Journal of Achievements in Materials and Manufacturing Engineering

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Energy efficient solutions for EAF steelmaking

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ABSTRACT

Purpose: To review an advanced solutions to improve the energy efficiency of electric arc furnace (EAF), and presentation of own new efficient low-cost solutions with regard to needs of electrometallurgical complex of Ukraine.

Design/methodology/approach: Numerical simulation and industrial experiment is used. The patterns and parameters of heat and mass transfer processes, hydromechanics in a steelmaking bath of an arc furnace, thermal operation of water-cooled elements and gas dynamics in EAF workspace, are the subject scope of the paper.

Findings: Energy-efficient solutions for steelmaking: bath geometry, design features of water-cooled elements (WCE), distributed aspiration system, and the mid-temperature scrap preheating.

Research limitations/implications: Influence of the bath depth on heat and mass transfer and heat loss by radiation; influence of the spatial structure of WCE on heat loss by radiation; the dispersion of aspiration on the amount of fugitive emissions through electrode gaps are established.

Practical implications: Grounds to improve EAF melting space, water-cooled elements, aspiration system and utilization of energy loss are obtained. Use of the set of solutions in 120-ton EAF can reduce energy consumption by 56-68 kWh/ton.

Originality/value: The new concepts of deep steelmaking bath, WCE with spatial structure and system of dispersed aspiration of the EAF are elaborated.

Keywords: Electric arc furnace energy efficiency, Deep bath, WCE with spatial structure, System of dispersed aspiration, Mid-temperature preheating of scrap

Reference to this paper should be given in the following way:

S.N. Timoshenko, A.P. Stovpchenko, Yu.V. Kostetski, M.V. Gubinski, Energy efficient solutions for EAF steelmaking, Journal of Achievements in Materials and Manufacturing Engineering 88/1 (2018) 18-24.

ANALYSIS AND MODELLING

1. Introduction

The possibilities of electric arc furnaces (EAF), with respect to a wide choice of initial charge (scrap, DRI/HBI, hot metal), variation of oxidation potential in the smelting process, low CO_2 emission, make it possible to use both in technological routes of "large" metallurgy, and for foundry purposes, providing about a third of world steel production behind the converter process [1]. EAF steelmaking in the "large" metallurgy is characterized by two-stage process with melting by-product in and the ladle steel finishing; a wide application of alternative energy (up to 30-40% of energy demand): fuel-oxygen burners (FOB) in the melting period and exothermic reactions in the liquid bath, caused by oxygen blowing, in the heating period; intensive applying of water-cooled elements (WCE) [2-4].

From typical energy and material balances of the EAF operating in "large" metallurgy [2-5] follows, that low energy efficiency is caused by the heat loss, mainly with off-gas emissions and in WCE that is ≥25% of total energy input. As well as iron loss that is 1.5-2.5% in form of fusion dust. According to AIST [2], efficient use of arc discharge energy in the EAF is close to the limit: input of energy over 1-1.2 MVA/ton practically does not affect on duration the heat. Therefore, assimilation of the input power, localization and utilization of heat and charge losses, diversification of energy supply are topical.

Utilization of heat loss with water is not justified because of low out temperature (≤50°C), this problem engaging with organic Rankine cycle. Regarding the off-gas, two ways of heat utilization are used: preheating the EAF charge and steam generation to obtain electricity [6].

Each 100°C preheating of loaded scrap reduces power consumption in the EAF by 13-15 kWh/ton [2]. Two types of preheating systems (PS) mainly are in operation. There are "Consteel" of "Tenova S.p.A.Co" (Italy) with conveyor feeding [7] and shaft systems: “EcoArc” of “JP Steel Plantech” (Japan) [8], “COSS” of “Fuchs Technology” (Germany) [9] and “Quantum” of “Siemens-VAI” (Germany, Austria), erecting now by “Primetals Technologies” (GB) [10]. These PS are used in the “flat bath” EAF technology. Claimed scrap temperature 600-800°C in fact is less, because of cold air influx [4].

The practice of PS has revealed the problem of emission of toxic dioxins and furans (PCDD/F), formed during heating over 500°C of ordinary scrap contaminated with organic products. Measures to minimize PCDD/F: FOB, thermal quenching, sorbents [11] in some cases nullify effect of PS, considering CO_2 emission, which is unacceptable because of limits. In addition, mentioned above PS deteriorate the conditions of CO post-combustion due to off-gas temperature decrease by cold charge.

Mid-temperature scrap preheating (300-450°C) is less energy efficient, but it avoids costs for neutralizing of PCDD/F. The technology realized in 175-ton EAF of “Icdas Celik” plant (Turkey) by “SMS Concast AG” (Switzerland) [12]. However, preheating of scrap in charging bucket is hampered by its thermal resistance.

Within the diversification of EAF energy supply, SMS Siemag (Germany) developed the concept of steelmaking process with heating and melting of scrap by primary energy sources, introducing about 70% of the required energy in reactor, followed by finishing in a low-powered EAF [13]. According to Yu. Toulouevski [3], perspective direction is fuel-arc furnace (FAF) with a predominant of the FOB component in the energy balance. FAF is elaborated both for the batch and continuous processes.

Use of new solutions in domestic EAF steelmaking, is problematic in a view of high costs.

2. Low-cost solutions to improve the EAF energy-efficiency

The set of solutions to reduce and utilize EAF energy loss is shown in a Figure 1.There are: improvement of the bath geometry (I), energy-saving WCE (II), system of dispersed aspiration (III), system of mid-temperature PS with improved CO post combustion (IV). Left side from EAF axis is new solutions, right side is conventional EAF.

2.1. Deep bath

The intensive technology in "large" metallurgy approximate the processes in the bath to the converter conditions, but the ratio of bath diameter to depth D_b/H_b (Fig. 1) in the EAF still averages 5-5.5, while in the converter it is close to 1. Lowering the criticality of such parameters as slag-metal specific surface area (there is ladle treatment) and durability of the wall lining (WCE are used) allows to correct traditional bath geometry by increasing depth for a given volume, to reduce energy loss of the radiating surface.

The expressions (1,2) [14] are determine: the capacity of radiation P_{rad} from bath, from electrodes (S_{rad}) with temperature T_1 on unit of receiving surface (S) with temperature T_2; the capacity of heat loss by radiation (P_{loss}).

$$P_{\text{rad}} = \sigma\varepsilon_r (T_1^4 - \grave{O}_2^4) \iint_{S_{\text{rad}}} \left[(\cos\theta \cdot \cos\gamma) / r^2 \right] dS_{\text{rad}} \quad (1)$$

$$P_{\text{loss}} = \int_S P_{rad} \cdot dS \quad (2)$$

where σ is Stephan-Boltzmann constant, ε_r is reduced emissivity factor [15], θ, γ are direction angles for radius-vector *r* to account of mutual irradiation factor.

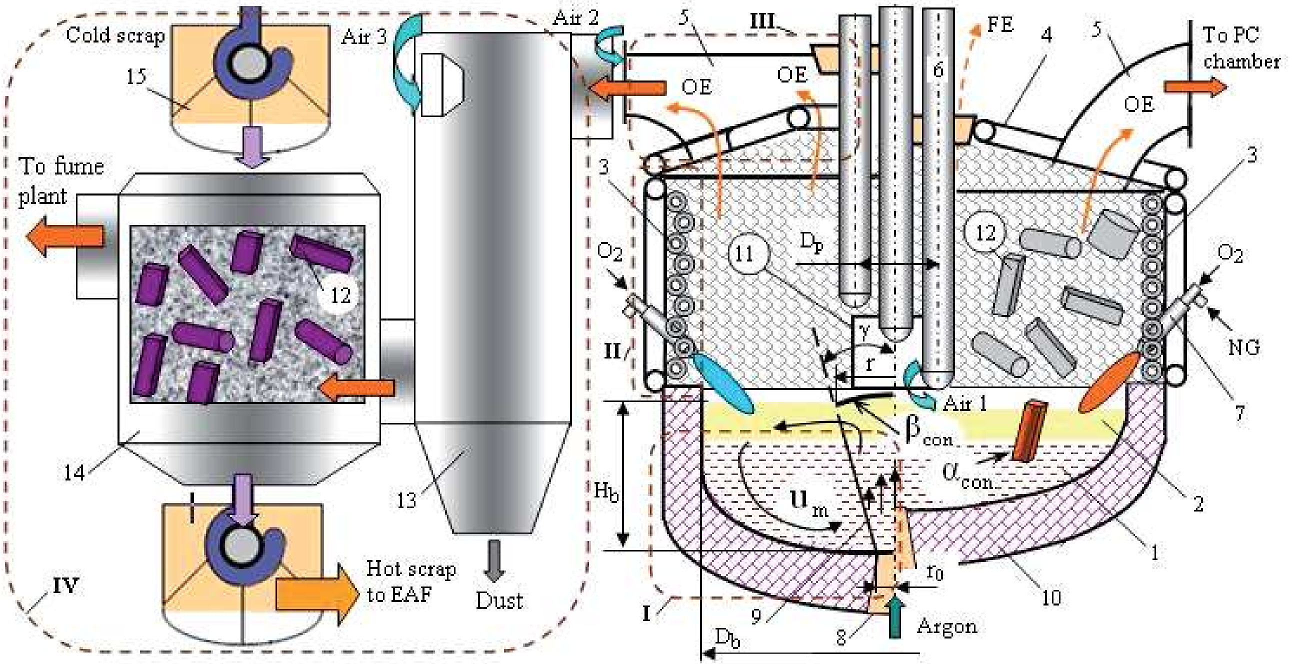

Fig. 1. Energy efficient solutions (I–IV) for the EAF. 1 – metal bath, 2 – slag bath, 3 – wall panels, 4 – roof, 5 – off-gas removal duct, 6 – electrodes, 7 – combined lance-burner, 8 – porous plug, 9 – two phase gas-metal region, 10 – bottom, 11 – slag door, 12 – scrap pieces, 13 – post combustion and duct separation chamber, 14 – preheating chamber, 15 – bucket. OE – organized emissions, FE – fugitive emissions, NG – natural gas, PC – post combustion. Other notations are in the text

Analysis of relative energy loss with cooling water depending on D_b/H_b ratio for 120-ton high-performance arc furnace is presented in a Figure 2. It takes into account a number of design and technological limitations [14] related to electrodes pinch diameter D_p (Fig. 1), type of EAF (AC or DC), technology mode (batch or continuous process).

The minimum on the curves is caused by increase of electrodes surface influence on total radiation power with reducing D_b. According to Figure 2, in the considered technology modes (1, 2, 3), the heat loss in WCE relative to the standard bath with ratio $D_b/H_b = 5$ reduces by 21, 26 and 27%, respectively.

Reduction of the slag-metal interphase surface due to the modernization of the bath requires justification possibilities of the refining in the furnace. With respect to the purging of liquid steel by an inert gas, the driving force of circulation in the bath is the difference in densities of surrounding metal and gas-metal two-phase region, formed with the opening angle γ in the bath above the porous plug (Fig. 1).

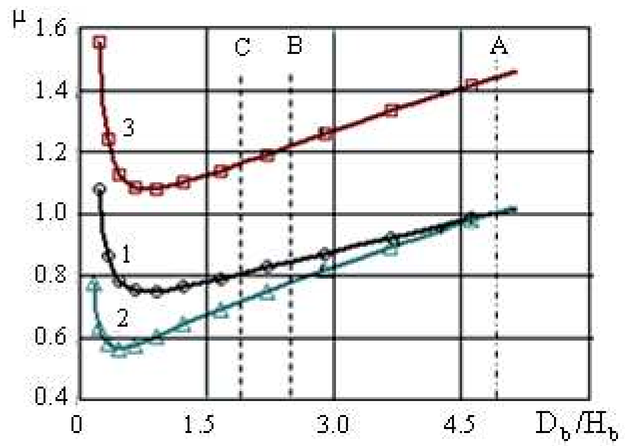

Fig. 2. Relative heat loss μ by radiation vs. D_b/H_b. 1 – AC EAF, batch process; 2 – DC EAF, batch process; 3 – AC EAF, continuous process. A – standard bath geometry; B,C – restrictions for D_b in batch (bucket charging) and continuous (conveyor charging) processes respectively

Heat and mass transfer in a pneumatically stirred steelmaking bath, according to the studies [16], is described by the following criteria equations:

$$Nu = 0,017 \cdot Re^{0,8} \cdot Pr^{0,33} \quad (3)$$

$$Sh = 0,079 \cdot Re^{0,7} \cdot Sc^{0,356} \quad (4),$$

where $Nu = \alpha_{con} H_b / \lambda$ is Nusselt number; α_{con} is heat transfer coefficient in liquid bath; λ, ν, C are heat conductivity, kinematic viscosity and heat capacity of liquid steel respectively; $Re = u_m H_b / \nu$ is Reynolds number; u_m is average velocity of circulation in the bath; $Pr = \rho C \nu / \lambda$ is Prandtl number; $Sh = \beta_{con} H_b / D$ is Sherwood number; β_{con}, D are mass transfer and diffusion coefficients in liquid bath; $Sc = \nu / D$ is Shmidt number.

According to [17], the average circulation velocity in the bath is a function of bath geometry (D_b, H_b) and the gas flow rate Q through the bottom porous plug:

$$u_m = 0,79 \cdot Q^{0,33} \cdot H_b^{0,25} / (0,5 D_b)^{0,67} \quad (5)$$

The kinetics of scrap pieces melting in a stirred bath is determined by its physical properties, specific surface area and α_{con} [18]. The kinetics of steel refining from phosphorus and sulfur characterizes by β_{con} and active interfacial surface of the bubbling "spot" of radius r (Fig. 1). The results of estimation α_{con} and β_{con} vs. D_b/H_b on the basis of (3–5), are shown in a Figure 3.

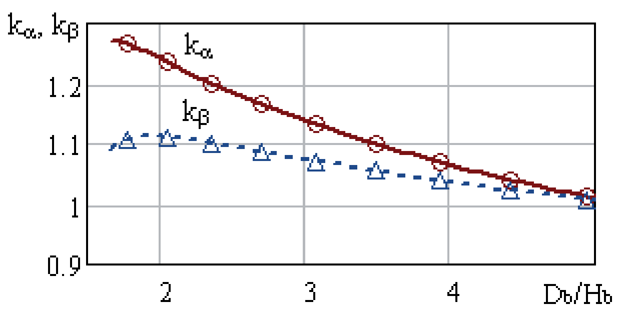

Fig. 3. Relative heat (k_α) and mass (k_β) transfer coefficients vs. D_b/H_b

Thus, decrease of D_b/H_b from 5 to 2.5 promotes to growth of α_{con} by 16%; β_{con} by 11%, and respectively, increases the heat and mass transfer intensity in the steelmaking bath, according to data [18].

2.2. Energy saving WCE

Traditional WCE are made with a the dense structure of tubes (Fig. 4a), which does not provide effective growth of slag thickness that is desirable from the positions of energy savings due to heat insulating and heat accumulating properties [19]. In contrast, the energy saving WCE (Fig. 4b,c) have a spatial structure, promoting slag deposition. The problem of stationary heat transfer in tubular WCE, covered by slag layer, is described by the equation [20]:

$$q - (1-\varepsilon) \cdot \sigma \cdot T_1^4 - \frac{(T_1 - T_2)}{(h_1/\lambda_1 + h_2/\lambda_2 + 1/\alpha)} = 0 \quad (6)$$

where q is falling heat flux; ε is panel emissivity factor; α is heat transfer coefficient from tube wall to water; $h_1, \lambda_1, h_2, \lambda_2$ are thicknesses and heat conductivities of tube and slag respectively; T_1, T_2 are temperature of radiating surface and water respectively.

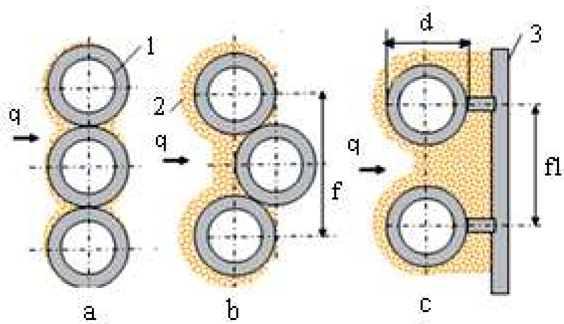

Fig. 4. WCE design types. 1 – tube, 2 – slag, 3 – casing. Notations are in the text

The numerical solution of (6) in 2D formulation conducted, using "ELCUT 6.2" software package. Initial conditions are: steel 20 tube h_1=10 mm, h_2= 5 mm, α = 6 kW/(m^{2}K), q = 250 kW/m^2. Results are shown in a Figure 5.

Optimal value of intertubular interval f (Fig. 4), when heat loss is minimal and is by 20-30% less, than in traditional WCE, constitutes 1.8-1.9 of the tube diameter d.

WCE of type's b and c (Fig. 4) are intended for high-powered EAF and foundry class furnaces respectively.

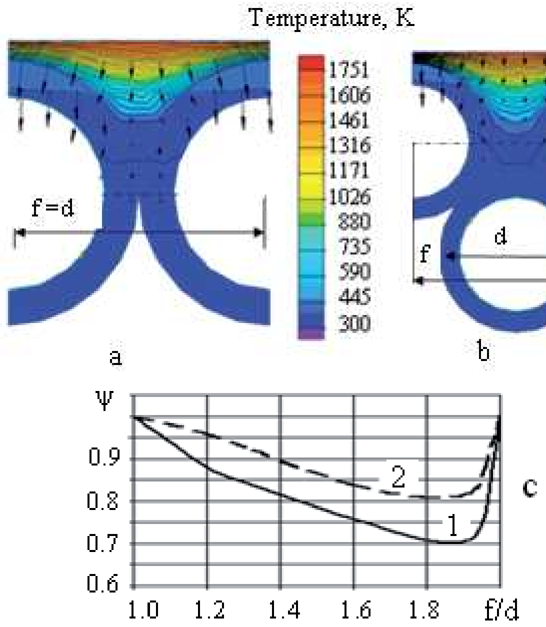

Fig. 5. Temperature field in traditional WCE (a) and in WCE with spatial structure (b); relative heat loss per 1 m^2 of WCE (ψ) vs. f/d (c) for λ_2=2 W/(mK) (1), λ_2=8 W/(mK) (2).The arrows show distribution of heat flow. Notations are in the text

2.3. System of dispersed aspiration

The principles of increasing, dispersing and approaching of suction surface to electrode gaps are realized to reduce fugitive emissions and air inflow [21] in the EAF. The aspiration system includes a chamber with a horizontal off-gas duct, connected with periphery of the sub-roof space (Figs. 1,6).

Preliminary analysis shows that off-gas flow in the EAF workspace is turbulent (*Re* ~10^5). Numerical simulation performed on the basis of Navier-Stokes (7) and continuity (8) equations using the *k*-ε turbulence model in "CosmosFloWorks" software package.

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

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

where ρ is density, w is velocity, p is pressure, τ is time, F is volumetric density of forces, η is dynamics viscosity coefficient of medium.

The following assumptions and boundary conditions are adopted: 120-ton typical AC EAF geometry; melting period is considered; air is taken as the working gas; heat exchange of gas with walls is absent; in outlet off-gas duct section underpressure is 15 Pa, average temperature of the exhaust gases is 1000 K; in the section of the slag door and on the surface of conditioned chamber above the roof are normal conditions; at the bottom of the well, melted by arcs in the burden, the gas flow rate is 4.5 kg/s and gas temperature is 1850 K at normal pressure; electrode gaps are 30 mm; other surfaces are real wall.

The velocity field is superimposed on the flow of fusion dust particles, generated by a conventional source that is the melting well bottom. The dust emission parameters: intensity 0.2 kg/s, average particle size 100 μm, density 3 g/cm^3 correspond to data [22]. The velocity and temperature of the dust particles are tied to the evaluating parameters of the gas flow.

The general picture of gas dynamics in the EAF workspace (Fig. 6) indicates that we have in the model a 100% suppression of fugitive emissions through electrode gaps. With regard to air inflow (Air1 in Fig. 1) into the furnace, it is reduced by 22%. Taking into account the average share of air inflow in total off-gas volume of 50%, expected reduction in heat loss with the off-gases is 11%.

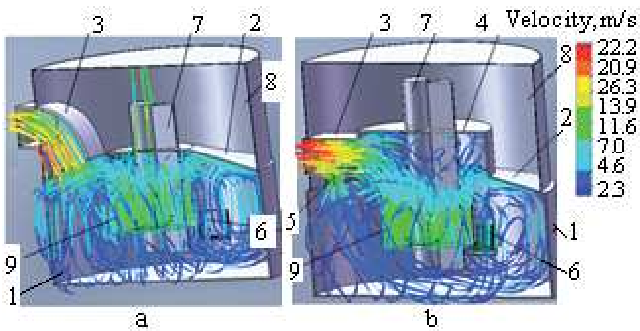

Fig. 6. Velocity field and tracks of dust and gas media in traditional aspiration system (a) and the system of dispersed aspiration (b). 1 – casing, 2 – roof, 3 – off-gas duct, 4 – aspiration chamber, 5 – peripheral channel, 6 – slag door, 7 – electrode, 8 – conventional chamber, 9 – melting well

2.4. Mid-temperature scrap preheating system

Taking into account shortcomings of the solution [12], in the proposed system of the scrap PS for domestic mini-mills, it is produced in a special chamber installed in the off-gas removal path with using charging bucket (Fig. 1).

Preliminary numerical solution of known Schumann problem (Fig. 7) show the possibility of heating 50% of total mass of scrap with a standard bulk density 0.9 t/m^3 in special chamber to 400°C in 22-25 min. by off-gas with flow rate 3 kg/s from 50-ton EAF. This allows without significant reconstruction of mini-mill production line, to reduce energy consumption in the EAF by 22-25 kWh/ton.

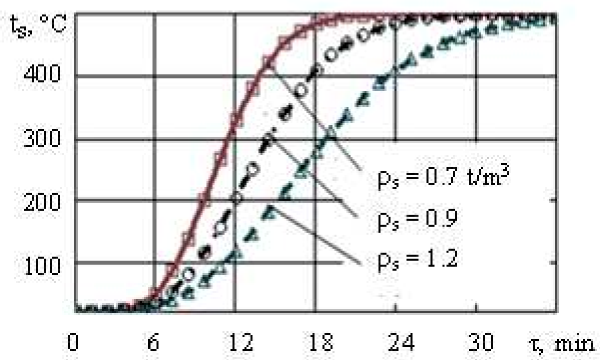

Fig. 7. Average scrap temperature t_S vs. preheating time τ and scrap bulk density ρ_S.

Scheme of scrap preheating operation in the existing infrastructure of the EAF complex in mini-mill is shown in Fig. 1. The scrap heating chamber is installed in the gas removal path after the post-combustion and dust settling chamber. Loading into the chamber and subsequent unloading of the heated scrap is carried out by means of buckets, bridge cranes, transfer cars, used in the shop.

The inflow of air into PC chamber is proposed to accomplish in two stages (Fig. 1). A stream Air 2, close to the stoichiometric for post-combustion reaction $CO + 0.5O_2 = CO_2$, is supplied for the purpose of burning CO to admissible level by laws. The main flow Air 3 provides, with account PC energy, the temperature of the gas mixture for preheating of scrap, which doesn't exceed 400°C.

3. Conclusions

Solutions are proposed for the modernization of the EAF based on changing the geometry of the bath in the direction of increasing its depth, energy saving WCE, a system of dispersed aspiration, and mid-temperature preheating of scrap. Estimation of energy savings for a set of solutions in 120-t AC EAF (with obtained data, with account of energy demand 610 kWh/t [2] and contribution of each item) is 56-68 kWh/t, the payback period is 0.5-2 years. Except energy saving, the proposals are aimed at reducing fugitive emissions, improve the efficiency of CO post-combustion and do not cause emission of toxic PCDD/F. Concerning technology readiness level, solutions II are widely used in industry, elaborations I and III are testing, and no. 4 is in the stage of technical proposal.

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