the heat flux of arcs is 90-96% formed by thermal radiation [3-7]. The share of thermal conductivity and convection accounts for 4-10% of the arc power.

The power released in the taxiway arc is distributed as follows: most of the power is released in the arc column $P_{st}$, part of the power is released in the anodic-cathode spots $P_{ak}$, the height of which is several microns, part of the power is taken by convection by the furnace gases $P_k$ washing the arc (1):

$$ P_D = P_{ak} + P_k + P_{st} $$

(1)

Based on the research results V.Pashkis, N.V. Okorov [4], A.V. Egorov [5], L.Ye. Nikolsky, V.D. Smolyarenko, N.L. Kuznetsov [3], A.N. Makarov [1] assume that 90% of the arc power is released in
the arc column in the arcs of high-power heavy-duty steel-making arc furnaces in the form of a heat radiation flux. Anode-cathode spots and gases washing the arc account for 10% of the arc power:

\[ P_D = P_{ak} + P_k + P_{st} = 0.1P_D + 0.9P_D \]  

(2)

The ratio of the useful power of the arc \( P_{pol} \) going for heating, melting of metal and slag, to the power of the RD arc characterizes the efficiency of the arc heat or the efficiency of the arc:

\[ \eta_D = \frac{P_{pol}}{P_D} \]  

(3)

Since the reference anode-cathode spot of the arc on the bath by thermal conductivity transfers all the power released in it to the metal, the reference spot on the graphite electrode, intensely radiating to the metal bath, and the gas washing the arc, transfer less than 80% of the power released in them to the metal bath, the expression for calculating the efficiency of the arc of heavy-duty EAF has the form [1]:

\[ \eta_D = \frac{P_{pol}}{P_D} = \frac{(0.8\cdot 0.1)P_D + 0.9P_{DM} \varphi_{DM}}{P_D} = 0.08 + 0.9\varphi_{DM} \]  

(4)

where \( \varphi_{DM} \) is the average angular emissivity of the arc column to the metal, showing the fraction of the power radiated by the arc column to the metal bath and metal charge.

In expression (4), which was used to determine the efficiency of arcs of heavy-duty 100 t EAF in the late 1990s and early 2000s, the share of power released in the arc column was taken equal to 0.9, in the anode-cathode regions 0.1. In the 2000s, the power of electric furnace transformers feeding 100 tons of chipboard was increased, since that time they began to use long arcs for metal melting. When using long arcs, the share of power released in the arc column has increased and it is necessary to correct the calculated expression (4) to calculate the efficiency of the arcs. In furnaces with a capacity of 3-50 tons, the fraction of the arc power released in the arc column is slightly less than 90%, therefore, expression (4) for furnaces with a capacity of 3-50 tons should be corrected.

3. **Investigation of the efficiency of EAF arcs**

The share of power released in the arc column was determined by the expression:

\[ \frac{P_{st}}{P_D} = \frac{I_D U_{st}}{I_D U_D} = \frac{U_{st}}{U_D} \]  

(5)

where \( I_D, U_{CT} \)— respectively, arc current and voltage across the arc column.

The share of power released in the anode-cathode spots was determined by the expression:

\[ \frac{P_{ak}}{P_D} = \frac{I_D U_{ak}}{I_D U_D} = \frac{U_{ak}}{U_D} \]  

(6)

where \( U_{ak} \) is the anode-cathode voltage drop, \( U_{ak} = 20V \) [1].

The results of calculating the distribution of the arc power in the column and anode-cathodic regions for the end of the melting period of the charge are shown in table 1.

From the results of the calculation and analysis of the calculated data in table 1, it follows that the share of power released in the arc column varies from 0.82 in the DSP-0.5 furnaces to 0.94 in the DSP-120 furnaces. The share of power released in the anodic-cathode spots of the arc varies from 0.18 in DSP-0.5 to 0.06 in DSP-120.

Considering the above, the analytical expression (4) for calculating the efficiency of EAF arcs for the entire range of furnace capacities takes the form:

\[ \eta_D = \frac{P_{pol}}{P_D} = \frac{0.8 \left( \frac{P_{pol}}{P_D} \right) P_D + \left( \frac{P_{ak}}{P_D} \right) P_D \varphi_{DM}}{P_D} = 0.8 \left( \frac{U_{ak}}{U_D} \right) + \left( \frac{U_{st}}{U_D} \right) \varphi_{DM} \]  

(7)
Table 1. Distribution of voltage drop in the column and anode-cathode regions of the arc of arc steel-making furnaces of the entire range of capacities.

| Parameter | DSP-0.5 | DSP-3 | DSP-6 | DSP-25 | DSP-50 | DSP-100 short arcs | DSP-100 long arcs | DSP-120 |
|-----------|---------|-------|-------|--------|--------|--------------------|------------------|--------|
| $U_D$, V  | 111     | 128   | 140   | 163    | 185    | 200                | 280              | 320    |
| $U_{st}$, V | 91     | 108   | 120   | 143    | 165    | 180                | 260              | 300    |
| $U_{st}/U_D$ | 0.18   | 0.16  | 0.14  | 0.12   | 0.11   | 0.10               | 0.07             | 0.06   |
| $U_{st}/U_D$ | 0.82   | 0.84  | 0.88  | 0.88   | 0.89   | 0.90               | 0.93             | 0.94   |

The influence of the design of the furnaces was investigated, in particular, the effect of the diameter of decay and electrodes and the distance from the arcs to the walls of the furnaces on the efficiency of arcs for the entire range of capacities from 0.5 to 120 tons (figure 1). Figure 1 shows a part of the working space of a chipboard, a wall, a metal bath, electrodes, electric arcs. Lining of the hearth, slopes, water-cooled wall panels are not shown. Figure 1 is a combined drawing for DSP-0.5-120 furnaces. The arrangement of electrodes, arcs, and walls of the furnaces in Figure 1 on a scale repeats their location in the furnaces DSP-0.5-DSP-120. The technical data of arc steel-making furnaces are given in table 2. Figure 1 shows an example of finding an arc of a DSP-100 furnace under a thick layer of slag.

Table 2. Technical data of electric arc furnaces.

| Parameter | G, t | S, MVA | D, m | d, m | r_st, m | $G_e$, kWh/t | $U_{21}$, V | $I_D$, kA |
|-----------|------|--------|------|------|---------|-------------|------------|----------|
| DSP-0.5   | 0.5  | 0.63   | 1.1  | 0.48 | 0.31    | 650         | 98-216     | 1.7      |
| DSP-1.5   | 1.5  | 1.25   | 1.5  | 0.52 | 0.49    | 540         | 103-225    | 3.2      |
| DSP-3     | 3    | 2.5    | 1.8  | 0.7  | 0.55    | 520         | 140-245    | 5        |
| DSP-6     | 6    | 5.0    | 2.27 | 0.9  | 0.69    | 475         | 130-291    | 9        |
| DSP-12    | 12   | 9.0    | 2.7  | 1.0  | 0.85    | 450         | 115-318    | 17       |
| DSP-25    | 25   | 15.0   | 3.54 | 1.25 | 1.15    | 440         | 130-390    | 23       |
| DSP-50    | 50   | 40.0   | 4.56 | 1.6  | 1.48    | 420         | 133-417    | 50       |
| DSP-100   | 100  | 80     | 5.4  | 1.4  | 2.0     | 385         | 300-829    | 80       |
| DSP-120   | 120  | 100    | 6.8  | 1.75 | 2.53    | 375         | 600-1100   | 75       |

Symbols used in table 2: G - capacity, t; S - power of the transformer, MVA; D, - bath diameter at the level of the slopes, m; d, - diameter of disintegration of electrodes, m; r_st - distance from walls to arcs, m; $G_e$ - specific energy consumption for melting, kWh/t; $U_{21}$ - secondary line voltage of the electric furnace transformer, V; $I_D$ - arc current, kA.

In order to exclude the influence of the height of the slag layer on the efficiency of the arcs and to reveal the influence of the design features of the furnaces, the distance from the arcs to the walls on the efficiency of the arcs, the calculation of the efficiency of the arcs was carried out to end the melting period in the absence of a slag layer $h_{st}$ on the metal bath in all furnaces. The arc length was determined by the expression [1]:

$$I_D = \frac{U_D - U_{st}}{\text{grad}U_{st}}$$  \hspace{1cm} (8)

where grad$U_{st} = 0.8V/mm$ is the voltage gradient in the arc column.

The height of the arc penetration $h_3$ in the absence of slag is equal to the height of the arc penetration into the metal $h_m$:

$$h_3 = h_m, h_2 = k_2 I_D$$  \hspace{1cm} (9)
where \( k_z \) is the coefficient of arc penetration into the metal bath, is determined from the graphs [1] and is equal to \( k_z = 0.8 \text{ mm/kA} \) for currents up to 10 kA, \( k_z = 1.25 \div 1.40 \) for currents, respectively, 60-80 kA.

**Figure 1.** Arrangement of arcs in furnaces of small and large capacity DSP-0.5-DSP-120 and the distance from arches to walls.

The calculation of the efficiency of arc furnaces DSP-0.5, DSP-100, DSP-120 was carried out according to the expression (7). For calculations, we used the data in table 1 and table 2. The average angular emissivity of the arc per metal bath was determined by the method described in [1], according to which the surface of the metal bath is divided into several hundred calculated areas of the same area \( F_k \), in this case, the calculation is 216 sites (figure 2) for each of which, according to the formulas set forth in [1], the fraction of the arc column radiation is determined taking into account its penetration into the metal bath, that is, the local angular emissivity of the arc column to the calculated area is determined. To calculate the local and average angular emissivity of the arc on the metal bath, the software package Microsoft, Excel, MathCad, Visual Fortran 6.0 was used.

### 4. Results of calculating the efficiency of arcs in a chipboard

Figure 2 shows the results of calculating the average angular coefficients of arc radiation on a metal bath \( \varphi_{DM} \), average angular coefficients of arc radiation on the walls and roof of the furnace \( \varphi_{DS} \), efficiency of arcs \( \eta_D \). As can be seen from figure 2, the closer the arcs are to the walls of the chipboard, the lower the average angular emissivity of the arc to the metal bath and the efficiency of the arc, and the greater the average angular emissivity of the arc to the walls and roof of the furnace and the specific power consumption for melting.

In the DSP-0.5 furnace, the arcs are very close to the walls, \( r_a = 0.31 \text{ m} \), therefore, the share of the thermal radiation of the arc on the walls, the roof is large and is \( \varphi_{DC} = 0.82 \), the proportion of the useful thermal radiation of the arc on the metal bath is small, \( \varphi_{DM} = 0.18 \), therefore, the efficiency of EAF-0.5 arcs is very low, \( \eta_D = 0.31 \), and the specific power consumption is high and amounts to \( G_e = 650 \text{ kWh/t} \) for melting the charge. In the chipboard furnace - 6, the distance from the arc to the
walls $r_w = 0.69$ m is greater than in the chipboard furnace - 0.5, respectively, the fraction of the thermal radiation of the arc on the walls and roof is less, $\phi_{DC} = 0.75$, more for the metal bath $\phi_{DM} = 0.25$ and more arc efficiency, $\eta_D = 0.35$, less specific power consumption for melting $G_e = 475$ kWh/t in comparison with an EAF furnace - 0.5.

Figure 2. Dividing the metal bath into 216 elementary computational sites $F_k$. Figure 3. Dependence of the efficiency of arcs, average angular coefficients of radiation of the column of arcs on the metal bath, walls, and vault on the distance from arcs to walls and furnace capacity.

In furnaces chipboard - 100, chipboard - 120, the diameter of the bath of which, respectively, 5.4 and 6.8 m, the ratio $d_e/D_v = 0.26$, which corresponds to the recommended, the arcs are close to the center of the bath and are removed from the walls at a distance, respectively, 2.0 and 2.53 m, which resulted in an increase in the efficiency of arcs to 0.46 and 0.49, respectively, and a decrease in the specific consumption of electricity for melting to 385 and 375 kWh/t.

5. Conclusion
Analytical studies of the efficiency of arcs have established the following. In furnaces of small capacity, the diameter of the casing, the metal bath is small, the arcs are close to the walls, and the fraction of the thermal radiation of the arcs on the walls and the roof is 4 times greater than the fraction of the thermal radiation of the arcs on the metal bath. The efficiency of small-capacity furnace arcs is small, and the specific power consumption is high. In large-capacity furnaces, the diameter of the casing and the metal bath is 5-7 m, the arcs are removed from the walls, the share of thermal radiation of the arcs per metal bath, the efficiency of the arcs increase compared to small-capacity furnaces, and the specific power consumption decreases. The results of calculating the efficiency of arcs are confirmed by the practice of operating an EAF. Specific power consumption for melting is 650-700 kWh/t in small-capacity furnaces, 375-385 kWh/t in large-capacity furnaces.

Thus, theoretical studies, the results of calculating the angular coefficients of thermal radiation of arcs on the bath, walls, vault, efficiency of arcs and the practice of operating arc steel-making furnaces are in harmonious agreement with each other, the results of the calculation are confirmed by the practice of operating furnaces: the more efficiency of arcs in EAF obtained by calculation, the lower the specific power consumption for melting the charge, obtained as a result of the practice of operating the furnaces. Since practice is a criterion for the truth of theoretical developments, in this case, the practice of operating the furnaces confirms the correctness of the methodology and the performed
calculations of the average angular coefficients of radiation of arcs per metal bath, walls, roof, efficiency of arcs of arc steel-making furnaces of the entire range of capacities from 0.5 to 120 t.

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