Analytical study of heat exchange and efficiency of arc in arc steel-melting furnaces of small and large capacity

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Abstract. An analytical study of heat transfer and efficiency of arcs in arc steel furnaces of small and large capacity, 1.5-20 tons and 100-120 tons, respectively. We found out that the reason for the increased specific consumption of electricity for melting the batch in small capacity furnaces is the low efficiency of arcs equal to 0.55-0.57 and the corresponding specific energy consumption for melting 475-500 kWh/t. In furnaces of large capacity the efficiency of arcs is 0.78-0.8 and specific energy consumption is 360-375 kWh/t.

1. Introduction
Arc steel-melting furnaces (ASF) of small capacity are characterized by high specific energy consumption for melting of the charge, and for smelting in general, constituting, respectively, 500-540 and 735-765 kWh/t for furnaces ASF-5 [1-3] and 450-490 and 680-715 kWh/t for furnaces ASF-20 [4,5]. In modern high-power furnaces of large capacity ASF-120, which are melting units, the specific power consumption for melting is 375 kWh/t [6].

From the comparison of specific energy consumption for melting furnaces of small and large capacity, it follows that small-capacity furnaces consume 35-45% more electricity for melting one ton of steel comparing to large-capacity furnaces [6]. Specific power consumption is 20-35% higher in both old and modern furnaces of small capacity, equipped with modern automated control systems (ACS), devices for foaming slag and other devices for intensification of melting [7]. This phenomenon of higher specific energy consumption for melting in low-capacity furnaces in comparison with the same indicator of high-capacity furnaces requires analytical study and subsequent explanation. The attempts are made to explain this phenomenon by a greater specific surface area of the metal, a large heat-emitting surface and large specific heat losses [7]. Nevertheless, with the transfer of large-capacity furnaces to water-cooled walls and roof, the specific losses in furnaces, including those with cooling water, increased [8], and the specific energy consumption in the furnaces remained at the level of 35-45% less than that for small-capacity furnaces. Consequently, the task of determining the reasons for the greater energy consumption for melting in furnaces of small capacity in comparison with the same value in furnaces of large capacity must be solved. To solve this problem, it is necessary to review the evolution of small and large capacity furnaces, calculate the efficiency of arcs in the process of melting the charge and analyze the changes in the efficiency of arcs in furnaces.

2. Comparison of energy parameters of melting in furnaces of small and large capacity
We will conduct an analytical review of the development of furnaces of small and large capacity and changes in the efficiency of arcs in the process of melting steel in furnaces. We will use the method
[9,10] and calculate the efficiency of arcs and other energy parameters of steel melting in furnaces of small and large capacity to explain the increased specific power consumption in the furnaces under consideration. We'll consider the technical characteristics of furnaces of small capacity, ASF-5, with a capacity of 2.8 MVA, and high-capacity ASF-100, with capacity of 45 MVA, the characteristics that the furnace had in the 1980s [4,11,13], and a modern furnace ASF-5 with a capacity of 5 MVA and ASF-120 with a capacity of 100 MVA. The method of calculation and analysis of the energy parameters of melting and efficiency of arc furnaces is described in [9,10].

Let's compare the technical specifications of ASF-5 with a capacity of 2.8 MVA, ASF-100 with capacity of 45 MVA operating in the 1980s with a complete cycle of melting.

The data such as power density, time of melting of the charge, the time of the melting in furnaces of small and large tonnage were almost equal. However, the specific consumption of electricity for pre-heating and melting in the ASF-5 is about 20-40% bigger than in the ASF-100. The walls and arch of the furnaces ASF-5, ASF-100 are lined. The wearout of the walls in the furnaces differed significantly. The current in the ASF-100 is 50 kA, it acts by a significant radial electrodynamic force on the arc, the latter acts by an axial force on the metal bath, causing a deepening in the bath in which the arc is immersed [11,12]. As a result of the influence of the radial electrodynamic force and the horizontal deflecting electromagnetic force, the arc is partially immersed in the metal bath and occupies an inclined position at an angle of 30–45° to the electrode axis. As a result of this position of the arc in ASF-100 its radiation in the lower part of the walls decreases, and increases in the middle part.

In modern high-power furnaces of high capacity (ASF-120) the melting of the charge is carried out, other technological operations are derived in the units of secondary processing of steel. The furnace is equipped with gas-oxygen burners (GOB), devices for foaming slag (FSD). Over the past 30 years, the characteristics of ASF-100 and ASF-120 have been increased the following parameters: specific power – by 2 times, the voltage and, accordingly, the arc length – by 2-3 times, current – by 1.5 times; the melting time of the charge – by 1.5-2 times, the specific energy consumption for melting – by 15%.

3. Calculation and analysis of energy parameters of melting and efficiency of arc in furnaces of small and large capacity

To calculate the average efficiency of arc furnaces during the melting period and the subsequent explanation of the increased specific energy consumption in small-capacity furnaces compared to large-capacity furnaces, the data for the energy balances of the smelts are required. The measurements of energy balances of furnaces are long, time-consuming, expensive experimental studies carried out on furnaces by teams that include, as a rule, researchers from several organizations. For example, in the late 1970s and early 1980s, All-Union Scientific Research Institute of Electrothermal Equipment (in Russian – VNIIETO) employees spent 10 years conducting experimental studies of the energy balance of furnaces of the whole range of furnaces of small, medium, large capacity form ASF-1.5 to ASF-200. The composition of the research team included staff from Centerenergochermet, South-east Energochermet, Research Institute of Metallurgy, All-Russian Research Institute of Automation of Ferrous Metallurgy (in Russian – VNIChAM) and employees of the factories, which conducted the study. The results of the energy balance of furnaces with a capacity from 1.5 to 200 tons are presented in [11]. Similarly to furnaces of small capacity of ASF-5 the main source of energy are electric arcs and specific power consumption for the last 30 years, despite the increase in power and productivity of the furnace by 1.8 times, has not changed, therefore, the conditions of heat exchange of arcs with metal, slag and the efficiency of arc furnaces have not changed. Thus, it is possible to use the data of energy balances of melts during the melting period in ASF-5 and ASF-100 [11] and the energy balances of the melting furnace ASF-120 [6] to calculate and analyze the efficiency of arcs and other energy indicators of melting, to calculate and explain the reasons for the increased specific consumption of electricity by small-capacity furnaces compared to large-capacity furnaces. We will use the results of studies of energy balances [6,11] and calculate the energy parameters of melting.
Specific power consumption for melting in ASF-120 is 375 kWh/t, in furnace ASF-100 is 425 kWh/t, or 13% more than in the ASF-120, in ASF-5 is 475 kWh/t or 27% more than in the ASF-120. The lower specific consumption of electricity for melting in ASF-120 is due to the use in the process of melting the charge of GOB and FSD [14,15]. However, the specific consumption of total energy for melting in the ASF-120 is higher than in ASF-100, ASF-5, the explanation of this phenomenon can be found in the energy balances of the melting period in the furnaces [6,11]. Data of energy balances [6,11] will be supplemented by the following calculations.

The specific useful energy Q_{um} of the melting period is defined as the sum of heat content of steel of Q_{st} and Q_{sl} slag:

$$Q_{um} = Q_{st} + Q_{sl}$$  \hspace{1cm} (1)

In furnaces of ASF-5, ASF-100, the advent of energy are: electricity Q_{e}, the energy of the oxidation reactions of Fe, Mn, Si Q_{F} and energy of the charge Q_{M}, so the specific useful energy arcs Q_{au} in furnaces ASF-5, ASF-100 we define as the difference between the useful energy Q_{um} and energy of the oxidation reaction Q_{F}, the energy of the charge Q_{M}, electrical losses ΔQ_{e}. Given that the reaction efficiency Q_{F} and the efficiency Q_{M} is 1, we obtain:

$$Q_{au} = Q_{um} - Q_{F} - Q_{M} - \Delta Q_{e}$$  \hspace{1cm} (2)

where η_{gc}, η_{kc} is the efficiency, respectively, of the GOB torch and the oxidation reaction of coke and electrodes.

In [10] the calculations of the efficiency of the torch GOB, the reaction of oxidation of coke and electrodes and useful energy arcs Q_{au} for the balance of the melting period the melting ASF-120, Q_{au} = 277 kWh/t. We present the value of Q_{au} in Table 1. The average efficiency of arc η_{av} for the period of melting is defined as the quotient of the division of the specific useful energy of arcs by the specific consumption of electricity released in arcs Q_{ea}:

$$\eta_{av} = \frac{Q_{au}}{Q_{ea}}$$  \hspace{1cm} (3)

where η_{gc}, η_{kc} is the efficiency, respectively, of the GOB torch and the oxidation reaction of coke and electrodes.

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$$\eta_{av} = \frac{Q_{au}}{Q_{ea}} = \frac{Q_{au}}{Q_{e} - \Delta Q_{e}}$$  \hspace{1cm} (4)

where Q_{e} is the supply of specific electrical energy.

The average thermal efficiency of the furnace for the period of melting is defined as the quotient of the useful energy by the supplied energy of Q_{e}:

$$\eta = \frac{Q_{au}}{Q_{e}}$$  \hspace{1cm} (5)

The energy balances data [6,11] as well as the results of calculations of the useful energy of the melting period, the useful energy of the arcs, the efficiency of the arcs, the thermal efficiency are presented in Table 1.
According to Table 1, dependences of change of average efficiency of arcs and specific consumption of electric power on melting depending on capacity, intensification of processes of melting of steel in furnaces are constructed (Figure 1). Depending on the capacity of the furnaces, the average arc efficiency increases from the minimum values of 0.55-0.57 in low-capacity furnaces without using GOB, FSD to 0.78-0.80 in heavy-duty furnaces, which use GOB, FSD (Figure 1, curve I). On the contrary, the specific energy consumption for melting the charge has the highest value of 475-500 kWh/t in low-capacity furnaces with the lowest efficiency, decreases depending on the increase in capacity and efficiency of arcs, reaching the lowest value of 360-375 kWh/t in heavy-duty furnaces with the highest efficiency of arcs (Figure 1, curve II).
4. Calculation and analysis of ARC efficiency in small and large capacity furnaces

The specific useful energy in the three surveyed furnaces is approximately the same, which confirms the correctness of the energy balances [6,11] and the calculations performed. A little bit higher useful energy in ASF-120 is due to the higher metal temperature and the higher amount and temperature of slag in the furnace. The total specific energy losses in ASF-100 have the lowest value of 25%, in ASF-120 is 33%, in ASF-5 is 36.5%. Specific energy losses of 33% in ASF-120 furnace are explained by the intensification of the steel smelting process in the furnace, the application of alternative energy sources, natural gas, coke, and, as a consequence, a 3.5 times increase in the specific losses when utilizing cooling gases. In ASF-5 is GOB, FSD is not used and the total specific losses are 36.5%, which can be explained by the low average for the melting period efficiency of arc $\eta_{av} = 0.57$. In furnaces ASF-100, ASF-120 average for the period of melting efficiency of arcs are, respectively, 0.67 and 0.78.

In the furnace ASF-5 average thermal efficiency is also the lowest value $\eta_t = 0.64$, the highest $\eta_t = 0.75$ in ASF-100, in the ASF-120 $\eta_t = 0.68$. In the ASF-100 energy to melt the charge is introduced by electric arcs, the efficiency of which $\eta_{av} = 0.67$, and the use of the oxidation reaction energy $Q_F$ with efficiency equal to one. In ASF-120 energy is introduced using arcs with $\eta_{av} = 0.78$, GOB with an efficiency of 0.45-0.55 and the oxidation reaction of coke and electrons with an efficiency of 0.35-0.45 [10], so the average thermal efficiency of the furnace $\eta_t = 0.68$. Input of energy into the furnace by means of electric arcs is the most effective way with the maximum efficiency, heat of GOB, coke and electrodes is less effectively used. However, the use of coke powder in FSD can increase the height of the slag layer and bury the arc in the slag, increasing their efficiency. In furnace ASF–100 that is not equipped with a FSD the height of the slag layer $h_s = 100$ mm and $\eta_t = 0.67$, in ASF-120, $h_s = 240-360$ mm and $\eta_t = 0.78$. In furnaces of ASF–5 the height of the slag layer $h_s = 35$ mm, the length of the arc in the period of melting is 115-135 mm, 60-70 % of the length of the arc is closed by the slag and the arc is 2/3 of the power radiates into the lining of the walls and the vaulting, which corresponds to the efficiency of the arc at the end of the melting of $\eta_t = 0.35-0.4$ [12]. At the beginning of melting when burning arcs in the well in the charge in ASF-5 is $\eta_t = 0.8-0.85$, and the average melting efficiency is equal to $\eta_{av} = 0.57$. Based on the fact that the average efficiency of arcs of ASF–5 is $\eta_{av} = 0.57$, it follows that during the period of melting about 43% of the heat radiation flux of arcs falls not onto the charge, the metal bath, the slag, but onto the lining of the walls and arch, causing their overheating, melting and the wear-out of the lining. Information on wear, the fusing of the lining of the walls of the arcs is described in detail in [1]
5. Conclusions
The analytical study revealed the reasons of the increased specific consumption of electricity for the melting of the charge in arc steel furnaces of small capacity of 1.5–20 tons, compared to the furnaces of large capacity of 100-120 tons. After performing the necessary calculations we can conclude that in furnaces of small capacity compared to large capacity furnaces, the arc energy efficiency of small capacity furnaces is lower by 27%. This explains the fact that specific energy consumption of small furnaces is higher than that of furnaces with large capacity.

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