Identification of working reactance of industrial arc furnace equivalent scheme based on known specific electric power consumption for melting of charge

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Abstract. Method of identification of working reactance of industrial arc furnace equivalent scheme based on known specific electric power consumption for melting of charge taking into account complex (radiation and convection) nature of arc heat exchange in melting space is presented. The solution of the multi-factor problem of determining the share of arc radiation power and convective heating of charge by arcs in the furnace useful power was proposed at MPEI on the basis of analytical methods of the developed electric arc heat exchange model (EAHEM). Method of calculation of specific electric power consumption for melting of solid charge for specified type of arc furnace design is considered.

1. Introduction
Identification of parameters of industrial arc furnace equivalent electric circuit, including reactance, is necessary for obtaining power and performance characteristics of furnace, design of electric modes, synthesis and adjustment of automatic furnace control system.

In order to identify the working reactance, the electric thermal problem is solved taking into account the complex (radiation and convection) nature of the electric arc heat exchange.

2. Accounting for the complex type of charge arc heating in the furnace melting space
Experience of arc furnaces operation and methods of modern theory of working processes in arc furnaces indicate complex nature of arc heat exchange in melting space caused by radiation and convection caused by arc column plasma movement. The changing structure of charge heating during the smelting process affects the rate of charge melting and thus the specific power consumption for charge melting.

Column plasma radiation has a volumetric character. In this regard, the calculation of arc emission power \( P_e \) is not possible without knowing the temperature profile of the column \( T(r) \)

\[
P_e = l_a \cdot 2\pi \int_0^{r_e} \sigma \cdot |T(r)| \cdot i \cdot r \cdot dr
\]  

(1)
where \( l_a \) – length of arc, \( r_a \) – radius of arc.

This calculation is illegal on the basis of the Stefan-Boltzmann law relating to body surface radiation.

This methodological problem in the calculation of arc emission power and the allocation of this power in the furnace useful power results in significant errors in the calculation of furnace performance when the furnace useful power is taken as the power of arc emission in the calculation of thermal characteristics. This is due to the fact that the share of arc radiation power in the melting process depends on many factors and primarily on:

- melting period and heat exchange conditions of the arc in each period of the working cycle;
- parameters of the furnace equivalent circuit;
- operating current of the arc.

Convective heating of the charge by arcs [1] is mainly due to the intense plasma motion in the column and depends not only on these factors, but in addition depends on the thermal regime of the graphite electrode [2], which varies from period to period in the melting process.

The solution of the multi-factor problem of determining the share of arc radiation power and convective heating of charge by arcs in the furnace useful power was proposed at MPEI on the basis of analytical methods of the developed electric arc heat exchange model (EAHEM):

- the method of universal characteristics of the arc [3] and
- the method of structural characteristics of the arc [2].

These methods are based on the provisions of the modern theory of arc heating [1] and allow us to link the projected furnace electric mode of the furnace with the conditions of its heat exchange in the melting space [2] and energy-physical processes in the plasma of the arc column of known chemical composition for a specific melting period. The mathematical apparatus of the developed methods was used to form a package of computer programs “tomed_dsp” for designing an arc furnace rational electric mode [4].

To illustrate the possibilities of the EAHEM method, we calculate the performance characteristics for the melting period of the charge in the well-known DSP-200 industry arc furnace (with a capacity of 200 tons) with transformer with a power \( S_t \) of 32 MVA and a diameter of 550 mm graphite electrodes [5]. Based on the furnace operation data, there are reliable experimental data on the specific electric power consumption for melting the charge 400kW·h/ton. Electric mode parameters during the melting of the charge: the secondary voltage of the transformer \( U_2 \) is 591.5 V, the operating arc current is 43.9 kA. Reduced values of furnace equivalent circuit resistance and reactance: resistance is 0.65 mOhm, reactance for the first harmonic of the short-circuit experience is 4.6 mOhm.

As a result of the calculation, without taking into account the influence of arc current distortion on the furnace equivalent circuit reactance, it is possible to identify the current parameters of the furnace electric mode. Calculation by the well-known methods of electrical characteristics (useful power, lining wear coefficient (LWC)) allow to calculate the current parameters of the furnace at the maximum points of these characteristics:

- arc current for the maximum value of useful power \( I_{pd} \) is 48.6 kA;
- arc current for the maximum value of LWC \( I_{rf} \) is 38.6 kA;
- maximum value of useful power \( P_{U \text{ max}} \) is 33 300 kW.

In the practice of designing a rational electric mode of arc furnaces [6], the operating arc current is usually taken within

\[
I_{\text{oper}} = [0.87-0.90] \cdot I_{pd}
\]
only on the electrical characteristics is not possible without taking into account the complex type of heating by charge arcs.

In this regard, the EAHEM method allows to calculate the structure of arc heating in the melting space of the furnace, taking into account the heat exchange conditions characteristic of a given melting period, and to link the heating characteristics with the electric mode. Calculations for DSP-200 furnace showed that the main components in the useful power of furnace going on the formation of heat flow in the melting space, the cost of electricity on the formation of the radiation power arcs and heat flux forced convection due to the plasma column motion.

Figure 1 shows the dependence on the arc current share of heat flow into useful power analyze DSP-200 in current range from 0.5 to 1.1 for the period of melting without taking into account the influence of the arc current distortion on the furnace reactivity.

As follows from the figure 1 graph the structure of heat flows in the furnace melting space depends significantly on the furnace impedance, supported by a power controller. For DSP-200 furnace operating current is 200 kA, the share of arc radiation is 0.252, the share of forced convection due to plasma motion in the column is 0.64. As the furnace impedance decreases, the proportion of arc radiation decreases to 0.2.

The convective heat flux withdrawn from the surface of the column under conditions of natural convection is associated with the processes of thermal conductivity in the plasma and does not play a significant role in heating the charge. Figure 2 shows the dependence of the share of electric power expense for the formation of this flow in the useful power of DSP-200 furnace during the melting of the charge. The share of electric power expense for the formation of this flow in the useful power of the DSP-200 furnace does not exceed 0.02. However, the values of the heat flux are the basic physical EAHEM factor determining the temperature profile of the arc, and hence the level of other heat fluxes generated by the arc in the melting space for the conditions of heat exchange of the arc in a particular melting period [2].

The EAHEM method thus allows to calculate the temperature profile of the arc column, to identify the arc length and, as a result, to calculate the arc radiation power in the melting space of the furnace.
on the basis of (1). The operating characteristic of the radiation power and the position of its maximum usually does not coincide with the maximum point of the operating characteristic of the LWC. This, in particular, is evidenced by the calculated characteristics for the DSP-200 furnace, presented in figure 3.

Figure 3. Characteristics of arcs radiation power and LWC for DSP-200 furnace during the melting of the charge.

The current value $I_e$ for the maximum arc radiation ($P_{e,\text{max}}=12\,460\,\text{ kW}$) is 28.9 kA. The current value $I_{rf}$ for the maximum LWC, respectively, is 38.6 kA. In this regard, the operating characteristic of the arc furnace is an empirical electrical characteristic and does not reflect the position in the operating mode of the furnace currents of the maximum irradiation and wear of the lining.

3. Calculation of specific electric power consumption for melting solid charge for a given type of furnace construction

As a result, based on the calculation of performance characteristics, which can be performed for a specific industrial furnace of a given type of construction, to predict the electric power consumption for melting the solid charge, you can use the formula of the EAHEM method for specific power consumption

$$p_{sp}\mid I = \left[274,39+\frac{189,025}{1+\left|\frac{G_f}{29,65}\right|^{0.6}}\right] \frac{K_{pl}|_b}{P_U}\left[0,85+0,15\cdot n_{pm}\right]^{0.5}\frac{P_U/I}{P_U/I_{\text{max}}^{0.5}}\cdot\frac{\text{kW}\cdot\text{h}}{\text{ton}} \quad (3)$$

where $G_f$ – furnace capacity in tons, $n_{pm}$ – indicator of the type of furnace design, $P_U$ – useful power.

For low power furnaces $n_{pm}=1$, for powerful furnaces $n_{pm}=2$, for high power furnaces $n_{pm}=3$, for high power furnaces $n_{pm}=4$, for ultra-high power furnaces $n_{pm}=5$.

In the formula (3), the base rate of melting the charge of low-power furnaces ($n_{pm}=1$) can be calculated by the generalized formula
\[
K_{pl}b = 529.5 \left[ \frac{1 + \left( G_f + 144.74 \right) / 181.485}{181.485} \right]^2
\]  
(4)

The melting time of the charge under current taking into account (3) and (4) can be calculated as

\[
\tau_m = \frac{G_f \cdot P_{sp}}{P_U}
\]
(5)

As studies have shown [7], the generalized formula (3) allows with a high degree of reliability to predict the electric power consumption for the melting of a solid charge when setting up and designing an energy-saving electric mode of the active period of the charge melting in the furnace.

For figure 4 on the basis of the described EAHEM method, the operating characteristic of the specific power consumption for melting the charge for the analyzed DSP-200 furnace without taking into account the influence of arc current distortion on the reactivity of the DSP is calculated.

As follows from the calculated characteristics (figure 4), the operating arc current of 43.9 kA on the operating furnace is near the current of 40 kA, at which the electric power consumption will have the lowest values. However, the analysis of the current electrical mode on rationality in this case is difficult because of not taking into account the influence of arc current distortion on the furnace reactivity. This problem of setting up the furnace electrical mode remains unsolved to date because of the methodological uncertainty of the methods used in practice [7].

4. **Method of identification of industrial furnace equivalent circuit working reactance**

The EAHEM method opens a practical opportunity to identify the index of influence of arc current distortion \(K_X\) on the furnace inductance

\[
X_e = K_X \cdot X_{SC}
\]
(6)

where \(X_e\) – the furnace equivalent circuit working reactance; \(X_{SC}\) – the reactance of the first harmonic of the short-circuit experiment.

If for a particular furnace it is known, obtained from the experience of operation, the reliable value of the specific power consumption for the melting of the charge, then it is possible to identify the indicator of the influence of arc current distortion on the furnace inductance. For the case of DSP-200 furnace with an operating current of 43.9 kA, the calculated value of the specific power consumption for melting the charge without taking into account the influence of arc current distortion \((K_X = 1)\) is 283.3 kW·h/ton, which is significantly lower than the value determined on the basis of experience – 400 kW·h/ton [5].

Using the EAHEM method for the melting period of the charge in the DSP-200 furnace, taking the values \(K_X > 1\), we find for the operating current of 43.9 kA the working point at which the specific power consumption for melting the charge will be equal to a certain accuracy to the experimental value of 400 kW·h/ton. When \(K_X = 1.2215\), the calculated value of the specific power consumption for melting the charge is 399.4 kW·h/ton. For the analyzed DSP-200 furnace, the value of the coefficient \(K_X\) during the melting period of the charge is 1.2215, which indicates an increase in the furnace working reactivity compared to the reactance for the first harmonic from the short-circuit experiment \(X_{SC}\) by 22.15%.

Table 1 shows the results of identification of the arc current distortion effect coefficient \(K_X\) for a number of industrial furnaces [5] with the values of specific power consumption for charge melting and charge melting time known from operating experience.
Table 1. Indicators of melting of the solid charge in the industrial furnaces.

| \( G_f \) | tons | 5 | 100 | 200 |
|---------|------|---|-----|-----|
| \( n_{pm} \) – experience | kW·h/ton | 510 | 420 | 400 |
| \( S_t \) | kVA | 2800 | 25000 | 45000 |
| \( U_2 \) | V | 257 | 573 | 591.5 |
| \( I_{oper} \) | kA | 6.3 | 34.6 | 43.9 |
| \( K_X \) | 1.1367 | 1.2225 | 1.2215 |
| \( p_{op} \) – calculation | kW·h/ton | 507.1 | 420.9 | 399.4 |
| \( \tau_{m} \) – calculation | h:min | 1:12 | 2:19 | 2:55 |
| \( \tau_{m} \) – experience | h:min | 1:05 | 2:00 | 3:06 |

Evaluation of the calculated and experimental melting time of the charge indicates a high degree of reliability of the proposed method of identification of the coefficient of influence of arc current distortion on the furnace reactivity during the melting of the charge.

It should be taken into account that the melting time of the charge and the specific power consumption for melting the charge, in addition to the parameters of the electric mode, depend on operational technological factors, including the mass and properties of the charge loaded into the furnace.

Thus, on the basis of the experience obtained, the value of the specific power consumption for the melting of the charge for the furnace operating in the industry can be obtained close to the real value of the working reactivity.

5. Summary

Thus, on the basis derived from experience, values of specific electricity consumption for the melting of the charge for serving industry arc furnaces by using the EAHEM methods, get close to the actual values of the working reactivity.

The described TOMED methods open the possibility to identify the effect of arc current distortion on the furnace reactivity on the basis of calculation of the operating characteristic of the specific power consumption for melting the charge. This requires a reliable value of the specific power consumption for melting the charge, obtained on the basis of generalization of the operating experience of a particular furnace.

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