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ENERGY EFFICIENT SOLUTIONS FOR SMALL CAPACITY ELECTRIC ARC FURNACES OF A FOUNDRY CLASS

The low specific power of the transformer in combination with the increased heat losses due to the geometrical factor and the unstable operation with long downtimes are predetermined by low technical and economic indicators of production, in comparison with the EAF of the "big" metallurgy. An urgent task is to search for low-cost methods to increase the energy efficiency of furnaces of this class by simulating the thermal work of the elements of the working space. Numerical simulation of heat transfer in the working space of foundry class AC EAF with a capacity of 3 tons has shown that with a duration of furnace downtime of 18–20 hours or more, replacing 40% of the walls lining and 16-20% of the roof lining by water cooled elements with a volumetric structure accumulating the skull, with using of “deep" bath with a reduced by 14–15% diameter of the radiating surface allows, at a given melting mass, to reach the energy consumption level of the furnace with a fully refractory lining and lower with a significant saving of refractories. Preloading scrap into the furnace in downtime increases energy efficiency, all other things being equal.

Keywords: *electric arc furnace, heat exchange during downtime, energy efficiency, bath geometry, energy-saving water cooled panels.*

Formulation of the problem

At the machine-building plants electric arc steel melting furnaces (EAF) of the foundry class of small (3–6 tons) capacity are widely used. The low specific power of the transformer in combination with the increased heat losses due to the geometrical factor and the unstable operation with long downtimes are predetermined by low technical and economic indicators of production, in comparison with the EAF of the "big" metallurgy. An urgent task is to search for low-cost methods to increase the energy efficiency of furnaces of this class by simulating the thermal work of the elements of the working space.

Analysis of recent research and publications

In view of the complexity of the physical and chemical processes in the EAF, the numerical models of heat and mass transfer usually describe the "liquid" melting period. D. Guo and G.Irons [1] found that about 80% of arc energy is transmitted by radiation, 15-18% - by thermal conductivity directly into the bath and 2-5% is lost in the electrodes. J-C. Gruber, T. Echterhof and H. Pfeifer [2] investigated the effect of the high-temperature region of the arc on the formation of gas flows in the working space of the EAF, estimated the energy losses with the inflow of cold air into the working space and the temperature distribution of the radiating surface of the electrodes. O. Gonzales, M. Ramirez-Argaez, F. Conejo [3] investigated the rate of heating of the liquid bath by electric arcs and established a positive effect on this factor of arc length. Heat and mass transfer in a stirred steel bath, according to the studies of M. Kawakami, R. Takatani, L. Brabie [4], and J. Li and N. Provatas [5], are determined by the heat transfer coefficient in the melt. In works [6, 7] the author shows the energy-technological advantages of a "deep" bath at a given melting mass in the EAF. More complex numerical models V. Logar, D. Dovžan, I. Škrjanc [8]; F.Opitz and P. Treffinger [9], as well as Yu.A. Stankevich et al. [10] suggest a description not only of the processes in the liquid bath, but also, with certain assumptions, the melting dynamics of the homogeneous charge by the arc discharge energy.

The above mathematical models are developed for the conditions of rhythmically working EAF of "large" metallurgy, in which the processes of heat accumulation by the lining do not have a noticeable effect on energy-technological indicators. A daily downtime of the low capacity EAF leads to a decrease of the average lining temperature from 900-1000 up to 150-200 ° C, and to compensate for its enthalpy, it is necessary to input energy commensurate with the theoretical specific value for smelting of liquid steel [11]. It is of interest to consider the possibility of replacing part of the lining with less heat-intensive water-cooled elements with reduced heat losses, taking into account the experience [12], and also using a "deep" bath to increase the energy efficiency of the foundry class EAF.

The purpose

The aim of the work is numerical studies of energy-efficient solutions for the modernization of a small capacity EAF of foundry class on the basis of reducing energy costs for heat accumulation by lining and reducing energy losses from bath radiation.

The main part

A scheme, showing the heat exchange in the EAF during downtime and constructive solutions for improving energy efficiency are shown in Fig. 1. The researches carried out with reference to typical 3-tons EAF with a transformer capacity of 1.8 MVA. Two cases of thermal operation of the furnace at downtimes are considered: the presence of scrap in the working space (100% of the charge for the next heat with account of the consumption coefficient) and the absence of scrap in the furnace. The latter case is related to the uncertainty of the steel grade after long periods of inactivity. For each of the cases, two variants were investigated: without water-cooled elements (WCE), as the basic solution, and with WCE. The relative area of the walls WCE is fixed and is 0.4. The relative area β_{wcr} of the roof WCE varies from 0 to 1. In the option with WCE, the effect of the bath geometry (initial and the "deep" bath) at a given melting mass on the heat loss in the WCE was also evaluated.

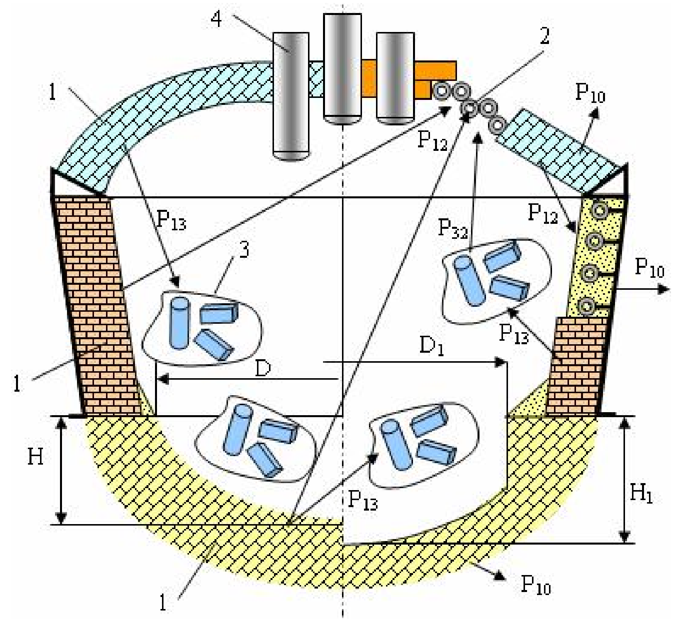

Fig.1 – Scheme of heat exchange in small-capacity EAF working space in downtime. 1–refractory lining (bottom, walls, roof); 2- water – cooling panels (walls, roof); 3–charge (scrap); 4–electrodes. Description – in the text

The change in the enthalpy of the lining during the idle time of the furnace τ_d is described in a one-dimensional setting by the following equation:

$$dQ / d\tau_d = P_{10} + P_{12} + P_{13}, \tag{1}$$

where P_{10}, P_{12}, P_{13} – the power of energy loss from external surface of the furnace to the environment, and from inner surface of the lining for WCE and scrap, respectively (see Fig. 1).

Parameter P_{10} includes the radiative and convective components considered in [12], taking into account the empirical dependence of the heat transfer coefficient by convection obtained by processing the experimental data [11]. In turn, the scrap, when heated, transfers part of the heat P_{13} to WCE, which is reflected in the process described by (1). When evaluating the heat transfer parameters P_{12}, P_{13}, in the engineering calculation, only the radiation component was taken into account.

The solution (1), performed numerically with steps of 0.1 hour in the MathcadV14 package, yields the energy expenditure on heat accumulation by enclosing the working space (lining, WCE) as a function of β_{wcr} and τ_d. They were used to assess the energy efficiency of the modernization of the EAF, which consisted of comparing the specific electrical energy consumption for the initial furnace and modernization options. In view of the comparative nature of the calculation, in the energy balance of the EAF, a number of consumable components (heat losses with dust and gas media, electrical losses), as well as incoming (heat of exothermic reactions) are accepted for the variants considered, and their evaluation is performed by traditional methods [13]. In the theoretical expenditure of energy on the heating process, melting of the metal charge and superheating of the bath to the temperature of steel tapping, slagging and alloying, the residual enthalpy of scrap was taken into account.

Heat loss with cooling water is determined taking into account the design solutions of the WCE, both traditional (with a dense pipes arrangement), and energy-saving ones [12] according to the calculation method [6]. The period of work with a liquid bath is considered as the most heat-stressed one. The resulting heat flow to the water-cooled element is a function of the mutual radiation of the bath, the surface of the electrodes, and the dust and gas environment in the working space of the EAF. The radiation of arcs shielded by electrodes and slag is taken into account indirectly through the surface temperature of the bath. The power of the heat flux from the radiation surface per unit of the receiving surface is determined by Stefan-Boltzmann law:

$$Q_{rad} = \sigma \cdot \varepsilon_r \cdot (T_{rad}{}^4 - T_{res}{}^4) \iint_{S_{rad}} \left[(\cos\theta \cdot \cos\gamma) / r^2 \right] dS_{rad}, \tag{2}$$

где σ – Stefan-Boltzmann constant; T_{rad}, T_{res} – temperatures of radiating and receiving surfaces; ε_r – reduced blackness; r – radius vector in the direction from the radiating to the receiving surface; $\theta,\ \gamma$ – directing angles. The integrand in (2) is the coefficient of mutual irradiation of the heat exchange surfaces.

The power of radiation energy loss by the heat-sensing cooled surface S, constitutes:

$$Q_{loss} = k_{av} \int_S Q_{rad} \cdot dS. \tag{3}$$

The averaging factor of the resulting heat flux k_{av} along the cooled surface of the energy-saving WCE with the developed slag depositions in (3), was estimated on the basis of the calculation of the steady-state heat transfer to the WCE by means of the ELCUT 6.2 package (Fig. 2) using the procedure, described in [12]. For standard panels with dense pipes structure, the k_{av} value is close to 1.

The version of the "deep" bath can be realized in the existing 3-ton EAF without significant structural changes in the furnace with a decrease the radiating surface diameter of the melt from D =

2,1 to D_1 = 1,8 m (Fig. 1). In this case, the depth of the bath H_1 with respect to the initial H increases according to the equation of the volume of the cylinder-spherical body.

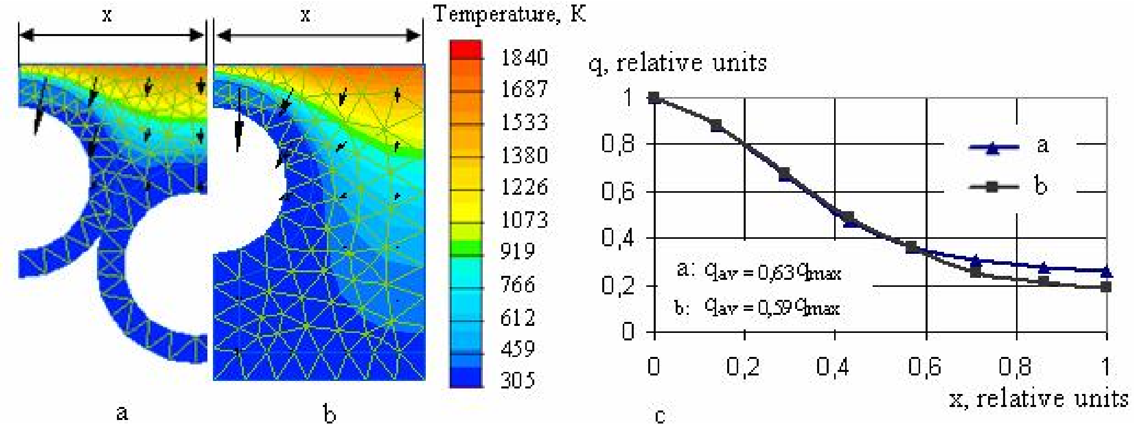

Fig. 2 – Temperature field of the roof panels with displaced pipe axes (a)
and wall panels with loosely laid pipes (b); an estimate of the average value
of the resulting heat flux of energy loss with water (c).
The arrows indicate the direction of the heat flow

The calculated specific heat loss with cooling water under conditions of a liquid period of 1.2 hours for 3-tons heat, obtained by numerical solution (2), (3) in the MathcadV14 package, are shown in Fig. 3.

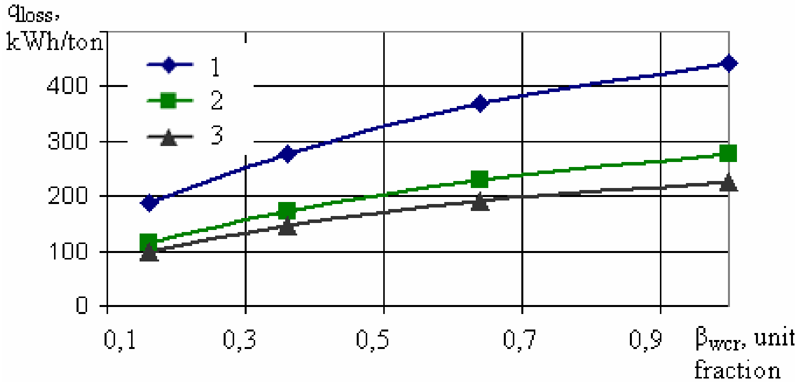

Fig.3 – Specific energy loss with cooling water q_{loss} vs. relative surface
of water- cooled roof β_{wcr}. 1–standard panels with dense pipes structure;
2–energy saving panels (fig. 2); 3–energy saving panels plus “deep” bath

According to calculations, the loss of heat with water using energy-saving WCE with the spatial structure that accumulates the slag is reduced by 37–39% in comparison with the traditional panels with a dense pipes arrangement. "Deep" bath allows to further reduce these losses by 13–18%. With increasing of parameter β_{wcr} from 0.16 to 1 the effect of reducing the radiating surface of the melt increases by 1.5 times.

The following empirical equations are obtained (in the Excel package), which relate specific losses of heat to water for conventional (Q_{wt}), energy-saving (Q_{we}) and energy-saving with "deep" bath (Q_{wedb}), respectively, kW·h/ton:

$$Q_{wt} = 138.8 \ln(\beta_{wcr} \cdot 100) - 204.68\,, \tag{4}$$

$$Q_{we} = 87.98 \ln(\beta_{wcr} \cdot 100) - 134.30\,, \tag{5}$$

$$Q_{wedb} = 68.36 \ln(\beta_{wcr} \cdot 100) - 92.66\,. \tag{6}$$

The energy efficiency characteristic of the proposed solutions for the modernization of the low-capacity EAF of the foundry class χ is the ratio of calculated specific electrical energy consumption to this parameter value in conditions of the refractory lining furnace. On the basis of joint solution (1) and (4–6), the dependences of parameter χ on τ_d (a) and on β_{wcr} (b), shown in Fig. 4 for cases of pre-loaded scrap and without it.

According to the above data, the increase in the duration of downtime of a small capacity foundry class EAF to 18–20 hours and more creates conditions for the energy efficiency of the partial replacement of refractory lining with energy-efficient WCE with a spatial structure for the formation of the slag garnissage, and "deep" bath. In typical 3-ton AC EAF with a transformer w specific power of 0.5–0.7 MVA/ton and a relative wall WCE area of 40%, the relative area of the roof cooling surface can be up to 20%. Preliminary loading of scrap significantly increases the possibilities of the solutions considered in the direction of both reducing the rational for the modernization of the EAF threshold duration of downtime, and increasing the relative area of water cooling.

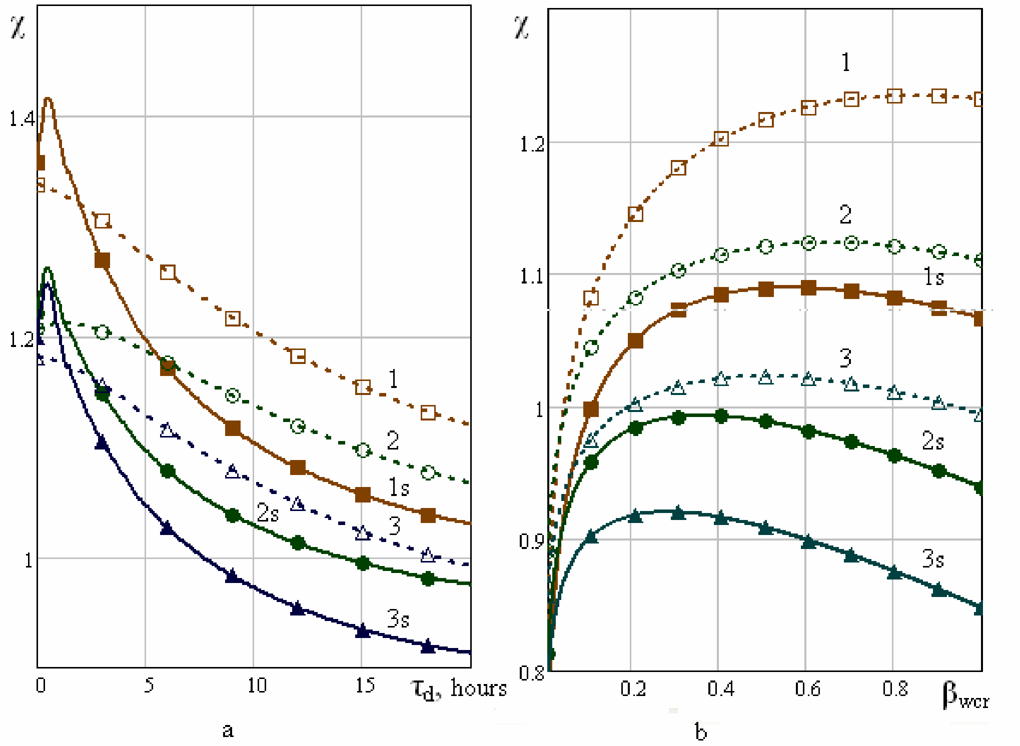

Fig.4 – Relative energy efficiency χ vs. EAF downtime period τ_d at $\beta_{wcr} = 0.16$ (a) and vs. relative surface of water- cooled roof β_{wcr} at $\tau_d = 20$ (b).
Relative surface of water- cooled walls is 0.4. 1 – standard panels with dense pipes structure; 2 – energy saving panels (fig. 2); 3– energy saving panels plus “deep” bath.
Index “s” means scrap, loaded in downtime period

Conclusions

Low-cost solutions for the modernization of a small capacity foundry class EAF on the basis of the use of energy-saving WCE and the improvement of the steelmaking bath geometry have perspectives in conditions of downtime in the furnace for about 18–20 hours or more and provide a reduction in energy consumption due to decrease of energy loss for the accumulation of heat by massive refractory lining. This decline is only part of the significant economic effect of reducing refractory consumption. The proposed solutions implementation is already starts through the introduction of a combined water-cooled roof in operating 3-ton AC EAF [14].

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ЕНЕРГОЕФЕКТИВНІ РІШЕННЯ ДЛЯ ДУГОВИХ ПЕЧЕЙ МАЛОЇ МІСТКОСТІ ЛИВАРНОГО КЛАСУ

Чисельне моделювання теплообміну в робочому просторі ДСП ливарного класу місткістю 3т показало, що при тривалості простоїв печі 18–20 годин і більше, заміна 40% футерування стін і 16–20% футерування зводу водоохолоджуваними елементами з об'ємною структурою, яка накопичує гарнісаж, поряд з використанням «глибокої» ванни зі зменшеним на 14–15% діаметром випромінюючої поверхні дозволяє, при даній масі плавки, досягти рівень енергоспоживання печі з повністю вогнетривкою футеровкою і нижче при істотній економії вогнетривів. Попереднє завантаження скрапу в піч підвищує її енергоефективність при інших рівних умовах.

Ключові слова: дугова сталеплавильна піч ливарного класу, теплообмін в період простою, енергоефективність, геометрія ванни, енергозберігаючі водоохолоджувані панелі.

ЭНЕРГОЭФФЕКТИВНЫЕ РЕШЕНИЯ ДЛЯ ДУГОВЫХ ПЕЧЕЙ МАЛОЙ ВМЕСТИМОСТИ ЛИТЕЙНОГО КЛАССА

Численное моделирование теплообмена в рабочем пространстве ДСП литейного класса вместимостью 3т показало, что при длительности простоев печи 18–20 часов и более, замена 40% футеровки стен и 16–20% футеровки свода водоохлаждаемыми элементами с объемной структурой, накапливающей гарнисаж, наряду с использованием «глубокой» ванны с уменьшенным на 14–15% диаметром излучающей поверхности позволяет, при данной массе плавки, достигнуть уровень энергопотребления печи с полностью огнеупорной футеровкой и ниже при существенной экономии огнеупоров. Предварительная загрузка скрапа в печь повышает ее энергоэффективность при прочих равных условиях.

Ключевые слова: дуговая печь литейного класса, теплообмен в период простоя, энергоэффективность, геометрия ванны, энергосберегающие водоохлаждаемые панели.

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