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ENERGY EFFICIENT WATER-COOLED ELEMENTS FOR FOUNDRY CLASS ELECTRIC ARC STEELMAKING FURNACES

Abstract. Low energy efficiency of foundry class electric arc steelmaking furnaces (EAF) mainly is caused by heat loss by massive lining during forced downtime. A low-power transformer doesn't allow, in the conditions of classical technology, practice of traditional water-cooled elements in order to replace partially the lining, what determines increased refractory consumption. The aim is energy and refractory savings. On the basis of numerical modeling of heat exchange by radiation in the EAF working space, taking into account capacity, bath shape factor, duration of technological period of heat, a multiple regression equation for power of heat loss with cooling water was obtained. Three-row water-cooled wall panels with a spatial structure are elaborated, which provide a decrease in heat loss by 14 %, in comparison with two-row ones. Estimates of optimal relative cooled surface of the EAF working space, providing refractory savings up to 25-30%, are substantiated.

Keywords: FOUNDRY CLASS ELECTRIC ARC FURNACE, WATER-COOLED ELEMENTS, ENERGY EFFICIENCY

Introduction

Possibility of a wide choice of original charge and variation of oxidation potential in melting process makes the electric arc furnace (EAF) a general-purpose unit in foundry shops of engineering industry

Energy-intensive classical technology with at usually low specific power of the transformer, irregular operation with forced downtime predetermine a much lower, in comparison with “large” metallurgy, energy efficiency of foundry class furnaces [1,2]. Flat and shallow steelmaking bath of the EAF enhances the problem due to increased heat loss by radiation in the conditions of long refining period.

Application of traditional for EAF of "large" metallurgy water-cooled elements (WCE) with one row tubes dense structure [3] substantially limited by reason of technological risks, causes high energy losses, which heightens refractory materials consumption. A promising solution seems to be WCE with a spatial tubes structure (one row untight, two-row), which is characterized by reduced on 25-35 % heat losses due to heat insulation and heat accumulation properties of deposit slag filling [4].

Known mathematical models of heat and mass transfer in the EAF workspace [5,6] don't pay sufficient attention to the thermal state and energy loss in WCE in relation to foundry class furnaces.

The development of WCE with reduced heat loss and grounding on the base of mathematical model an optimal relative cooled surface of workspace, taking into account the peculiarities in foundry class EAF, are urgent.

Purpose

Work aims to improve energy efficiency and refractory savings in the EAF due to WCE design improvement.

Method

Mathematical modeling and numerical study of thermal state of WCE in foundry class EAF workspace.

Main research material

A mathematical model of heat exchange by radiation, adapted to the EAF conditions [7], was used. It deals with primary sources of radiation: surfaces of bath, arcs and electrodes. Insignificant contribution of secondary radiation, caused by dust and gas environment, was not taken into account in given comparative analysis.

Scheme of radiant heat transfer heat in AC EAF is shown in Fig.1.

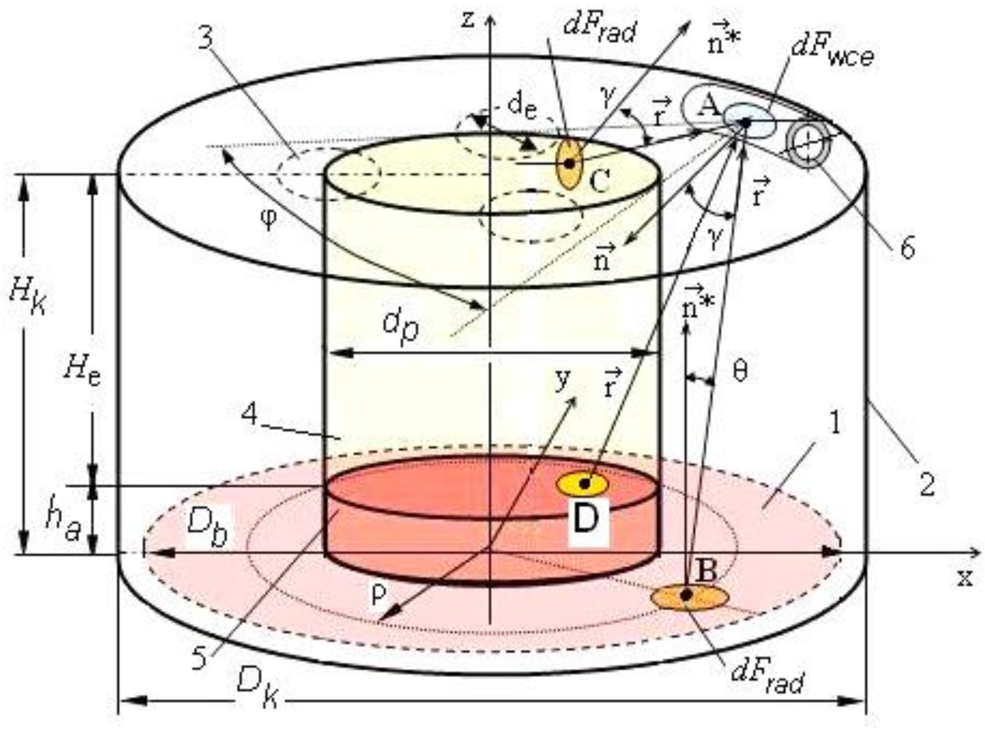

Fig. 1. Scheme of heat exchange by radiation in the EAF workspace. 1 – bath, 2 – casing, 3 – electrode, 4,5 – conditional surfaces of electrodes and arcs, respectively, 6 – WCE.

x, y, z, φ, ρ – coordinates; γ, θ – direction angles, r – radius-vector.

Radiation heat exchange workspace formed by bath with diameter D_b, casing with diameter D_k and height H_k, electrodes with diameter d_e, height H_e and pitch diameter d_p, arcs with length h_a. The elementary area dF_{wce} around point A, located on the tubular WCE, receives radiation from each elementary area dF_{rad} of bath, electrodes and arcs around the points B, C and D, accordingly. Emitting surface of arcs and electrodes is the lateral surface of cylinders with diameter d_p. Arc length is approximated by dependence from EAF capacity M, t: $h_a = 0.15 + 0.003M$, m. Temperature of the bath surface, arc and WCE is taken 1820, 3550 and 1100 K, respectively. Temperature of electrode radiating surface $T_e = 3050 + 19200\zeta^4 - 48000\zeta^3 + 40400\zeta^2 - 13800\zeta$, K is a function of relative height of given point of conditional cylinder surface above the bath ζ, obtained basing on data [6].

The power of heat loss with cooling water by working WCE surface F_{wce} (m^2) with temperature T (K) from radiating surface F_{rad} (m^2) with temperature T_{rad} (K), taking into account mutual irradiation factor, is, kW:

$$P_{wce} = \sigma\varepsilon(T_{rad}^4 - T^4) \int_{F_{wce}} \iint_{F_{rad}} \left(\frac{\cos\theta \, \cos\gamma}{r^2} \right) dF_{rad} dF_{wce} \tag{1}$$

where σ – Stefan-Boltzmann constant, kW/(m^{2}K^4); ε – reduced emissivity of heat exchange surfaces; θ, γ, r – direction angles and radius vector, respectively; k_{wce} – averaging coefficient of heat flux on WCE surface.

Evaluations of energy loss (1) seems convenient by approximation with multiple regression equation versus capacity of the furnace, steelmaking bath shape factor m (diameter to depth ratio) and relative area of water-cooled wall surface β_w. In the context of 3-12-ton foundry class EAF this is, kW:

$$P_{wce} = k_{wce}\left(50.78M + 46.63m + 833.75\beta_w - 282.31\right) \tag{2}$$

The expression (2) was obtained under the condition that relative area of cooled roof surface, realized in central part, critical in terms of refractory resistance, is, from the design positions, 0.25-0.32. Averaging coefficient of the heat flux k_{wce} depends on WCE design.

Taking into account the world [8] and domestic [4] experience in the area of energy-saving WCE, a three-row panel (Fig. 2) with a spatial structure has been developed for foundry class EAF.

Introduction of additional row of pipes contributes to increase thermal resistance to the passage of heat flux to water due to a stable slag deposition within spatial structure.

Stationary heat exchange between EAF working space and tubular WCE, filled with thermal equilibrium layer of slag, is described by the equation:

$$q - (1 - \varepsilon_{wce})\sigma T_1^4 - \frac{(T_1 - T_2)}{(b/\lambda + b_g/\lambda_g + 1/\alpha_w)} - \alpha_k(T_3 - T_0) = 0 \qquad (3)$$

where q – heat flux; ε_{wce} – emissivity factor; α_w, α_k – heat transfer coefficient from pipe wall to water and into environment, respectively; $b, \lambda, b_g, \lambda_g$ – thickness and thermal conductivity of slag and pipes, respectively; T_1, T_2, T_3, T_0 – temperature of working surface, water, outer surface and environment, respectively.

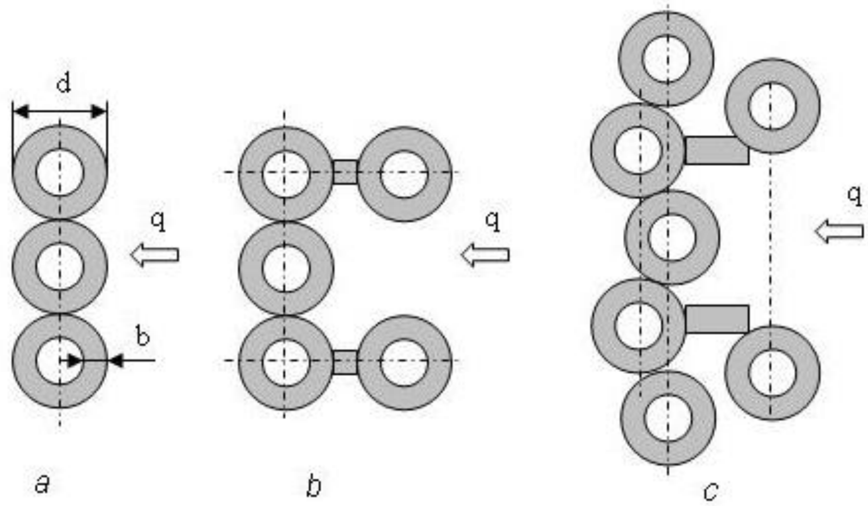

Fig. 2. WCE of traditional design with dense tubes structure (a); two-row (b) and three-row (c) panels section with spatial structure. Arrow shows actual heat flux direction. Designations are in the text

Two-dimensional problem of WCE thermal state in the EAF workspace was simulated in application package ELCUT 6.2 by the finite element method. Energy loss through outer WCE surface was neglected. Initial and boundary conditions of numerical modeling are given in Table 1.

Table 1 – Initial and boundary conditions of numerical modeling

Name of block (B) and edge (E), its number in Fig. 3	Heat conductivity (λ) for block. Temperature (T) heat transfer coefficient (σ, α), emissivity (ε) for edge	Dimensions, mm
Slag (B1)	$\lambda = 2.5$ W/(m·K) [9]	d = 60, b = 10
Pipe (B2)	$\lambda = 42$ W/(m·K), steel-20	
Working surface (E1)	$\sigma = 5.67 \cdot 10^{-8}$ W/(m^2·K^4); T= 1900 K; $\varepsilon = 0.7$.	
Cooling surface (E2)	$\alpha = 3000$ W/(m^2·K); T=320 K.	

Thermal fields in the WCE under action of heat flux q for reviewed panels options are shown in Fig. 3.

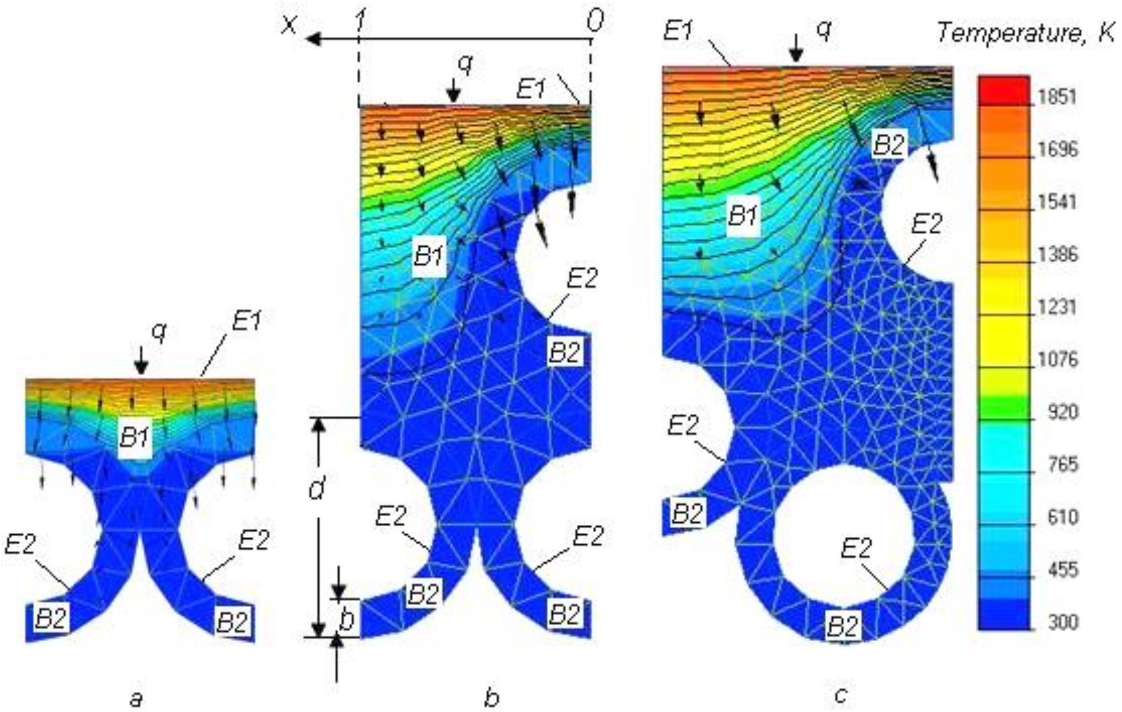

Fig.3. Temperature fields in traditional (*a*), two-row (*b*) and proposed three-row (*c*) WCE. Lines are isotherms; arrows show heat flux value and direction. Designations are in Table.

Integral heat loss with cooling water, evaluated by means of package on edges E2, presented in Fig. 4.

According to calculations, the transition from traditional panel to WCE with spatial two-row structure reduces heat loss with cooling water by 30 %, and three-row design gives additional 14% energy savings in comparison with two-row panel.

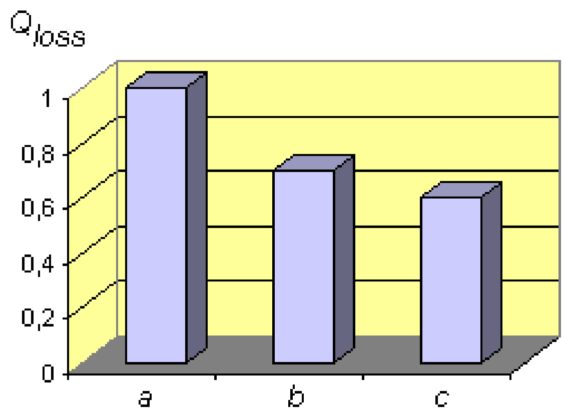

Fig. 4. Relative heat loss with cooling water Q_{loss} for reviewed WCE options *a*, *b*, *c* according to Fig. 2,3.

Analysis of heat flux, passing along direction x of working surface modulus (edge E1 in Fig. 3) through spatial WCE structure to cooling water, is shown in Fig. 5. Pursuant to numerical modeling, spatial structure promotes increasing of panel thermal resistivity and, respectively, reduction of heat loss with cooling water.

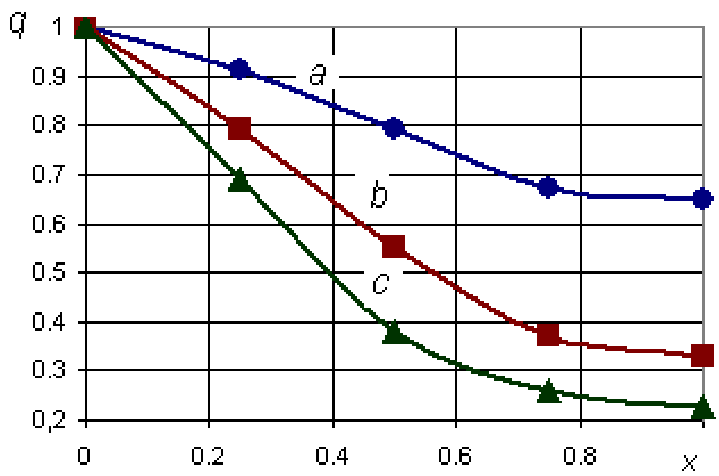

Fig. 5. Relative heat flux q distribution along WCE modulus relative coordinate x for panels design options a, b, c according to Fig. 2, 3.

On the base of these data, the values of averaging coefficient of heat flux on WCE surface for panel options were obtained, in a first approximation, as half-sum of the boundary relative heat fluxes in considered modulus. For traditional, two- and three-row panels k_{wce} is 0.82, 0.67 and 0.61, respectively.

The energy balance of refining period in 3-12-t EAF is made for next conditions: melting of structural steel; forced bath inert gas stirring; reduction of bath shape factor from traditional 4.5 to 2.5; combined roof with central water-cooled part with relative area 0.25-0.32. For proposed three-row WCE an average relative cooled surface of walls in 3-12-t EAF can reach 0.5-0.6. Given value of β_w ensures reduction in refractory consumption up to 25–30 %.

Conclusions

Three-row water-cooled wall panels with a spatial structure are elaborated, which provide a decrease in heat loss by 14 %, in comparison with two-row ones, and by 40% in comparison with traditional one-row dense structure WCE.

Estimates of optimal relative cooled surface of the EAF working space, providing refractory savings up to 25-30%, are substantiated.

References

1. Biswas, S., Peaslee, K., Lekakh, S. (2012). Melting energy efficiency in steel foundries. *AFS Transactions 2012 © American Foundry Society, Schaumburg, Il. USA*, 449-456.
2. Mironov, Yu.M., Petrov, V.G. (2010). Thermal losses and power efficiency of arc steelmaking furnaces. *Metally (Russian Metallurgy)*, 12, 1141-1144.
3. Toulouevski, Yu., Zinurov, I. (2010) *Innovation in Electric Arc Furnaces. Scientific Basis for Selection*. Berlin (Germany): Springer-Verlag. 258 p.
4. Timoshenko, S..M., Doroshenko, A..V., Dyadkov, B.P., Tischenko, P.I., Onischenko, S.P. (2018). Energoeffektivnyye resheniya pri modernizatsii malotonnazhnykh dugovykh staleplavil'nykh pechey liteynogo klassa (Energy-efficient solutions for the modernization of low-tonnage arc furnaces of foundry class). *Metall i lyt'e Ukrayny (Metal and casting of Ukraine)*, 3-4, 34-40.
5. Logar, V., Dovžan, D., Škrjanc, I. (2012). Modeling and validation of an electric arc furnace. *ISIJ International*, vol. 52, 3, 402-423.
6. Gruber, J-C., Echterhof, T., Pfeifer, H. (2016). Investigation on the Influence of the Arc Region on Heat and Mass Transport in an EAF Freeboard using Numerical Modeling. *Steel research international*, vol. 87, no.1, 15–28. DOI: 10.1002/srin.201400513.
7. Timoshenko, S.N. (2016). Computer modeling bath geometry to improve energy efficiency of electric arc furnace. *System Technologies. Regional interuniversity collection of scientific works*. Dnipro: NMetAU-IVK Systemni tekhnolohiyi, 3, 33-39.
8. Patent US 5772430. F27D 9/00. M. Pavlicevic, G. Gensini, A. Poloni, R. Sellan (1996). Cooling device with panels for electric arc furnaces. Danieli &Co Off. Mec., Spa (Italy).
9. Kruger, K., Ehrbar, A., Timm, K. (1998). Schlackenanbackungen und thermische Verluste eines Drehstrofens. *Stahl und Eisen*, 9 (118), 63-67.