Выполнено численное моделирование нестационарной задачи электродугового нагрева сталеплавильной ванны, перемешиваемой инертным газом через донные пористые пробки. Для 120-т печи переменного тока показана возможность ускорения нагрева жидкой ванны до температуры выпуска на 12…16% и снижения потерь тепла на 5…6% при уменьшении отношения диаметра ванны к её глубине с традиционного 5,5 до 3,0.

Ключевые слова: геометрия ванны, численное моделирование, энергоэффективность.

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SIMULATION OF ELECTRIC ARC FURNACE OFF-GAS REMOVAL SYSTEM IN ORDER TO INCREASE ITS THERMAL EFFICIENCY

On the basis of hydrodynamic equations a mathematical model of electric arc furnace exhaust flue gas removal is developed, which was validated by numerical calculations and physical experiments. Using the application package CosmosFloWorks in SolidWorks software, numerical simulations of advanced off-gas removal system of modern 120-ton electric arc furnace, aimed at improving the energy efficiency of steel production, have been made. The possibility of reducing specific energy consumption by 10 ... 13 kW·h per ton of steel by lowering heat loss with technological gas and dust emissions is shown.

Keywords: electric arc furnace, off-gas removal system, numerical simulations, thermal efficiency

State of the problem

Electric arc furnaces (EAF) melt about 40% of the world steel production. Modern steelmaking technology in the EAF is accompanied by off-gas emissions 100 ... 270 m^3/hr (under standard conditions) per ton of steel [1] with the dust content 15 ... 60 g/m^3 [2]. Off-gas composition is presented mainly by nitrogen, oxygen, carbon oxide and dioxide, water vapor. Melting dust contains mainly iron oxides, carbon particles and other burden metals oxides mixture. Specificity of the EAF off-gas removal process is that:

- due to a relatively small cross section area of the suction the elbow gas flow velocity under the negative pressure in the gas cleaning system is high, and that contributes to removal of charge materials from the furnace in form of oxidized dust and small particles;

- suction of air into the furnace mainly through the slag door, constituting more than half of the total off-gas emission promotes oxidation of charge materials and increases energy loss.

All mentioned causes a lower thermal efficiency and increased consumption factor of metal in the EAF in comparison with the converter.

Localization of dust and gas environment in the EAF is one of the ways to improve the thermal efficiency of electric melting process, in which the energy loss due to the off-gas constitutes in average 15% of the energy input [2]. Preliminary economic evaluation of reducing the off-gas emission by 1% for industrial scale 120 –ton EAF constitutes 70…75 thousand dollars a year.

In [3] for solving this problem a concept of distributed gas suction is proposed, according to which the furnace roof is designed as exhaust duct with increased surface for off-gases absorption, which should ensure the reduction of dust and gas flow rate and suction of air into the furnace. However, the practical implementation of the idea was hampered by the conflicting requirements to the roof in terms of gas removal and thermal operation in capacity of the EAF working space screen.

Formulation of the problem

It is of interest both theoretically and experimentally to investigate the exhaust off-gas duct model to optimize its design parameters as applied to the problem of removing the off- gas emissions from the EAF in order to increase the thermal efficiency of steel production.

The results of theoretical and experimental research

A method of calculating the exhaust off-gas duct is developed in the framework of ventilation theory based on the integral law of mass conservation and momentum balance (Bernoulli) equation [4, 5]. In this theory, the gas parameters are averaged over the cross section of the flow, and the viscosity is taken into account by coefficient of resistance, which is determined experimentally.

Let us consider a linear exhaust gas duct of constant cross-section with length L, width a and height h (Fig. 1).

On the lateral side of the duct n holes (slits) are located at the same distance from each other, through which the inflow of gas from the surrounding space takes place. The region between adjacent slots is the duct section. One end of the duct is plugged, and in the other end air is pumped out at the rate of Q_k.

It is necesary to find the area of the slits σ_i, providing a uniform air inflow along the length of the duct.

The calculations were performed for the duct with the following dimensions: length L = 1,0 m, width a = 0,05 m, height h = 0,25 m. The geometrical dimensions of the duct ($L >> h >> a$) allow us to consider it as two-dimensional.

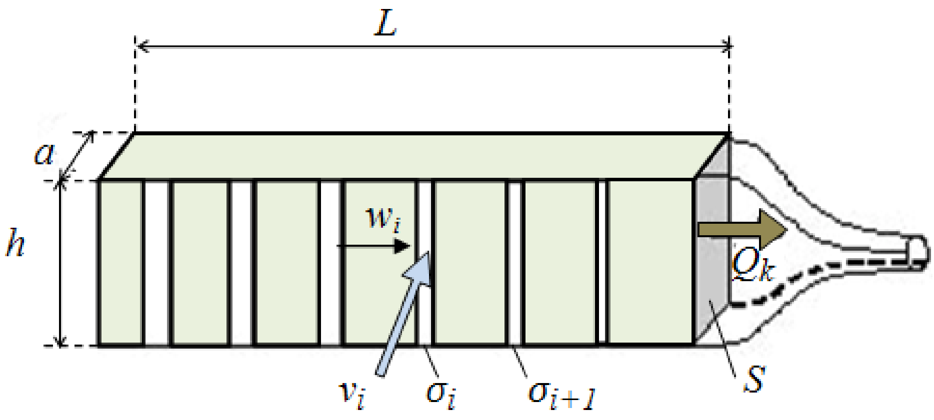


Figure 1 –The sketch of the exhaust off-gas duct (designations are given in the text).

For the case of uniform suction the flow rate through a single slit is

$$\delta Q = \frac{Q_k}{n} \tag{1}$$

Air flow rate through cross section of the duct behind the slit under number *i* will be

$$Q_i = w_i \cdot S = i \cdot \delta Q , \tag{2}$$

where w_i is the average longitudinal velocity of the air along the duct in the middle between the slits, $S = a \cdot h$ is the cross-sectional area of the duct; i is the section (slit) number.

Amount of air flowing through the gap is

$$\delta Q = v_i \cdot \sigma_i , \tag{3}$$

where v_i is the average rate of air flow in the slit, which depends on the depression in the duct and is connected with the static pressure p_i in the section by Bernoulli equation

$$p_i = p_a - \frac{\rho \cdot v_i^2}{2\mu^2} \tag{4}$$

where μ is the flow coefficient, depending on the shape and thickness of the slits [4]; ρ is the gas density; p_a is the pressure outside the duct.

Let us write the momentum equation in the projection on the duct axis for two sections i and $(i+1)$ located in the middle between two adjacent sections

$$p_i + \rho \cdot w_i^2 = p_{i+1} + \rho \cdot w_{i+1}^2 + \delta p , \tag{5}$$

where δp is the pressure loss due to friction, which is defined by formula

$$\delta p = \frac{\lambda}{4} \cdot \frac{\rho \cdot w_i^2}{2S} \cdot S_1 = \frac{\lambda_i^2 \cdot S_1}{8S^3} \cdot \rho \cdot \delta Q^2 \qquad (6)$$

Here $S_1 = \dfrac{2(a+h) \cdot L}{n}$ - lateral surface area of one section of the duct; λ - the friction factor in the duct.

After substitution the expressions (2), (3), (4) and (6) in (5) and the transformations we obtain the following recurrence relation for determining the area of the slits:

$$\sigma_{i+1} = \frac{\sigma_i}{\sqrt{1 + \dfrac{2\mu^2 \cdot \sigma_i^2}{S^2} \cdot \left(2i + 1 + \dfrac{\lambda \cdot S_1}{8S} \cdot i^2 \right)}}. \qquad (7)$$

The resulting formula can estimate the size of slits for a given geometry of the duct from the position of uniform gas flow along the length of the intake duct. Knowing the area of slits and gas flow rate in each slot (initially set to the same), we can find the average flow rate for each slit.

The next step was to assess the adequacy of the considered mathematical model by solving the problem of the flow in the exhaust in a more precise gas dynamics formulation. To do this, the exhaust off-gas duct, calculated in accordance with (7), was modeled using the application package CosmosFloWorks in SolidWorks software, for the case of air. Preliminary analysis showed that the investigated flow is turbulent. The calculation is performed numerically based on the Navier-Stokes equation (8) and continuity equation (9) using the $k-\varepsilon$ model of turbulence.

$$\frac{\partial \vec{w}}{\partial \tau} + (\nabla \vec{w}) \cdot \vec{w} = -\frac{1}{\rho} \cdot \nabla p + \eta \cdot \nabla^2 \vec{w} + F \qquad (8)$$

$$div \vec{w} = 0 \qquad (9)$$

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

Scheme of calculation model of the duct and the obtained air velocity field are shown in Fig. 2.

The boundary conditions of the problem were: depression 50 Pa on the suction face 1, normal (pressure and temperature) conditions on slits 2 ... 5, the "real" wall - the rest of the fluid body boundaries. Duct sizes were set according to the above model (Fig. 1 and description of it), slit 5 width was 20mm, and slits 2 ... 4 widths were calculated using formula (7).

On the basis of the velocity field the average flow (inflow) of air for each slot duct is obtained.

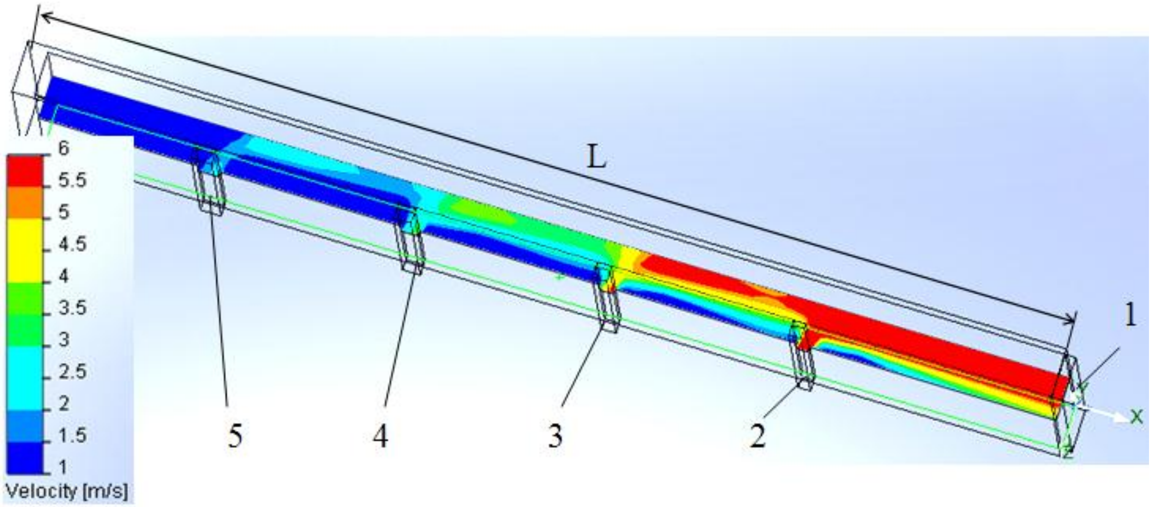


Figure 2 – Scheme of calculation model of the duct and velocity field obtained by numerical simulations (designations are given in the text).

In accordance with the above procedure we carried out experimental exhaust off-gas duct, in which we measured air inflow by the rate of its sucking in each of the duct slits in order to verify conformity with the estimated equation (7).

Experimental device (Fig. 3) includes exhaust off-gas duct 1 with four slits connected through a Witoszynskyj's nozzle 2 with fan 3.

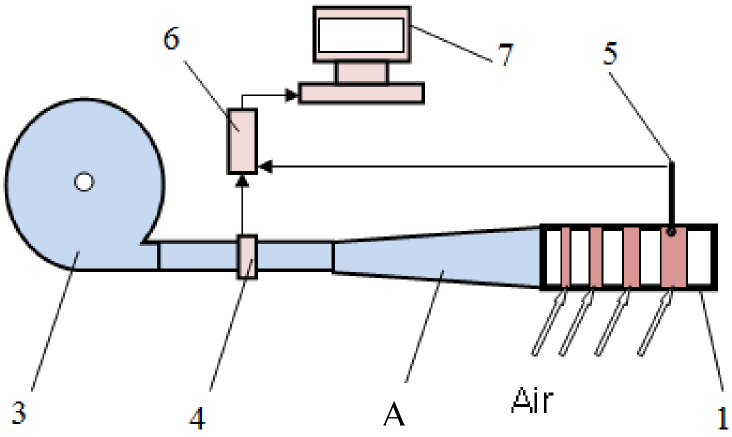
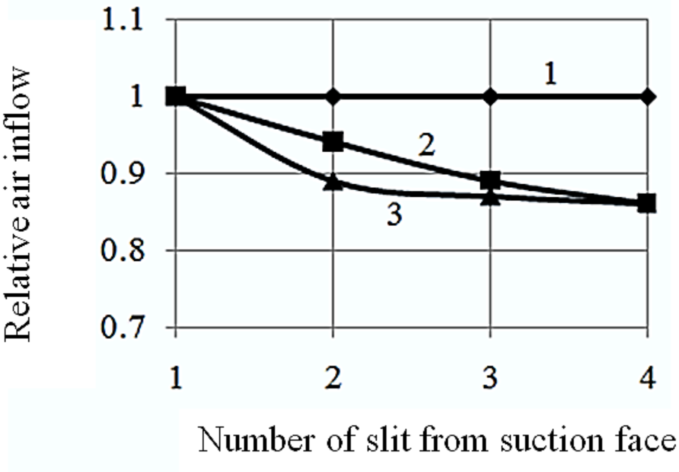


Figure 3 – Scheme of experimental device (designations are given in the text).

The negative pressure was measured on the straight part by means of differential manometer 4 and controlled by throttle valve of the fan to maintain the values of 50 ± 10 Pa, adopted in the numerical calculation. Air velocity in the exhaust duct slits was measured by hot-wire anemometer 5 in three points of each slit. The signals from the measuring devices after processing the analog-to-digital converter 6 were recorded and analyzed by computer 7.

The comparison of the relative values of the air inflows into the slits along the duct (Fig. 4) calculated by the proposed method (based on numerical simulations by means of the application package CosmosFloWorks and experimental data) showed that the compared values differ no more than 15%.



1 – calculation by proposed procedure; 2 – obtained by means of CosmosFloWorks; 3 – experimental data.

Figure 4 - Comparison of air inflows along the exhaust duct.

This allows using this highly simplified mathematical model for engineering design of the EAF off-gas removal system.

We propose a new design of the EAF off-gas removal system (Fig. 5a), in which, in contrast to the traditional pattern (Fig. 5b), we used circular exhaust off-gas duct 1 with variable by half-perimeter (due to the symmetry of the gas stream) width of the slits.

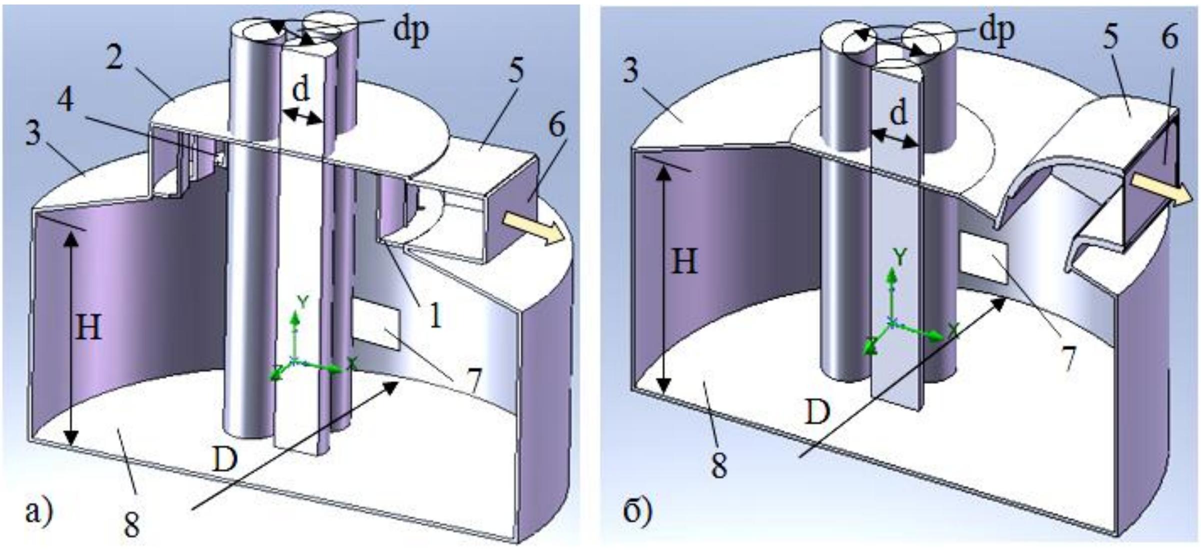


Figure 5 – Off-gas removal system with top chamber and exhaust duct (a) and traditional EAF off-gas removal system (б). Designations are given in the text. The arrow shows direction of the off-gas suction.

This duct was mounted in top camera 2 of the roof 3. Parameters of the slits 4 were calculated by the formula (7) from the position of process off-gas uniform flow along the duct perimeter: the area of slits increases with their angular position (0 ... 180^0) with respect to the longitudinal axis of the suction elbow 5.

The effectiveness of the proposed technical solutions of the EAF off-gas removal system was estimated using the application package CosmosFloWorks in SolidWorks. The calculation is performed numerically based on the Navier-Stokes equation (8) and continuity equation (9) using the $k-\varepsilon$ model of turbulence.

The boundary conditions are (see Fig. 5): depression 100 Pa to face 6 of suction elbow; normal (in terms of pressure and temperature) conditions in the furnace slag door 7; gas flow rate from bath 8 (CO output by oxygen blowing of steel bath with injection of carbon powder) 2,2 m^3/s at the temperature 1850K; the "real" wall – on the rest of the fluid body boundaries. Dimensions of the furnace (see Fig. 5) correspond to 100 .. 120 tons modern EAF and are the same for options a) and b): diameter of the bath D = 5500 mm; height of the working space H = 0,6 D; electrode diameter d = 600 mm; electrodes split diameter d_p = 1250 mm; the size of the slag door is 700x600 mm; suction elbow cross section is 1500x750 mm.

The objective was to obtain the velocity field of the gas medium in the furnace with regard to off-gas removal system options a) and б) in comparable conditions and to estimate air flow in the EAF slag door.

Fig. 6 shows gas flow trajectories in the EAF workspace.

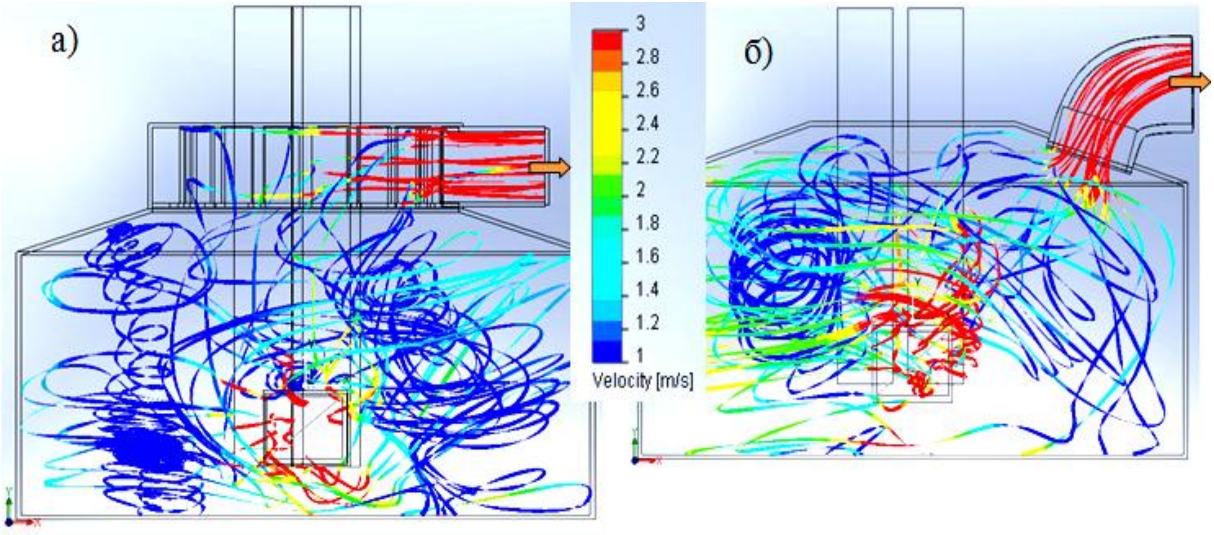


Figure 6 – Gas flow trajectories in the working space for EAF with proposed off-gas removal system (a) and traditional one (б).

Visualization of the trajectories gives an indication of a less intense nature of gases motion in a furnace equipped with the proposed off-gas removal system (option a)), compared to the traditional (option б).) This, apparently, is connected with the division of a single powerful vortex in the EAF working space into two less powerful vortexes.

Fig. 7 shows the vertical (suction elbow axis) and horizontal (on the border of the furnace casing and roof) sections of the velocity field of the studied variants of the EAF off-gas removal systems.

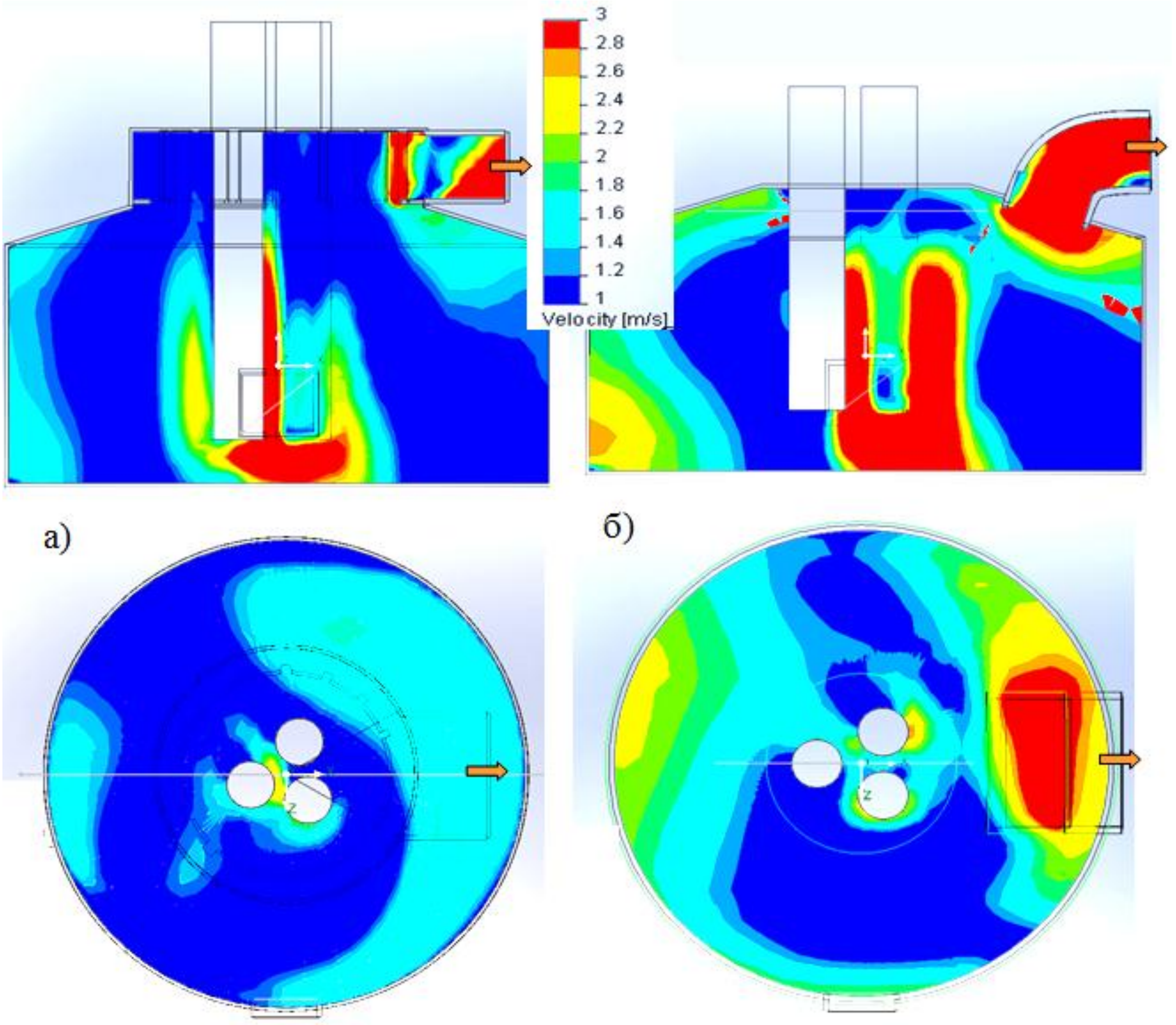


Figure 7 – Vertical and horizontal velocity field sections for gas flow in the EAF working space with proposed off-gas removal system (a) and traditional one (б).

The analysis of these data indicates a more uniform distribution of velocities and lower average values of this parameter of the gas flow, in particular, the vertical velocity component for the proposed variant of gas removal. In practice, this will reduce the removal of dust from the furnace thus reducing the specific consumption of metal charge.

The estimation of air inflow in the EAF slag door for gas removal systems was performed. Fig. 8 shows the calculated curves of the velocity distribution of air suction on the diagonal of the EAF slag door, obtained by solving the problem using CosmosFloWorks application package.

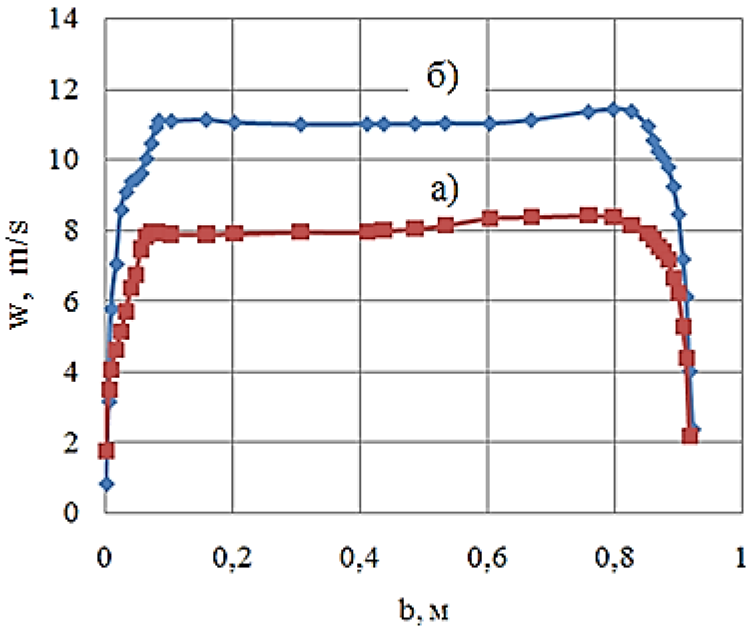


Figure 8 – Distribution of air inflows velocity (w, m/s) along slag door diagonal (b, м) for EAF with proposed off-gas removal system (a) and traditional one (б).

According to represented data, the use of exhaust duct with calculating parameters provides lowering of average air inflows velocity through EAF slag door from 11,2 to 8,2 m/s, and, correspondingly to decrease by 27% the air inflows rate in comparison with traditional off-gas removal system.

The proposed design of exhaust off-gas duct, in contrast to the above mentioned roof with distributed gas suction [3], has a number of significant differences, the main one of which is the vertical position of the suction plane of the annular exhaust duct. This solution, in comparison with horizontal exhaust duct in solution [3], greatly reduces its susceptibility to the falling irradiative heat flux from the liquid bath, which allows to use more efficiently exhaust off-gas duct for the purpose of gas removal without compromising thermal performance of the roof.

Proceeding from the average performance of modern EAF intensive smelting technology [2] (for the specific energy consumption with regard to steel production of 600 ...650 kW-h/ton, the share of energy loss with technological off-gases15% and the proportion of air inflows in the total volume of the furnace off-gases 50%) when using the proposed off-gas removal system we should expected the decrease of the specific energy consumption by 1,8 ... 2%.

Thus, the use of the proposed EAF off-gas removal system will reduce electricity consumption by 10 ... 13 kW-h/ton of steel only by lowering the suction of the cold air into the furnace. This will allow for high-performance 100 ... 120 ton EAF to save (with the price of electricity $ 0,08 per 1 kW-h), on average, 900 thousand U.S. dollars a year. In Ukraine the cost of the roof including the proposed off-gas removal system (it weighs about 45 tons) for these furnaces will be about 450 thousand U.S. dollars and payback period for the modernization of the EAF off-gas removal system does not exceed six months.

Conclusion

On the basis of hydrodynamic equations we developed a mathematical model, that allows, according to given geometrical and operational process parameters, calculating the exhaust off-gas duct, which provides a uniform dusty gas flow from the EAF working area.

Solution of the problem of the media flowing in the given exhaust off-gas duct (in a more precise gas dynamics formulation) by means of applying the package CosmosFloWorks in SolidWorks software, as well as the physical model experiment, confirmed the adequacy of the proposed method and the possibility of its practical implementation for estimating the EAF off-gas removal system in order to improve thermal efficiency of steel production process.

Comparative numerical simulation of the gaseous medium flow for the cases of improved and traditional off-gas removal systems applied to modern 120-ton EAF operating by intensive technology showed the possibility of reducing the specific energy consumption by 10 ... 13 kW-h/ton of steel by lowering the heat loss with technological off-gas emissions.

REFERENCES

1. Kuhn R. Continuous off-gas measurement and energy balance in electric arc steelmaking / R. Kuhn, H. Geck, K. Schwerdtfeger // ISIJ International. – 2005. – Vol. 25. – No. 11. – P. 1587-1596.
2. Toulouevski Yu.N. Innovation in Electric Arc Furnaces / Yu.N. Toulouevski, I.Y. Zinurov // Scientific Basis for Selection: Springer-Verlag Berlin Heidelberg. – 2010. – 258 p.
3. Tischenko P.I. Povyshenie effectivnosti pervichnogo gazoudalenija pri modernizatsii dugovykh staleplavilnikh pechei (Increasing of the efficiency of the EAF primary off-gas removal system) / P.I. Tischenko, S.N. Timoshenko, N.B. Dun // Bulleten nauchno-tekhnicheskoi informatsii “Chernaja metallurgija”. – 2006. – №2. (in Russian).
4. Povkh I.L. Tekhnicheskaja gidromekhanika (Technical Hydrodynamics) / I.L. Povkh. – Leningrad: Mashinostroenije, 1976. – 504 p. (in Russian).
5. Taliev V.N. Aerodinamica Ventiljatsii (Aerodynamics of Ventilation) / V.N. Taliev. – Moscow: “Strojizdat”, 1979. – 295 p. (in Russian).

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МОДЕЛЮВАННЯ СИСТЕМИ ГАЗОВИДІЛЕННЯ ДУГОВОЇ СТАЛЕПЛАВИЛЬНОЇ ПЕЧІ З МЕТОЮ ПІДВИЩЕННЯ ЇЇ ЕНЕРГОЕФЕКТИВНОСТІ

На основі рівнянь гідродинаміки розроблена математична модель витяжного газоходу системи газовидалення дугової сталеплавильної печі, що пройшла перевірку адекватності шляхом чисельних розрахунків й фізичного експерименту. З використанням пакета прикладних програм CosmosFloWorks виконаний чисельний розрахунок удосконаленої системи газовидалення сучасної 120-т дугової печі, спрямованої на підвищення енергоефективності процесу виплавки сталі. Показано можливість зниження питомої витрати електроенергії на 10...13 кВт-г/т сталі за рахунок зменшення втрат тепла з технологічними пилогазовими викидами.

Ключові слова: дугова сталеплавильна піч, система газовидалення, чисельне моделювання, енергоефективність.

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МОДЕЛИРОВАНИЕ СИСТЕМЫ ГАЗОУДАЛЕНИЯ ДУГОВОЙ СТАЛЕПЛАВИЛЬНОЙ ПЕЧИ С ЦЕЛЬЮ ПОВЫШЕНИЯ ЕЕ ЭНЕРГОЭФФЕКТИВНОСТИ

На основе уравнений гидродинамики разработана математическая модель вытяжного газохода системы газоудаления дуговой сталеплавильной печи, которая прошла проверку адекватности путем численных расчетов и эксперимента. С использованием пакета прикладных программ CosmosFloWorks выполнено численное моделирование усовершенствованной системы газоудаления современной 120-т дуговой печи с целью повышения энергоэффективности процесса выплавки стали. Показана возможность снижения удельного расхода электроэнергии на 10…13 кВт.ч/т стали за счёт уменьшения потерь тепла с технологическими пылегазовыми выбросами.

Ключевые слова: дуговая сталеплавильная печь, система газоудаления, численное моделирование, энергоэффективность.

УДК 669.18

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КЛАССИФИКАЦИЯ РЕЖИМОВ ПЕРЕМЕШИВАНИЯ ЖИДКОЙ СТАЛИ В КОВШЕ ПРИ ПРОДУВКЕ ИНЕРТНЫМ ГАЗОМ

В статье представлены результаты исследования процессов перемешивания жидкой стали в ковше при продувке инертным газом для ковшей с одним и с двумя продувочными узлами при различном их расположении. Определено рациональное расположение продувочных узлов. Исследования выполнены путём математического моделирования в прикладном пакете ANSYS.

Ключевые слова: схемы перемешивания, футеровка, ковш, продувочная фурма, диапазон расположения продувочных фурм, термические напряжения, поток.
