

ANALYSIS OF ENERGY EFFICIENT SOLUTIONS OF A SMALL CAPACITY ELECTRIC ARC FURNACE AND THEIR SYNTHESIS IN A NEW GENERATION 15-TON UNIT

On the basis of mathematical modeling and numerical experiment were analyzed the factors to increase energy efficiency of the electric arc furnace (EAF) of a small capacity. Optimization of depth of the steelmaking bath is performed, which in combination with the bath blowing by an inert gas provides lowering of radiation heat loss by 21%; enhances heat- and mass transfer by 11-16%, heating and homogenization of liquid steel by 8%. Implementation of energy saving water-cooled panels and a system of dispersed aspiration reduce heat loss and fugitive emissions. The synthesis of innovative solutions in 15-t EAF will reduce total energy consumption by 3 - 5%.

Keywords: electric arc furnace, energy efficiency, geometry of the bath, energy-saving panels, dispersed aspiration system.

На основі математичного моделювання і чисельного експерименту проведено аналіз чинників підвищення енергоефективності дугової сталеплавильної печі (ДСП) малої місткості. Виконано оптимізацію глибини сталеплавильної ванни, що в поєднанні з продувкою інертним газом, зменшує втрати тепла випромінюванням на 21%; прискорює процеси тепло- і масообміну на 11-16%, нагріву і усереднення металу на 8%. Енергозберігаючі водоохолоджувані панелі і система розосередженої аспірації сприяють зниженню втрат тепла і неорганізованих викидів пилогазового середовища. Синтез інноваційних рішень в 15-т ДСП дозволить знизити загальне енергоспоживання на 3 - 5%.

Ключові слова: дугова сталеплавильна піч, енергоефективність, геометрія ванни, енергозберігаючі панелі, система розосередженої аспірації.

На основе математического моделирования и численного эксперимента проведен анализ факторов повышения энергоэффективности дуговой сталеплавильной печи (ДСП) малой вместимости. Выполнена оптимизация глубины сталеплавильной ванны, что в сочетании с продувкой ванны инертным газом, снижает потери тепла излучением на 21%; ускоряет процессы тепло- и массообмена на 11-16%, нагрева и усреднения металла на 8%. Энергосберегающие водоохлаждаемые панели и система рассредоточенной аспирации способствуют снижению потерь тепла и неорганизованных выбросов пылегазовой среды. Синтез инновационных решений в 15-т ДСП позволит снизить общее энергопотребление на 3 - 5%.

Ключевые слова: дуговая сталеплавильная печь, энергоэффективность, геометрия ванны, энергосберегающие панели, система рассредоточенной аспирации.

Formulation of the problem. The general trend of the steel industry, including Ukraine, is the development of energy efficient and environmentally friendly mini-mills on the basis of EAF. As the charge for them it can be used not only scrap, but also metallized materials, including those obtained from the accumulated technological and reproducible metallurgical wastes. In the last decade there has been a tendency to build micro-mills targeted at a relatively small (up to 100-200 thousand tons per year) regional needs in the

metal specific brands and profiles [1]. There is a need for a new generation of energy-efficient EAF for such enterprises.

Analysis of recent research and publications. The leading in steelmaking equipment companies "Siemens-VAI Metals Technologies, "Danieli" created a series of special new generation micro-EAF with a capacity from 5 to 35 tons. The general trends of technical solutions are [2, 3]:

- Modular design to quick change the capacity and technological options of the EAF;

- Widespread use of water-cooled wall and roof elements;

- Utilizing the heat of exothermic reactions with purge the liquid bath by oxygen and carbonaceous powder injection and due to forced mixing by carbon oxidation products;

- Foamed slag practice to reduce electric heat loss by arc radiation and improve heat energy transfer to liquid bath.

Energy efficiency of the EAF determines, mainly, by radiation heat loss, absorbed in water-cooled panels, and by off-gas removal, which together make up more than 90% of total energy loss [4]. This position is more pronounced for micro-EAF, in which the specific energy loss with cooling water and the off-gas removal through traditional “suction elbow” considerable higher than in large furnaces. Thus, the use of cooling and aspiration systems, typical for high-performance EAF, leads to increase of energy loss in a small capacity EAF.

According to above mentioned, actual task of Ukrainian industry is development and implementation of energy efficient and competitive EAF with average capacity 12-15 tons, which can operate both with intensive technology as a smelting unit at a micro- mill, and with classic technology in foundries.

The purpose. This work aims to analyze the factors increasing the energy efficiency of micro-EAF on base of mathematical and numerical modeling of heat and mass transfer, fluid and gas dynamics in the workspace and to synthesize in appropriate innovative solutions of a new-generation domestic 15-ton furnace.

The main part. The base of proposed solutions is shown schematically in Fig. 1. Here at the left side is a new furnace vertical section, and at the right side is traditional one. Let's consider the proposed solutions to improve energy efficiency of the furnace.

1. Optimization the workspace geometry and activation the steelmaking bath

The loss of heat by radiation with cooling water depends mainly by ratio between bath and electrodes pitch diameter D_b / D_p , i.e. between main radiating surfaces: the bath and the electrodes. Depth of the bath H_b – is a secondary factor, related to the bath diameter through the equation for volume of cylinder-spherical body. Using the mathematical model of radiation heat loss

evaluation [5], was calculated the relative energy loss by radiation in 15-ton EAF in dependence on D_b/D_p . In the model total radiated power from considering sources: the surface of the bath and the electrodes, according to the model, is the result of integration of the elementary heat flux from emitting to receiving surfaces, based on Lambert's law, thermal heat transfer characteristics of the objects and the geometry of furnace workspace (the coefficients of mutual irradiance). Benchmark is a standard 12 – ton EAF [6]: $D_b/D_p = 5.0-5.3$, which corresponds to $D_b/H_b = 3.9- 4.3$. The initial conditions were as follows: bath temperature 1900 K, $D_p = 0.6$ m, workspace height (over the bath) 1.5 m. Results of calculation in package MathCad V14 represented in Fig.2.

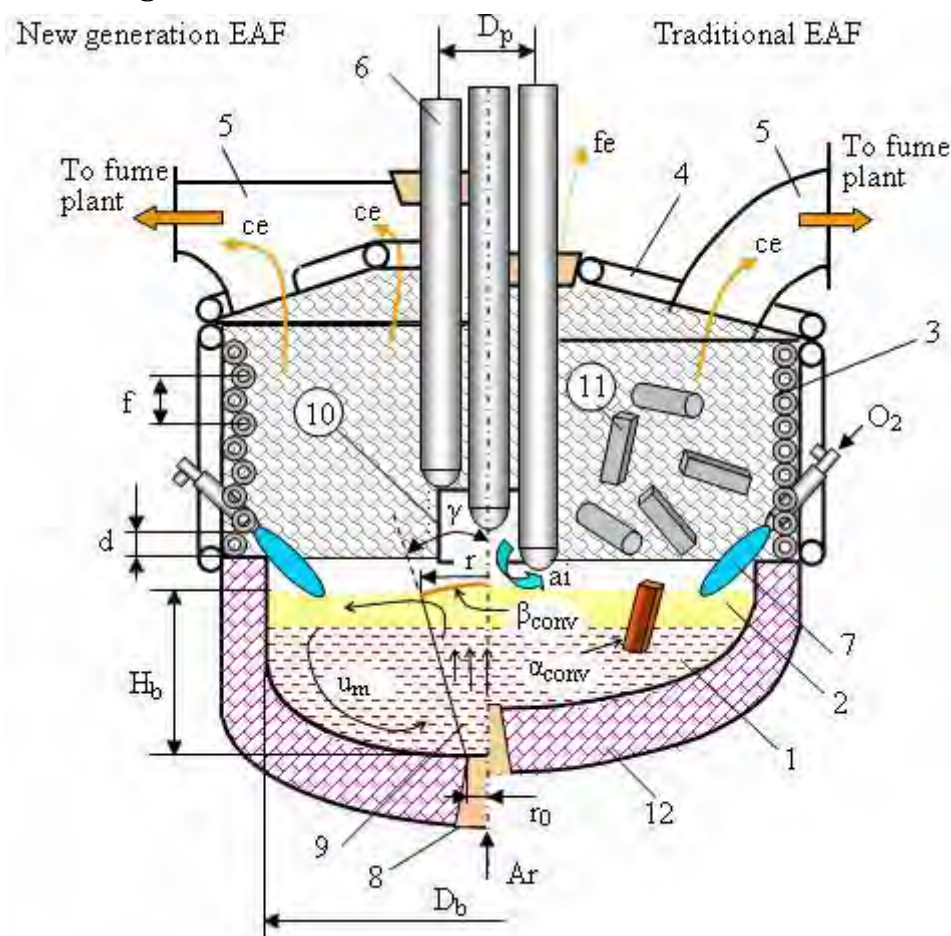


Fig.1 – Schematic representation of new EAF design features to increase energy efficiency.

- 1- metal bath; 2- slag bath; 3- wall panels; 4- roof;
 5- exhaust duct; 6- electrodes; 7- oxygen lance; 8- porous plug,
 9- two-phase area; 10- slag door; 11- charge; 12 – bottom;
 ce – controlled emissions; fe – fugitive emissions; ai – air inflow

Minimum of radiant heat loss on the curve is explained by the change the dominant factor from the bath to the electrodes at low D_b/D_p . At the intensive technology with foamed slag practice critical value D_b/D_p is lower and, respectively, the effect of deepening the bath is higher than at

traditional classic technology, where the arc radiation is not completely shielded by the slag. Certain restrictions on reducing D_b / D_p (increasing bath depth) make the method of loading a charge into the EAF. When bucket loading (the most common option), these limitations, related to the volume of the workspace above the bath, are much more, than in the case of continuous loading a charge into the liquid bath (process "Consteel"). For the EAF with a bucket loading reduction D_b / D_p from the traditional level 5.3 to 4.5 (this corresponds to decrease D_b / H_b from 4.3 to 3.2) reduces heat loss with the water by 21%.

The consequence of reducing the ratio D_b / D_p , in addition to improving energy efficiency of the EAF, is the possible decline of the extraction refinement of metal out of reducing the reaction surface metal-slag. This factor, in many respects is caused by historically formed tend to have a shallow bath in traditional EAF design [6].

With the development of the heat intensification means, reduction of metal-slag surface compensates by increasing the rate of circulation in the bath. The average metal velocity in the bath u_m is a result of formation the two-phase area over the bottom plug, purging with argon, which have an opening angle γ . Mentioned parameters (see. Fig. 1), according to [7, 8] are a function of the bath geometry, a porous plug radius r_0 , inert gas flow rate Q and modified Froude number $Fr_m = ((u_m^2 / g \cdot r_0) \cdot \rho_g / \rho)$, where g - acceleration due to gravity; ρ_g, ρ – density of inert gas and liquid steel correspondingly:

$$u = 0.79 \cdot Q^{0.35} \cdot H_B^{0.25} / (0.5D_B)^{0.67} \quad (1)$$

$$\gamma / 180 = 0.915 \cdot Fr_m^{0.12} \cdot (H_b / D_b)^{-0.254} \cdot (2r_0 / D_b)^{0.441} \quad (2)$$

These parameters determine the rate of heat exchange (melting of scrap) and mass transfer (refining from contaminants) in the bath through the following empirical relations [9, 8]:

$$Nu = 0,017 \cdot Re^{0.8} \cdot Pr^{0.33} \quad (3)$$

$$Sh = 0.079 \cdot Re^{0.7} \cdot Sc^{0.356} \quad (4)$$

where $Nu = \alpha_{conv} \cdot H_b / \lambda$ - Nusselt number; α_{conv} – coefficient of heat transfer from the molten bath to scrap fragment; λ – thermal conductivity of the liquid steel; $Re = u_m \cdot H_b / \nu$ -Reynolds number; u_m –average flow velocity in the bath; ν - kinematic viscosity of liquid steel; $Pr = \rho \cdot C \cdot \nu / \lambda$ – Prandtl number; C – heat capacity of liquid steel; $Sh = \beta_{conv} \cdot H_b / D$ – Sherwood number; β_{conv} – mass transfer coefficient of the reagent in the stirring medium; D – diffusion coefficient of the reagent in liquid steel; $Sc = \nu / D$ – Schmidt number.

The kinetics of melting the scrap in a stirred bath (residues unmelted by arcs radiation) is determined by scrap thermal characteristics, a specific

surface area of the scrap pieces and by coefficient of convective heat transfer in the bath α_{conv} (see. Fig.1), which is obtained from (3). Kinetics of steel refining from contaminants (sulfur, phosphorus) is determined by the coefficient of convective mass transfer β_{conv} , which is obtained from (4), and the active reaction surface - plume area with radius r (see. Fig.1). Results of relative α_{conv} and β_{conv} estimations depending on ratio D_b/H_b , made in the package MathCad V14, are shown in Fig. 3. Benchmark is a standard 12 - ton EAF [6] with $D_b/H_b = 4.3$

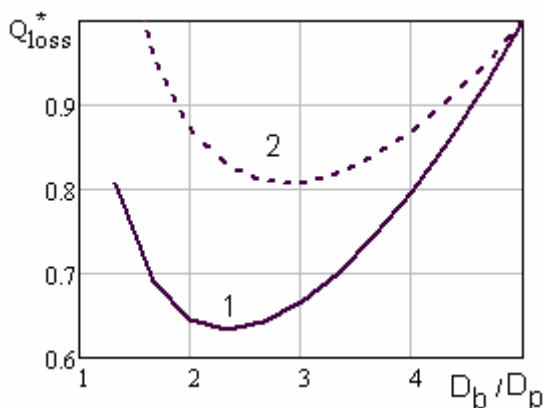


Fig. 2 – Relative heat loss Q_{loss}^* with cooling water vs. ratio (D_b / D_p).

- 1- arcs are screened by foamy slag (intensive technology),
- 2- arcs are not screened

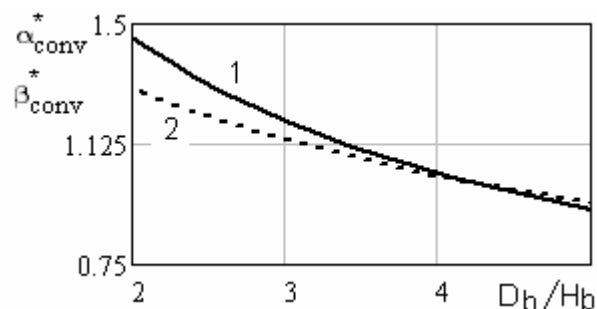


Fig. 3 – Relative heat transfer (α_{conv}^*) and mass transfer (β_{conv}^*) coefficients vs. ratio D_b / H_b 1- α_{conv}^* ; 2- β_{conv}^* .

Results, shown in Fig.3, demonstrate that deepening the bath promotes to improve heat- and mass transfer, i.e. intensification of melting and refining of steel. So reduction of ratio D_b/H_b from typical 4.3 to 3.2 (taking restrictions into account) can improve α_{conv} by 16% and β_{conv} by 11%. According to experimental data [10], there is a proportional relationship between α_{conv} and the rate of melting of the scrap in the steel liquid bath. According to Fick's law, increasing of β_{conv} in deepened bath promotes intensification of reactions in the metal-slag interface, taking into account the positive factor of growth the barbotage plume, and, correspondingly, active reaction surface, in a deeper steelmaking bath.

It should be noted that the deep bath, according to [11], promotes reduction homogenization (mixing) time and heating time according to the relation:

$$\tau_{mix} = k \cdot [Q \cdot \rho_g \cdot R_g \cdot T_b \cdot \ln(1 + H_b / 1.48) / (\mu \cdot M)]^{-0.4}, \quad (5)$$

where k – empirical factor; R_g – universal gas constant; T_b – temperature of melting bath; μ – inert gas molecular mass; M – heat mass; 1.48 – steel column hydrostatic height.

For the examined conditions, the expected relative reduction of homogenization time and liquid bath heating time is 8%.

2. Energy saving water cooled panels

Implementation of innovative panels with offset axes of pipes (see. Fig. 1) instead of traditional panels with dense pipes arrangement [12] allows improving the conditions for accumulating and maintaining of thermal equilibrium layer of skull (garnissage). Skull, due to its heat insulating and retaining properties, reduces heat loss with cooling water. The two-dimensional problem of stationary heat transfer in the system: radiation sources - water-cooled tubular panel, covered with a layer of skull, in simple linear case described by the following equation:

$$q - (1 - \varepsilon) \cdot \sigma \cdot T_b^4 - \frac{(T_b - T_w)}{(h_1 / \lambda_1 + h_2 / \lambda_2 + 1 / \alpha)} = 0 \quad (6)$$

where σ - Stefan-Boltzmann constant; q – falling heat flux; ε – emissivity of the panel; α - heat-transfer coefficient from a tube internal surface to water flow; $h_1, \lambda_1, h_2, \lambda_2$ – thicknesses and heat conductivities of skull and panel tube correspondingly; T_b, T_w – temperature of irradiation surface (bath) and water correspondingly.

The problem was solved in the application package ELCUT 6.2. Boundary conditions were as follows. The surface of the skull takes radiant heat flux: the temperature of the emitting surface of 1900 K, the emissivity of the panel is 0.8. The inner surface of the pipe is cooled by water: heat transfer coefficient 6 kW/(m².K) wall temperature 350 K. The outer surface of the pipe: free convection, the surface temperature 470 K, heat transfer coefficient 20 W/(m².K). Blocks: steel tubes (the thermal conductivity 45 W/(m.K)); skull (thermal conductivity 2 and 8 W/(m.K) [12]). The results of calculation in form of a temperature field is represented in Fig. 4, and integral indicator - the relative heat loss per 1m² of the panel surface – in Fig. 5.

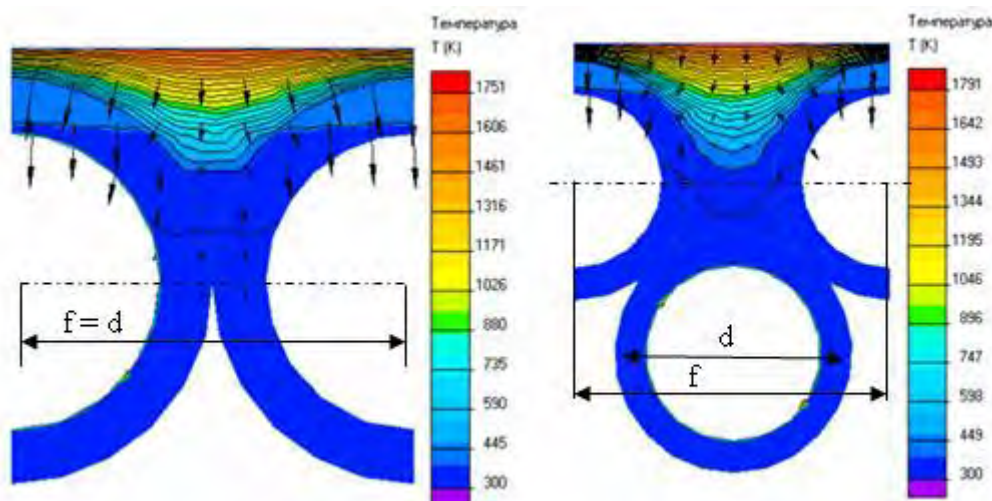


Fig.4 – Temperature field in traditional panel (a) and in panel with offset axes of pipes (b). Arrows indicate heat flux. Designations are given in the text and in Fig.1

According to calculations, there is an optimal value of inter-pipe distance (f), which is 1.8-1.9 of pipe diameter d . The panels of appropriate design provide decreasing of heat loss with cooling water by 20-30% depending of skull thermal properties.

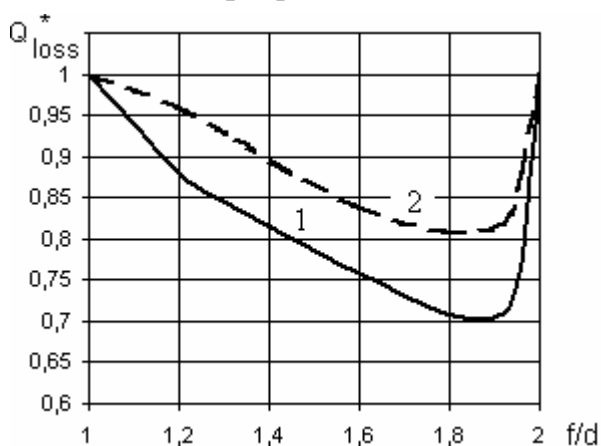


Fig.5 – Relative heat loss per 1 m² of panel Q_{loss}^* vs. spacing on pipes centers (f/d). 1, 2 skull heat conductivity 2 and 8 W/(m·K) correspondingly

3. System of dispersed aspiration.

The system of dispersed aspiration of dust gas environment [13] involves the off-gas suction not only from the periphery of the roof, as in the conventional system, but also from the central region, where the electrodes pass into the furnace (see Fig. 1). This ensures reduction of fugitive emissions in the electrode gaps and air inflow in the slag door, which causes lowering of energy efficiency of the EAF and increasing consumption of electrodes.

Testing of proposed technical solution was hold with the aid of the application package CosmosFloWorks in SolidWorks. The calculation is performed numerically on the basis of Navier-Stokes equation (7) and continuity equation (8) using the $k-\varepsilon$ model of turbulence. Among mass forces the gravity is taken into account.

$$\frac{\partial \vec{w}}{\partial \tau} + (\nabla \vec{w}) \cdot \vec{w} = -\frac{1}{\rho} \cdot \nabla p + \eta \cdot \nabla^2 \vec{w} + F \quad (7)$$

$$\text{div} \vec{w} = 0 \quad (8)$$

where ρ - density, w - velocity, p - pressure, τ - time, F - volume forces, η - dynamic viscosity.

Boundary conditions were as follows (Fig. 6): negative pressure 20 Pa in a face of exhaust duct; normal pressure and temperature in the slag door and electrodes gaps (surface of arbitrary cup); volume flow rate 1.5 m³/s out of the bath at a temperature of 1900 K due to oxygen blowing and carbon powder injection into liquid steel; the "real" wall - the rest boundaries.

Dimensions of the furnace correspond to 15 - ton EAF and for option a (conventional) and b (proposed aspiration system): diameter of the bath 3.2m; height of the shell 1.5m; electrode diameter 0.4 m; electrodes pinch diameter 0.6m; the size of the slag door 0.5x0.4m; flow area of the exhaust duct 0.8m².

To verify the thesis about loss of charge materials, a movement of smelting dust particles in the EAF was investigated by using a special in-built

sub-program “particle study”. Initial conditions were as follows. Molten bath *in* generates the dust particles of average size $2 \cdot 10^{-5}$ m and density of $3 \text{ kg} \cdot \text{m}^{-3}$ with mass flow rate of $0.05 \text{ kg} \cdot \text{s}^{-1}$ uniformly over the surface due to oxygen blowing and carbon powder injection.

The objective was to obtain a calculation of the velocity field of the gaseous medium in the furnace with regard to off-gas removal system design a) and b) in comparable conditions and assess, in particular the air inflows through slag door and fugitive emissions.

The results of calculations - a velocity field superimposed with the melting dust particle tracks, applied to the conditions of the period of melting, shown in Fig. 6. Cup 1 over the roof is arbitrary to estimate fugitive emissions into the electrodes gaps. The “well” 2, melted in scrap volume due to electrodes boring down, generates the dust and gas flow.

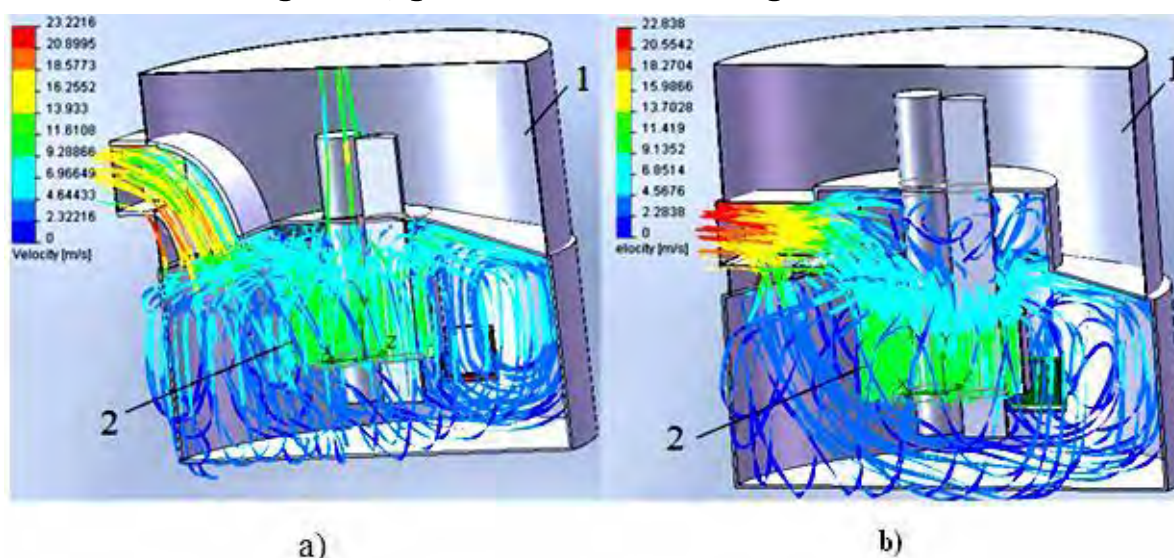


Fig. 6 - Velocity field of dust-gas medium and the tracks of dust particles for the traditional system (a) and system of dispersed aspiration (b). Designations are in the text

The overall picture of the gas dynamics in the furnace indicates a more efficient localization of fugitive emissions using the dispersed aspiration system, which is evident by observation the number of tracks of dust particles passing through the electrode gaps in the space over the roof. The results of the integral characteristics are shown in table 1.

Table 1

Comparison of aspiration systems

System	Parameter name and averaged value in relative units			
	Air inflow	Fugitive emissions	Dust removal through electrode gaps	Total off-gas flow rate
Traditional	1	1	1	1
Dispersed	0.78	0.65	Not observed	0.86

Obtained data show the advantages of dispersed aspiration system from the positions both energy efficiency and ecological safety.

Conclusions. Analysis, mathematical modeling and numerical simulation of innovative energy saving solutions for modern EAF of small capacity were hold. The main one is deepening of the steelmaking bath, taking into account the existing technical and technological restrictions, which in combination with blowing an inert gas through the bottom porous plug provides lowering of radiation heat loss by 21%; enhancing of heat- and mass transfer by 11-16%, heating and homogenization time by 8%. Implementation of energy-saving water-cooled panels and system of dispersed aspiration reduce heat loss with cooling water up to 20% and fugitive off-gas and dust emissions up to 60%.

Synthesis of mentioned solutions will reduce the power consumption in the furnace not less than by 3 - 5% in comparison with the analogs. The presented solutions seem convenient for revamping of existing EAF too. It is not expensive, with pay-off period within one year.

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