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Calculation and analysis of the arcs efficiency of small and large capacity arc steel-melting furnaces

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Abstract. In the course of the research, the calculation and performed analysis of the arc efficiency of furnaces ASF-5 and ASF-100 power furnaces were performed and the average arc efficiency for melting was determined. The reasons of the increased specific consumption of electric power on charge melting by arc steel-melting furnaces of small capacity in comparison with heavy-load furnaces are revealed. Efficiency of arcs of low-tonnage furnaces is much less than the same indicator of modern heavy-duty arc steel-melting furnaces (ASF). Low efficiency of arcs of light-duty furnaces leads to a significant specific power consumption for smelting, comprising 700-750 kWh/t, that is 1.9-2 times higher than the specific energy consumption in modern furnaces ASF-120, amounting to 375 kWh/t. With the use of devices for foaming slag in furnaces ASF-5 the average melting efficiency of furnaces can be increased, and the specific electricity consumption for melting will be reduced to 440-480 kWh/t.
Keywords: electric arc, furnace, steel, efficiency, thermal radiation

1. Introduction

Modern advances in steel electrometallurgy are determined by a new generation of energy-saving arc steel-melting furnaces (ASF). Electric furnaces are considered as steelmaking units, providing a breakthrough in modern metallurgy. The results and prospects for the development of furnaces and electric steel production show the complex path of the innovation process from the emergence of a new technical idea to its implementation and entry into the market of modern technologies and equipment. New technological solutions lead to radical innovative changes in the design of furnaces and in the design solutions of electric steelmaking shops and complexes.

In the process of reconstruction, it is important to choose the direction of technical re-equipment of furnaces to increase productivity, reduce energy consumption and environmental impact. Furnaces of small capacity, these include furnaces with a capacity of 1.5 to 20 tons of metal, are characterized by increased specific electricity consumption for melting the charge and for melting as a whole, which is, respectively, 700-750 kWh/t for 5-ton ASF-5 furnaces. In modern high-power high-capacity furnaces with a capacity of 80 to 180 tons, which are melting units, the specific electricity consumption for melting is 375 kWh/t. Figure 1 the filling of the charge in a small capacity ASF-5 (a) and a large capacity furnaces-120 (b) is shown.

From the comparison of the specific energy consumption for melting in small and large capacity furnaces, it follows that small capacity furnaces consume 35-45% more electricity for melting one ton of steel compared to large capacity furnaces. Specific power consumption is 20-35% higher both in

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old and modern low-tonnage furnaces equipped with modern automated control systems (ACS), devices for slag foaming and other devices for smelting intensification [1, 9, 13].

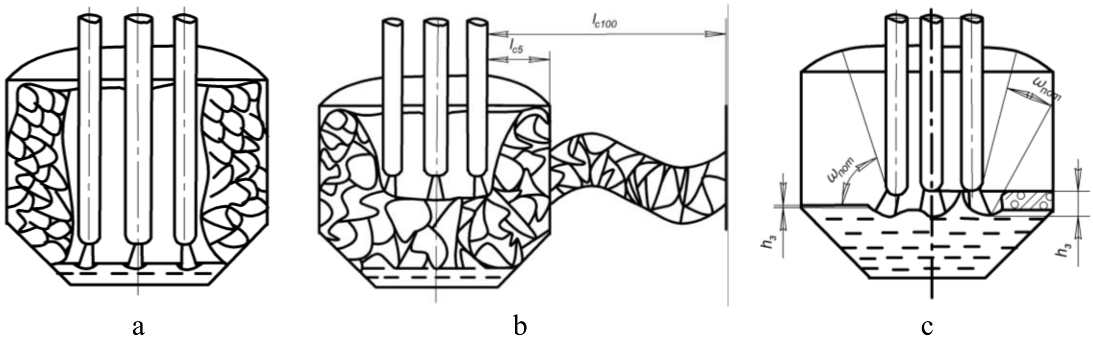

Figure 1. Cutting wells and melting the charge in the furnace ASF-120 (a), ASF-100, ASF-5 (b) and deepening the arc in the metal and slag in the furnace ASF-120 (right side figure c), ASF-5 (left side figure c).

It is necessary to solve the problem of determining the causes of high power consumption for melting in low-capacity furnaces compared to the same indicator of high-capacity furnaces. To do this, we reviewed the development of low-tonnage and heavy-duty furnaces, and calculated the efficiency of arcs in the process of melting the charge and analyzed the changes in the efficiency of arcs in furnaces.

2. Analysis of ASF of small and large capacity

We will analyze the development of small and large capacity furnaces and changes in the efficiency of arcs in the process of melting steel in furnaces. According to the method developed by the author [2, 3], the efficiency of arcs and other energy parameters of steel melting in low-tonnage and heavy-load furnaces were calculated. We reviewed and compared the technical characteristics of the ASF-5 and ASF-100 furnaces, which the furnaces had in the 1980s and in the 2010s. The method of calculation and analysis of energy parameters of melting and efficiency of furnace arcs is described in [2, 3, 12].

In the 2000s, transformers with a capacity of 5 MVA were installed on the ASF-5 furnace. The specific capacity of modern ASF-5 furnaces is 1000 kVA/t, it exceeded the specific capacity of modern ASF-100 furnaces by 20%. However, by increasing the capacity of the furnace ASF-5, without the use of other methods of intensification of melting, breakthrough technical and economic results of the furnace could not be obtained [15, 16].

We found out that equipping a furnace ASF-5 with a transformer of 1.8 times more power, without the equipment of gas-oxygen burner (GOB) and devices for slag foaming (DSF), led to higher furnace productivity by 1.8 times, but did not reduce the specific consumption of electricity for melting and for melting. This approach was not effective. Furnaces ASF-5, ASF-100 worked in the 1980s in equal conditions. We compared the technical characteristics of the furnaces ASF-5, capacity of 2.8 MVA, and furnaces ASF-100, capacity of 45 MVA, working in the 1980s with a full cycle of melting. In ASF-100 furnaces the maximum of thermal radiation of arcs is opposite to arcs in the middle of height of walls from level of a bath of metal [4]. On the lining in the middle of the height of the walls formed hot spots from thermal radiation arcs, causing reflow lining. In the lower and upper parts of the walls refractories had wear not exceeding 20-30% [4]. However, since the refractories in the central part of the height of the walls had a wear of 90-95%, it was necessary to stop the furnace for repair, destroy the masonry of the old walls, install new masonry walls. The walls lined with refractory brick in furnaces ASF-100 had a small resistance to an average of 200 heats.

In the ASF-5 furnace, the arc current is 6.3 kA, it does not have significant radial and axial forces, does not cause a deepening in the metal bath, the arc deviation is 15-20° to the electrode axis. As a result of this position of the arcs in the ASF-5 furnace, the maximum thermal radiation of the arcs and the wear of the walls are concentrated mainly in the lower part of the walls near the slopes [4]. After each melting, the walls are restored with refractory powder. In ASF-100 furnaces it is impossible to restore walls as filling powder rolls down from a vertical surface of walls. Resistance of lined vaults of furnaces ASF-5, ASF-100 differs slightly as the reason of wear of lining of arches in furnaces of small and big capacity is radiation of a high-temperature surface of electrodes [4].

In modern high-power heavy-duty furnaces ASF-120 charge melting is carried out, other technological operations are derived in the units of secondary processing of steel. The furnace is equipped with oxygen-gas burners, devices for foaming slag [5,11,19]. For the thirty-year period at heavy-load furnaces of ASF-120, in comparison with ASF-100 the following parameters increased: specific power in 2 times, tension and, respectively, arc length in 2-3 times, current in 1,5 times; the melting time of the charge decreased by 1.5-2 times, the specific electricity consumption for melting by 15%, the furnaces were equipped with water-cooled panels of walls, vaults, modern ACS, GOB, DSF (Figure 2).

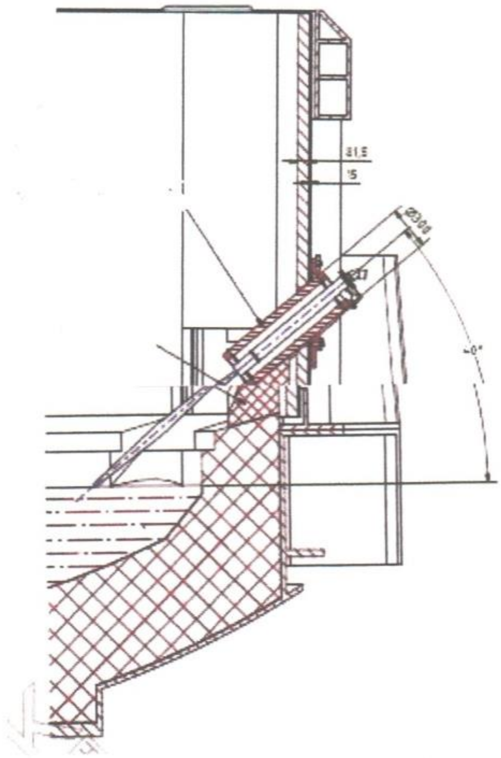

Figure 2. Combined use of the manipulator for foaming slag and oxygen burner in the furnace

3. Calculation of the arcs efficiency of ASF of small and large capacity

Calculations revealed that, depending on the capacity of the furnaces, the average efficiency of arcs increases from the minimum values of 0.55-0.57 in low-tonnage furnaces without the use of GOB, DSF to 0.78-0.80 in heavy-duty furnaces in which GOB, DSF are used. The specific power consumption for charge melting, on the contrary, has the highest value of 475-500 kWh / t in low-tonnage 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 [5,6].

In the ASF-5 furnace, the average thermal efficiency has the lowest value $\eta_h = 0.64$, the highest $\eta_h = 0.75$ in the ASF-100 furnace, in the ASF-120 furnace $\eta_h = 0.68$. In the furnace 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 energy of the metal oxidation reaction C efficiency equal to one. In the furnace 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 [3], so the average thermal efficiency of the fur-

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nace η_h = 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 DSF allows to increase the height of the slag layer and to bury the arcs in the slag, increasing their efficiency. In furnaces ASF-100 without DSF slag layer height h_{sl} = 100 mm and η_a = 0.67, in furnaces ASF-120, h_{sl} = 240-360 mm and η_a = 0.78. In ASF–5 furnaces, the height of the slag layer h_{sl} = 35 mm, the arc length during the melting period is 115-135 mm, 60-70% of the arc length is not covered by slag and the arc radiates 2/3 of the power to the lining of the walls and arch, which corresponds to the efficiency of the arc at the end of the melting η_a = 0.35-0.4 [4]. At the beginning of the melt when burning arcs in the well in the charge in the furnace ASF–5 η_a = 0.77, and the average for the melting efficiency is equal η_{av} = 0.57. Based on the fact that the average efficiency of arcs ASF-5 η_{av} = 0.57 it follows that during the melting period about 43% of the thermal radiation flux of arcs falls not on the charge, metal bath, slag, but on the lining of the walls, the arch, causing their heating, melting, wear of the lining. Due to the fact that in the ASF-5 furnaces the arcs are at a distance of less than 1 m from the walls, the radiation of the arcs reaches the walls and is uselessly spent on heating and melting the lining. The efficiency of arcs in ASF-5 furnaces is reduced compared to ASF-120 furnaces, in which the arc radiation does not reach the lining and is useful for heating and melting the charge.

The average fusion efficiency of arcs of the furnace ASF-5 34% less than the average for the period of melting and smelting on the whole efficiency of arcs η_{av} = 0.78 furnace ASF-120 and 16% less than η_{av} = 0.67 furnace ASF-100. The low average melting efficiency of low-tonnage furnace arcs is the reason for the increased specific energy consumption in the furnaces. The average melting efficiency of arcs in low-tonnage ASF-5 η_{av} = 0.58 (Figure 3, c), which corresponds to the specific consumption of electricity for melting 700-790 kWh/t. The average melting efficiency of arcs in heavy-duty furnaces, in ASF-100, which worked in the 1980s under the same conditions as low - tonnage furnaces with a full melting cycle, is η_{av} =0.67-0.72, and the specific electricity consumption is 420-460 kWh/t [4,5]. The ARC efficiency increases with the depth height h_d of the arc penetration into the metal and slag. In ASF-5 furnaces, the arc depth height h_d =37-40 mm, the average arc efficiency during the melting period η_{av} = 0.57, the specific electricity consumption for melting is 475 kWh/t. In ASF-100 furnaces, the depth height of the arc h_d = 140-150 mm, the average efficiency of the arc η_{av} = 0.67, the specific power consumption for melting is 425 kWh / t.

In furnaces of ASF-120 height of deepening of arcs h_d= 240-410 mm, average efficiency of arcs η_{av} = 0.78 (Figure 1,b) specific energy consumption for melting of 375 kWh/t. Thus, the larger the height of the slag layer , penetration of the arc into the metal and slag, the greater efficiency of the arc and the less the specific energy consumption in furnaces. By foaming slag in low-tonnage furnaces up to 100-150 mm, it is possible to bury the arc in the slag and increase their efficiency during the melting period and for melting as a whole to η_{av} = 0.72-0.74, and the specific electricity consumption for melting and melting as a whole is reduced to 440-480 kWh/t, reduce the melting time, increase the productivity of furnaces.

The results of energy balances in small and large capacity furnaces [6-8], as well as the results of arc efficiency calculations show that it is impossible to achieve efficiency at the beginning of the melting period in small capacity furnaces greater than η_a = 0.77 (Figure 3, a). For the first 20 mins of the melting period, the average efficiency of arcs furnace ASF-5 amounted η_{av} = 0.77, analyzed over the first 20 minutes of the period, the melting efficiency of the arcs in furnaces ASF-120, ASF-100 made up η_{av} = 0.83 (Figure 3, b) or 8% more compared to low-tonnage furnaces. Since the specific consumption of electricity in the furnaces is directly proportional to the efficiency of arcs, the specific consumption of electricity for the first 20 minutes. Melting in the ASF-5 furnaces will be 8-10% more than in the ASF-120, ASF-100 furnaces.

Figure 1 shows a section of the working space during the cutting of wells and melting of the charge in furnaces ASF-120 (figure 1, a), in furnaces ASF-5, ASF-100 (figure 1, b) and the penetration of arcs into metal and slag in the liquid periods of melting in the furnace ASF-120 (right part figure 1,c), in the furnace ASF-5 (left part figure 1,c). Lining of the hearth, slopes, walls, arch, water-cooled panels are not shown. On the figure 1 different scales of construction of furnaces are accepted, therefore furnaces ASF-120, ASF-100, ASF-5 are represented in identical dimensions. In the furnace ASF-120 arcs at the beginning of the melting period introduced a large power, about 70 MW, arcs for 6 min. cut one common well in the charge and burn inside the well (figure 1, a). At such position of arcs their efficiency is equal to $\eta_a = 0.93$ and 93% of power of arcs is radiated by them on a metal bath and a firm charge and it is useful spent on their heating and melting. Arc radiation power loss is 7%.

a

b

Figure 3. Charge loading in small-capacity chipboard DSP-5 (a) and large-capacity chipboard DSP-120 (b)

In the ASF-5 of power of arcs at the beginning of melting is 2.7 MW, this power is not enough for cutting a common well in the charge for 6 minutes. In the ASF-5 of melting the charge, the arcs create three shallow wells, 1/3 the height of the charge, which after 10-12 minutes of melting are combined into one common well (figure 1, b). Cutting wells in the furnace ASF-5 is slow, there are collapses of the charge and short circuits of the arc, the molten metal flows down into the bath (figure 1, b). Part of the thermal radiation of the arcs comes out of the well and falls on the central part of the arch of the furnace, the efficiency of the arcs is reduced. The depth of wells with the melting of the charge in a furnace ASF-5 lasts 20 minutes. Through 17-20 shadowing electrodes and arc in furnace ASF-5 are lowered until liquid metal baths, their length expands in 8-10 times and, so as wall on 1/2 - 2/3 its heights freed from charge, then arc radiate 60-65% capacity on vault and wall and 35-40% on charge and bath metal, efficiency arcs declines until 0.35-0.40. At the 20th minute of melting, the voltage stages are switched, the voltage, current, length, power of the arcs and reduced efficiency of the arcs is increased to 0.44. Similarly, during all periods of melting, oxidizing, refining, reduce the voltage, length, current, arc power, increasing the efficiency arc within 0.5-0.76. However, such maneuverable operation of the ASF-5 furnace does not lead to a significant increase in the efficiency of the furnace arcs during the melting period, which is $\eta_{av} = 0.57$.

Compared with the ASF-5 furnace ASF-100 worked in a similar mode of melting charge, the power of the arcs was 25-26 MW, which is not enough to cut through the well for 5-6 minutes the well cutting in the furnace ASF-100, similar to the furnace ASF-5, lasted 20 minutes, after which the arcs burned on a liquid metal bath. However, the average efficiency of arcs in the furnace ASF-100 for the melting period $\eta_{av} = 0.67$, and in the furnace ASF-5 the same $\eta_{av} = 0.57$. Therefore, the reason for the lower efficiency of arcs during the melting period in the ASF-5 furnace compared to the same indicator in the ASF-100 furnace is not the slow cutting of wells, but another, let's find it.

In the furnaces ASF-100, ASF-120 the distance between the arcs and the refractory or water cooled panels of the walls is more than 3m and the thermal radiation of arcs passing between adjacent arcs voids between the pieces of the charge, gets into pieces following radial layers of the charge and does not reach the walls, it is useful spending on heating and melting of the charge. During the next melting in the open periods, the temperature of the lining of the walls in the ASF-100 furnace reaches 1500°C. After filling the charge and the beginning of melting, cutting wells in the charge, the lining temperature begins to decrease. The decrease in the temperature of the lining of the walls of the furnace ASF-100 is due to the fact that the thermal radiation of the arcs does not reach the lining of the walls and the lining, which has a temperature of 1500°C, begins to give thermal energy to a colder charge. The process of transferring thermal energy to the charge by lining the walls continues during the entire period of melting of the charge [17, 18].

On the whole, for melting the efficiency of arcs in furnaces ASF-100 η_{ASF} = 0.68-0.72 and the specific consumption of electricity for melting 475-500 kWh/t, which is 35-50% less than in low-tonnage furnaces ASF-5, where Q_e = 640-750 kWh/t and the arc is half immersed in slag [20]. The above is illustrated in figure 1,where the right side of the figure shows schematically thermal performance of the arc furnace ASF-100, in the left part of the figure thermal performance of the arc furnace ASF-5, and the solid angle of the loss ω_{con} demonstrates the loss of thermal radiation of the arc, thermal radiation arcs on the walls and roof of the furnace, the solid angle of the loss of thermal radiation of the arc ω_{con} minimum in heavy furnaces ASF-100, ASF-120 and the maximum in light-duty furnaces of ASF-5.

4. Conclusion.

The reasons of the increased specific consumption of electric power on charge melting by arc steel-melting furnaces of small capacity in comparison with heavy-load furnaces are revealed. The compared furnaces ASF-5, ASF-100 worked in equal conditions without gas-oxygen burners, devices for foaming slag with a full cycle of melting. The performed calculations helped to find out that in low-tonnage furnaces compared with heavy-duty furnaces, the efficiency of arcs is less important, which affects the increased specific consumption of electricity in low-capacity furnaces compared to heavy-duty furnaces. To increase the efficiency of arcs and reduce the specific power consumption in low-tonnage furnaces, it is necessary to increase the slag height by using slag foaming devices.

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References

[1] Bershiczkij I M and Protasov A V 2015 Nekotory`e osobennosti i perspektivy` razvitiya malotonnoj e`lektrometallurgii [Some features and prospects of development of low-tonnage electrometallurgy] *Elektrometallurgiya* **10** 28-35 [In Russian]

[2] Kuznetsov M S et al 2010 Vliyanie massy metalloshihty I tolshiny shlaka na tekhnologiyu vyplavki stali v dugovoj pechi [Influence of mass of a metal charge and thickness of slag on technology of melt of steel in the arc furnace] *Electrometallurgy* **2** 2-6 [In Russian]

[3] Shakirov Z, Shumakov A M, Uryupin G P, Zinurov I Y and Zapolsky A A 2013 Osobennosti tekhnologii vyplavki stali v elektropechi DSP-120 Consteel i puti ee sovershenstvovaniya [Peculiarities of the technology of smelting steel in an electric furnace DSP-120 Consteel and ways of its improvement] *Elektrometallurgiya* **9** 2-7 [In Russian]

[4] Nikolsky L E, Smolyarenko V D and Kuznetsov L N 1981 *Teplovaya rabota dugovykh staleplavilnykh pechej* [*Thermal operation of arc steel-melting furnaces] (Moscow: Metallurgiya) [In Russian]*

[5] Makarov A N 2019 Raschet i analiz vzaimosvyazi KPD i raspolozheniya dug s e`lektropotrebleniem v dugovy`x staleplavil`ny`x pechax maloj i bol`shoj vmestimosti. Chast` I. Raschet i analiz vzaimosvyazi KPD dug i e`lektropotrebleniya [Calculation and analysis of the relationship between efficiency and location of arcs with power consumption in arc steel furnaces of small and large capacity. Part I. Calculation and analysis of the relationship between arc efficiency and power consumption] *Metallurg* **4** 29-35 [In Russian]

[6] Samways N 2005 Revitalized with a new continuous steelmaking process *Iron and Steel Technology* **6** 29-45
[7] Nikol\`skij L E, Smolyarenko V D and Kuzneczov L N 1981 *Teplovaya rabota dugovy\`x staleplavil\`ny\`x pechej* (Moscow: Metallurgiya) [In Russian]
[8] Evstratov V G, Kiselev A D , Zinurov I Yu , Shaxirov Z X , Mamenko Yu F , Shumakov A N and Gindullin M G 2012 Osobennosti teplovoj raboty\` e\`lektropechi DSP-120 Consteel na Ashinskom metallurgicheskom zavode [Features of thermal operation of electric furnace ASF-120 Consteel at Ashinsky metallurgical plant] *Elektrometallurgiya* **8** 2-6 [In Russian]
[9] Gudim Yu A, Zinurov I Yu, Kiselev A D and Shumakov A M 2005 Racional\`ny\`e sposoby\` intensifikacii plavki v sovremenny\`x dugovy\`x staleplavil\`ny\`x pechax [Rational methods of intensification of melting in modern arc steel furnaces] *Elektrometallurgiya* **9** 2-6 [In Russian]
[10] Makarov A N, Rybakova V V and Galicheva M K 2014 Electromagnetic and the Arc Efficiency of Electric Arc Steel Melting Furnaces *J. of Electromagnetic Analysis and Applications* **6** 184-92
[11] Makarov A N 1994 Raschet izlucheniya dugi zaglublennogo plazmotrona v plazmenno-dugovoj pechi [Calculation of arc radiation of a buried plasmatrona in a plasma-arc furnace] *Izvestiya vuzov. Chernaya metallurgiya* **6** 14-6 [In Russian]
[12] Makarov A N 2016 Calculations of heat transfer in torch furnaces by gas volume radiation haws *Word J. of Eng. and Technology* **4** 488-503
[13] Krivandin V A 2001 E\`nergosberezhenie kak rezul\`tat neprery\`vnogo sovershenstvovaniya teplovoj raboty\` i konstrukcii nagrevatel\`ny\`x ustrojstv [Energy saving as a result of continuous improvement of thermal operation and design of heating devices] *Izvestiya vuzov. Chernaya Metallurgiya* **7** 48-54 [In Russian]
[14] Kuzneczov L N, Pirogov N A and Egorov A V 1981 Raschet parametrov dugovy\`x staleplavil\`ny\`x pechej dlya plavki metallizirovanny\`x materialov [Calculation of parameters of arc steel furnaces for melting metallized materials] *Issledovanie v Oblasti Promyshlennogo Elektronagreva: sb. tr. VNIIE\`TO* 88-97 [In Russian]
[15] Borovinskih S V 2007 V Rossiyu prihodit innovacionnyj elektrostaleplavilnyj process [Russia comes innovative steelmaking process] *Elektrometallurgiya* **9** 13-6 [In Russian]
[16] Bourne K and Granderat R 2013 Potentsialnye vozmozhnosti I problemy utilizatsii tepla v staleplavilnykh pechah [Potential opportunities and problems of utilization of heat in steelmelting furnaces] *Metallurgicheskoye Proizvodstvo i Tekhnologii* **2** 8-19 [In Russian]
[17] Timofeev E S, Timofeeva A S and Fedina V V 2009 Issledovanie e\`nergotexnologicheskogo rezhima DSP-150 pri plavke stali s primeneniem v shixte goryachebriketirovannogo zheleza [Investigation of energy-technological regime of ASF-150 during steel melting with application of hot-briquetted iron in charge] *Elektrometallurgiya* **8** 6-9 [In Russian]
[18] Makarov A N 2017 Izmenenie KPD dug v processe plavki v dugovy\`x staleplavil\`ny\`x pechax [Change of efficiency of arcs in the process of melting in arc steel-melting furnaces] *Metallurg* **4** 55-8 [In Russian]
[19] Argenta P and Corbella M 2006 EAF integration info the blast furnace route at Wheeling Pittsburgh *MPI International* **2** 42-7
[20] Makarov A N 2014 Theory of radiative heat exchange in furnaces, fire boxes, combustion chamber is replenished by four new laws *Science Discovery* **2** 34–42