NEW GENERATION OF THE EAF PANELS WITH RENEWABLE SLAG: LOWERING OF HEAT LOSS, COMBINING OF DUTIES FOR ENERGY SAVING

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Water-cooled walls and roof panels are an integral part of high-powered EAF. A fee for its functions performance is increasing of energy consumption up to 10-15% through heat losses with cooling water. So energy saving problem is very important: each percent of energy consumption lowering will effect a saving 0,14-0,17 USD/ton of steel (150000 USD/year for 100-ton EAF).

More than 10 year's experience in panels design led us to elaboration a mathematical model of heat exchange between working space of operating EAF and water-cooling panel. Using of the model promotes elaboration of advanced design solutions for panels, grounding on renewable slag coating operation. There is a new generation of multi-layer panels, where a role of slag renewable coating, as heat- insulation and protective material, is extremely high. Optimal conditions for attachment and fixing of equilibrium working slag layer on the heat absorption elements provide by application the principles of spatial and non-dense arrangement of these elements.

1. Mathematical model of heat exchange in the system: EAF working space – operating panel.

The model means for calculation of key design parameters of panels in order to minimize the heat loss and evaluations of design solutions efficiency from different positions.

Acceptable adequacy of the model provides by combination of general theoretical heat-engineering considerations and obtained experimental data, such as: a) thermal properties of slag- heat conductivity, porosity, gas permeability; b) conditions of slag formation and destruction in operating EAF; c) radiation reflecting ability factor for different panels design solutions.

The calculations of panels starts from obtaining data regarding density of falling radiation heat flux distribution upon the EAF walls and roof. The direct methods of it measurements are hampered, and the existing procedures of calculation remain far from practice of a modern arc furnaces operation. Present model allows falling radiation heat flux calculations with the regard for furnace installation and the technology parameters, such as:

- geometry of working space;

- active power value;
- kind of a utilized electrical current;
- oxygen purge by super-sonic lance operation;
- of coal introduction into a bath;
- foaming slag practice;
- burners operation and position;
- post combustion of carbon monoxide in the furnace space.

The model also takes into consideration a factor of non-simultaneity of action of the indicated stimulus sources on the panels for calculation of specific heat loss value during the heat.

A general principle of falling heat flux q calculation in given point is integration on a surface of a Lambert stimulus source S_{rad} with regard for its position concerning the recipient of heat:

$$q = B \int_{S_{rad}} \frac{(\vec{n}', \vec{r})(\vec{n}, \vec{r})}{r^4} dS_{rad} , \qquad (1),$$

where $\vec{n}', \vec{n}$ - normal lines to elementary platforms of an emitter and recipient of heat; r- a position vector from a radiant to a detector, $B=R/\pi$ brightness of a stimulus source.

A density of energy flow R of a bath and electrodes surface is instituted in their medial temperature on a Stefan-Boltzmann law; other stimulus sources are instituted in density of its thermal (electrical) power distribution with allowance for its anisotropy and utilization efficiency.

Results of falling heat flux calculations for 100-ton EAF (active power 35 MW; casing diameter 7m; height of walls 2,4m; three electrodes of 610 mm diameter; pinch diameter 1,74m; 3 wall burners each 2 MW capacity positioned 1,2m over slag line) are given in fig. 1a, 1b for walls and roof correspondingly.

The main features of the new generation of panels are:

- a renewable slag layer on heat absorbents;
- a principle of a spatial arrangement of heat absorbents.

These factors ensure high stability of panels and lower heat loss with cooling water. Let's esteem tendered modifications of two-row panels: 1) baseline model with exterior (versed to a casing of EAF) dense tubes row and interior (versed in working space) non-dense tubes row; 2) with non-dense staggered pipes arrangement in both rows; 3) with non-dense tunnel pipes arrangement in both rows. The relevant calculation schemes of the indicated alternatives are reduced in fig. 1a (versions 1,3) and fig.1b (version 2).

A stationary heat exchange in a system: working space of EAF - water-cooling panel with a stratum of slag is considered.

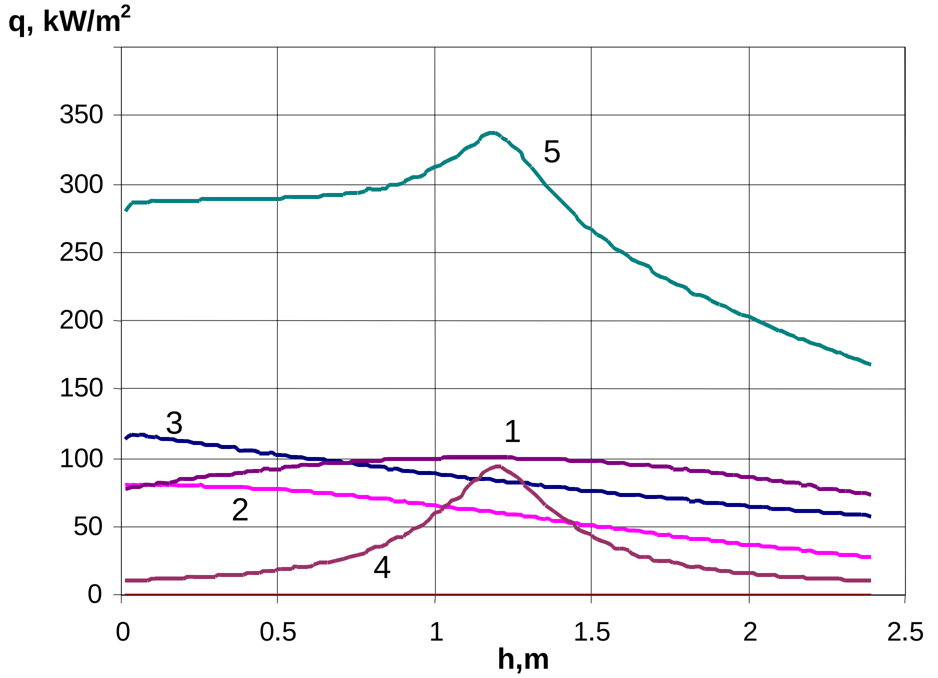


Fig.1a. Falling heat flux (q) distribution on walls height (h). Radiation sourses:1-melt, 2-arcs, 3-electrode, 4-burners, 5-total.

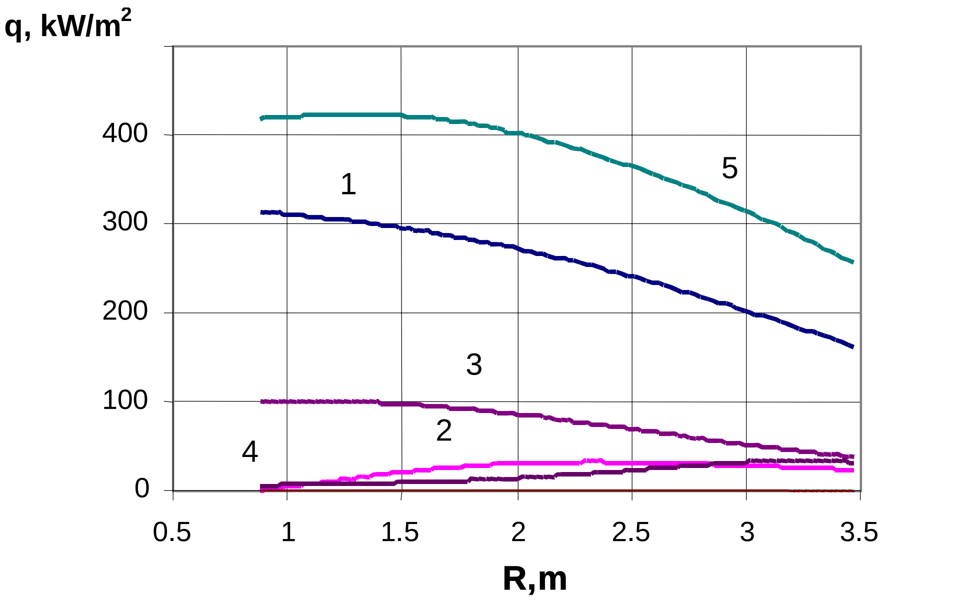


Fig.1b. Falling heat flux (q) distribution on roof radius (R). Radiation sourses: 1-melt; 2-arcs; 3-electrode, 4-burners, 5-total

The steel casing of EAF on the part of working space is enclosed by two rows of tubes of external diameter *d* with an interval between axes *f*, installed apart *b* (in clear) from a cover and (or) among themselves. Falling heat flux from a working area on the panel is *q*. Heat rejection is ensured by water with temperature T_w, circulating in tubes. Heat rejection due to free convection from a casing is neglected. At EAF operation slag deposits on tubes and between it.

It is required to calculate an inter-tubular interval *f,* which one at given parameter *b* will provide minimum heat loss with cooling water.

The one-dimensional problem about transiting a part of heat flux through two infinite plates to cooling water is considered The elementary unit of heat exchange of length *f* comprises calculation areas *I, II* (fig. 1a) or *I, II, III* (fig. 1b): slag and material of a tube. Their thickness are *y, h (h *),* thermal conductivity λ_1, λ_2, accordingly.

Other part of heat is re-radiated to working space.

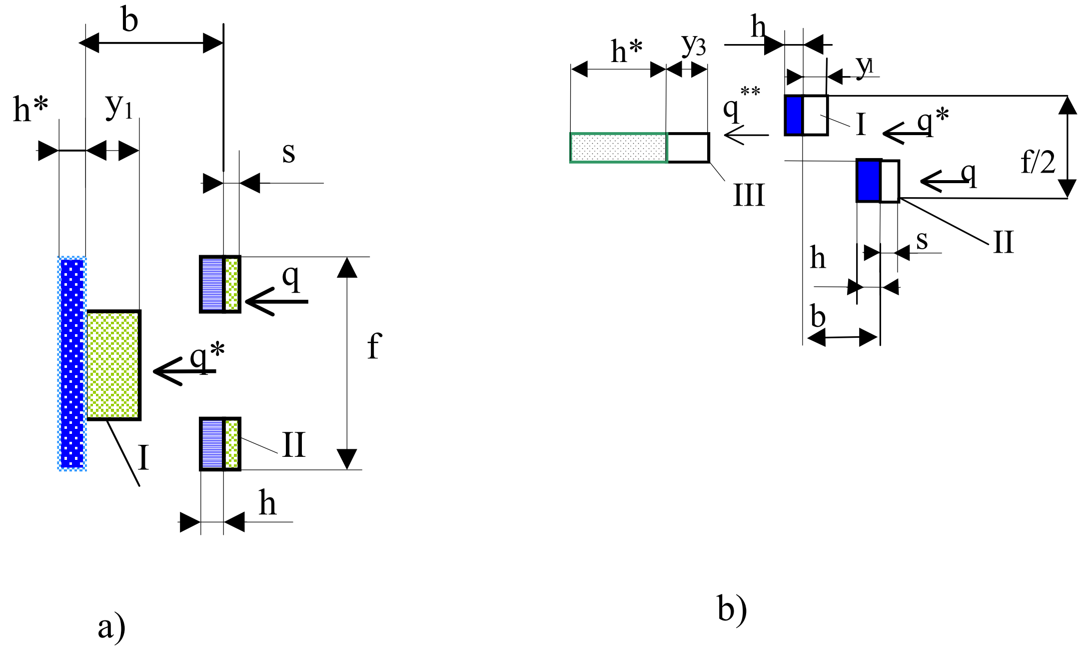


Fig. 2 – Calculation schemes of 2-row panels modifications.

a) for baseline and tunnel pipes arrangement;
b) for staggered pipes arrangement,

I,II,III – calculation areas.

In calculation area *II* for all surveyed cases the heat exchange is featured by the equation:

$$q - k\sigma T_0^4 - \frac{1}{(y/\lambda_1 + h/\lambda_2 + 1/\alpha)}\left(T_0 - T_w\right) = 0\,, \tag{2}$$

where σ - Stefan-Boltzmann constant; k - reflecting capacity of a slag surface, defined experimentally; α - heat-transfer coefficient from a wall of a tube to water.

By a numerical solution (2) can be find a temperature of a working slag surface T_0 pays and an equilibrium thickness of glag $y=s$ from a wievpoint of a beginning of its fusion: $T_0=T_f$..

The heat losses with water in calculation area II constitutes:

$$Q_2 = (q - k\sigma T_0{}^4)d \tag{3}$$

For calculation area *I* the equation (2) is valid with following modifications:

- The falling heat flux is screened by tubes and rate of its magnitude for cases 1), 2) is equal: *q * = q (f/2) / (b+d);* for a case 3): *q * = q (f/2) / (b+2d);*
- Effective length of a heat-conducting metal stratum for a case 1): h * = h; for a case 2): *h * = h+b+f/4*; for a case 3): *h * = h+b+f/2*.

The minimum (equilibrium) slag thickness $y=s$ corresponds to a requirement of its fusion: $T_0=T_f$, maximal – to a requirement of complete clogging of tubular annulus: for cases 1), 2*): y = b+d+s;* for a case 3): *y=d+2d+s*. There are also other two limitations for slag thickness:

- $2y \geq b$, that means the condition of persistence of its presence in space between rows, as a requirement of safe maintenance of the panels;
- Tk < 200^0 C (for a case 3), i.e. lack of overheat of a casing temperature above admissible on the accident prevention in a critical region between tubes.

The heat losses with water in calculation area I constitutes:

For cases 1), 3) $$Q_1 = (q^* - k\sigma T_0{}^4)(f - d) \tag{4}$$

For a case 2) $$Q_1 = (q^* - k\sigma T_0{}^4)d$$

In calculation area *III* the falling heat flux (concerns only to a case 2) is screened and defines by the equation: *q ** =q (f/2) / (2d+b)*. An effective length of a metal heat-conducting stratum is equal to : *h * = h+b+f/4*.

The heat losses with water in design field(area) III are instituted as:

$$Q_3 = (q^{**} - k\sigma T_0{}^4)(f - 2d)\,. \tag{5}$$

The limitations on equilibrium slag thickness, operating in this calculation area, correspond reduced above.

The specific heat loss flow with a water-cooled panel defines generally on the equation:

$$q_{nom} = (Q_1 + Q_2 + Q_3) / f \qquad (6)$$

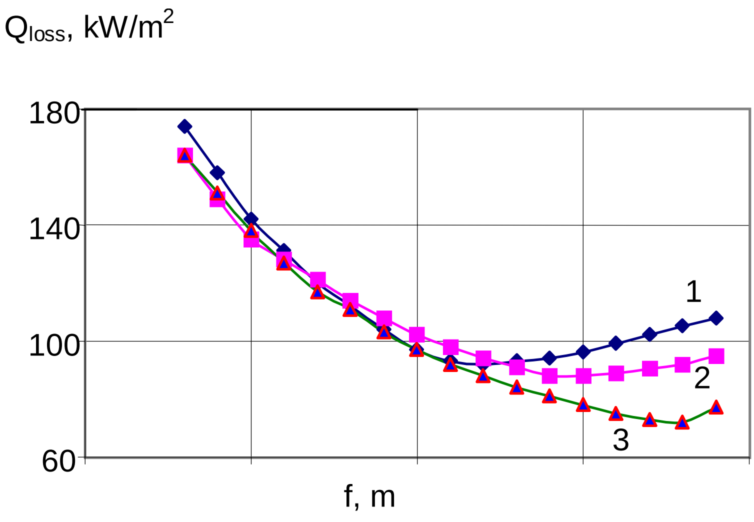
The reflecting ability factor of a water-cooled panel k is instituted on the basis of experimental data obtained by direct method of measurements of a falling and reflected heat flow in working EAF.

$$k = q_{refl} / q = a \ln q_{calc} + b \qquad (7)$$

where q- falling heat flow ; q_{refl} - reflected heat flow; q_{calc} – calculated value of falling heat flow (fig.1); *a, b* - empirical coefficients.

2. New wall panels solutions performance.

An example of calculation of an inter-tubular interval f for versions of panels 1,2,3 of a requirement of minimization of heat loss is reduced in a fig. 3 for following values of performance parameters: q= 400 kW/m^2; b=80 mm, d=76 mm, h=12 mm, α= 5000 W/m$^{2\cdot}$K, λ_1=2,5W/m$^\cdot$K, T_f=1350^{0}C, λ_2= 40 W/m$^\cdot$K.



1,2,3- wall panels modifications (by text).

Fig.3 – Heat loss (q_{loss}) in dependence on inter-tubular interval (f).

A fig. 4 represents comparative value of heat loss with cooling water for panels of tendered modifications (for baseline version its value is 1) at different magnitudes of falling heat flux.

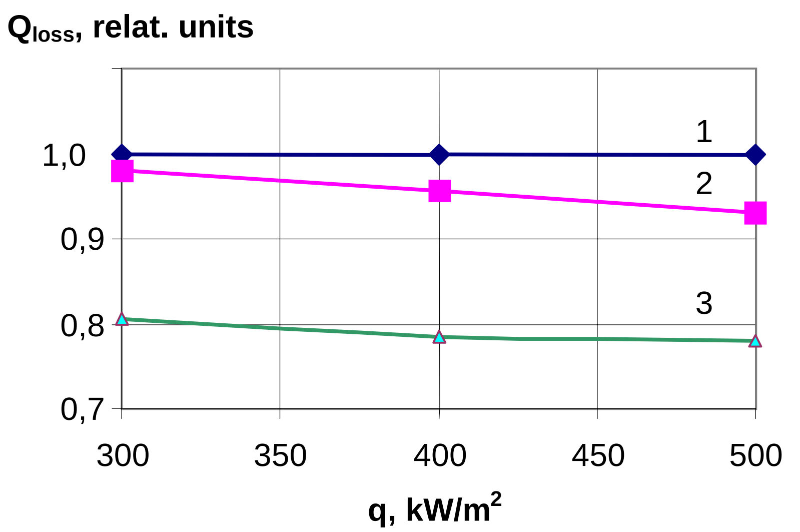


Fig.4 - Relative heat loss in panels (Q_{loss}) of baseline (1) and new modifications (2,3) versus heat load (q).

From reduced data follows the next conclusions:

- For all design alternatives of wall panels there is an optimum magnitude of an inter-tubular interval *f*, supplying minimum heat loss at a given heat load.
- At a given heat load q = 400 kW/m^2, typical for high powered, the panels with a tunnel pipe arrangement are most effective from a point of view of minimization of heat loss.
- The panels with staggered and, especially, with a tunnel pipe arrangement tend to growth of effectiveness of energy saving in matching with baseline modification at magnification of a heat load. So, at usage of panels with a tunnel pipe arrangement heat loss lowering in matching with baseline modification is 19 % at q=300 kW / m^2 and 22 % at q=500 kW / m^2.

3. New roof panels solutions performance.

The in-service experience of major capacity EAF (100 ton and more) testifies that the power loss with cooling water, compound during a heat for a roof and walls are correspondingly 5-6 and 1,8-2,5 MW·h. Thus the stability of water-cooled roofs is much lower than stability of walls, as during operation of the furnace the roof exposes to more intensive thermal shocks. Therefore perfecting of a construction of water-cooled roofs and, first of all, systems of their cooling, is an actual problem.

As a result of searching the optimum shape of water-cooled roof is performing the panels in form of spirals having in vertical profile the shape of a delta circuit with rounded angles.

Design features of the roof are:

- Usage of principles of non-dense spatial pipe laying and their thermal shields by a restored working slag stratum with the purpose of a decrease of power losses;
- Sector location of panels shaping a cooled surface of a roof;
- Declination of panels to horizon on particular angle and shaping in vertical profile of a roof of arc structure;
- The panels are covered from above by steel screen supplying particular gas-tightness of constructions;
- Values, calculated on the basis of a mathematical model, of an inter-tubular interval *f* at a set value of a clearance between a tube and screen, supplying minimum heat loss with water and lack of overheat of the screen over admissible magnitude.

The critical level of temperature of a steel screen of a roof constitutes 200°C. Its overflow induces deformation of metal constructions and reduces its durability because of thermal fatigue. So this factor must be taken into account in roof panels calculations as one of limitations.

The decrease of heat loss and of stresses in water-cooled devices is promoted by availability on their surface of a slag stratum. The requirements of its shaping both retention for walls and roof of the EAF hardly differ. As the roof in process of heat is subject to more sharp drops of temperature, and in time of charging is cooled faster, than walls, the thickness of a slag stratum on its surface will be less. The outcomes of monitoring of a state of a surface of walls and roof conducted during industrial trials, testify that the magnification of clearances between tubes in cooled panels promotes increasing of slag mass, accumulating on a panel surface. Due to improving of requirements for upbuilding and retention of slag, its mass constitutes, on calculations, 2-3 ton for 100-ton EAF. Heat accumulating by slag can be usefully utilized for heating up of charge by each consequent heat, that meliorates as a whole duty of the furnace.

3.1. Integrated functions of a gas-suction system by a modern roof.

In conventional EAF the suction of gases from working space is yielded through an orifice in a water-cooled roof (4-th hole). At such system o gas suction rushing to diminish unorganized outbursts of gases through clearances in electrode orifices reduces in an amplification of air inleakage in a working window in view of localization of exhaustion. The speed of gases motion in the field of an orifice in a roof reaches 30-50 m/s, that promotes loss of materials particles from furnace and negatively influences on material and thermal balances of the heat.

The new concept of a water-cooled roof, in which one pressure drop created by an exhauster fan is proposed, is transmitted through a roof suction elbow into a toroidal chamber, formed by tubular water-cooled panels. The off-gases are sucked in the toroidal chamber by distributed along a roof perimeter surface, constitutes not less than 45-50 % of a roof total area, through gas-distribution grid. Thus the vertical component of a sucking gas velocity in this case is 10-20 times less, than at a traditional suction system, and, therefore, losses of materials and heat with off-gases, as supposed, will be much lower.

Let’s consider calculation of parameters of a gas-distribution grid of the roof.

The scheme of design model is reduced in a fig. 5. The toroidal chamber of a roof is formed by N panels - sections of an equal cross-section disposed on a circle. It is necessary to define aggregate square of tubular annulus of each panel to provide uniform (by flow rate value) suction of gases with all sections - panels at common given off- gases flow rate Q_0.

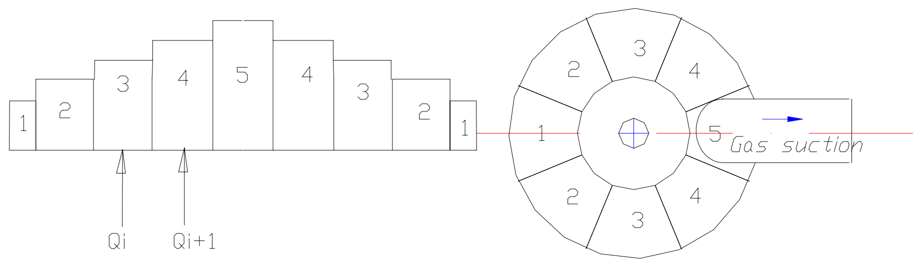


Fig.5. Scheme of the principle of gas-distribution suction using in roof design.
1-5 numbers of panels in physical model of the roof.

Let’s allocate two adjacent sections with the numbers *i* and *i+1* and conduct in the middle of sections vertical cross-sections. Let's note balance of mass for these cuts:

$$Q_{i+1} = Q_i + \delta Q_i ,$$
$$\delta Q_i = \sigma_i \upsilon_i \qquad (8),$$

where *Qi, Qi+1*- inflow of gas from working space of panel into i and $i+1$ section of a roof; σ_i - total inter-tubular area of i –section; υ_i - entrance velocity of gas into i- section of a roof.

At a uniform suction the inflow of gas in each of sections identical and equals to:

$$\delta Q_i = \delta Q = Q_0 / N \qquad (9).$$

The gas consumption in cut i is interrelated to a velocity of gas in this cut w by a relation:

$$Q_i = w_i F_i = i \cdot \delta Q_i \qquad (10),$$

where *Fi* - sectional area of section i.

Let's note a Bernoulli's relation for surveyed cuts.

$$\rho_i + \frac{\rho w_i^2}{2} = \rho_{i+1} + \frac{\rho w_{i+1}^2}{2} + \delta p_i \qquad (11),$$

where p_i, p_{i+1} - static pressure in cuts i and $i+1$; δp_i - friction pressure drop due to friction; ρ - off gas density.

Pressure drop due to friction defines under the formula:

$$\delta p_i = \frac{\lambda}{4} \int_i^{i+1} \frac{\rho w_i^2}{2} \cdot \frac{dS_i}{F_i} = \frac{\lambda}{4} \cdot \frac{\rho w_i^2}{2} \cdot \frac{S_i}{F_i} \qquad (12),$$

where *Si* - perimeter of i- section.

The static pressure is interrelates to a velocity of sucking gas by a relation:

$$p_i = p_a - \frac{\rho \upsilon_i^2}{2\mu^2} \qquad (13),$$

where μ- coefficient of a velocity depending on the shape of an orifice;
p_a - atmospheric pressure.

After transformation the relations reduced above the recurrent equation is received for definition of square of total inter-tubular area of each section of a roof from a requirement of a uniform suction of off-gases by each panel on perimeter of the toroidal chamber of a roof.

$$\sigma_{i+1} = \frac{\sigma_i^{\,2}}{\sqrt{1+\mu^2\left[\frac{(i+1)^2}{F_{i+1}^{\,2}} - \frac{i^2}{F_i^2} + \frac{\lambda}{4}\cdot\frac{S_i}{F_i}\cdot\frac{i_2}{F_i^2}\right]\sigma_i^{\,2}}} \tag{14}$$

Thus, having a total inter-tubular area of a panel under gas-suction elbow, as and cross-section of the toroidal chamber (it can be both stationary values, and variable on perimeter of a roof), given parameters, one can calculate by the equation (14) squares of total inter-tubular areas of remaining panels with allowance for symmetries. Then the inter-tubular distances (parameter of a grid) for each panel calculates.

Experimental researches on model.

For a mechanical similarity of flows on the model and the real object it is necessary to fulfil conditions geometrical, kinematics and dynamic similarity.

At a geometrical similarity sizes of model and the natures are proportional, and the angles are equal:

$$l_m / l_r = idem\,, \varphi_m = \varphi_r \qquad (15).$$

At a kinematics similarity the velocities of streams in model and in a nature in points are proportional:

$$\vartheta_m / \vartheta_r = idem \qquad (16).$$

At a dynamic similarity the forces operating on compatible devices in both flows are proportional:

$$Eu = \frac{P}{\rho \upsilon^2} = idem, \lambda = idem \qquad (17),$$

where *Eu*- Euler number; *P* - static pressure; ρ - density of gas; υ - velocity of gas; λ- resistance coefficient.

The model of a roof of 100-ton EAF is carried out in scale 1:10 and is schematically introduced in a fig. 5. The uniform of a suction is ensured with all panels of a roof (by flow rate of sucking gas) in model by regulating of a gas-distribution grid parameter of each panel. This parameter for given case is the square of a sucking slot of each panel calculated by using the equation (14). Thus the panel under a suction elbow has minimum value of indicated parameter, and diametrically opposite panel - maximal. For the traditional scheme of an input of the off-gases in a roof suction elbow in a direction of a normal line to a surface of a roof, seems correct a consideration a half of the roof in view of a symmetry of a gas stream concerning a midline driving through an axis of the elbow.

Parameters of model: diameter of a roof 600mm, velocity of air in the suction elbow 6m/s, air consumption 95m^3/hour, exhaustion underpressure in the suction elbow 11 Pa are reduced on the basis of surveyed above theory of the similarity to parameters of a real object (100-ton EAF): diameter of a roof 7m, velocity of gas in suction elbow 22m/s, off-gas flow rate 10^5 Nm^3 /hour, underpressure in the suction elbow 100Pa.

The measuring of air inflows flow rate into a hydraulic grid of panels of a roof were performed by a thermo-anemometer gauge for cases: 1) identical parameter of a hydraulic grid for all panels; 2) variable parameter, calculated by the equation (14). In both cases the aggregate square of a sucking surface is identical.

Distribution of air consumption sucked from working space of model in each panel of a roof, calculated on a basis of measured velocities of streams, is reduced in a fig. 6.

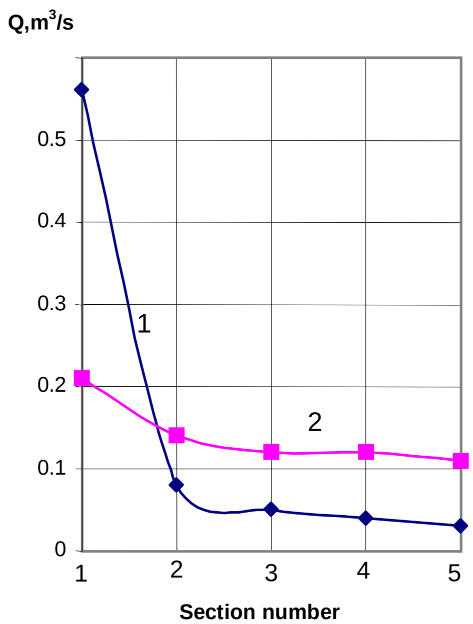


Fig.6. Distribution of air flowrate (Q) in roof sections in the model. 1- uniform grid parameter; 2- variable grid parameter.

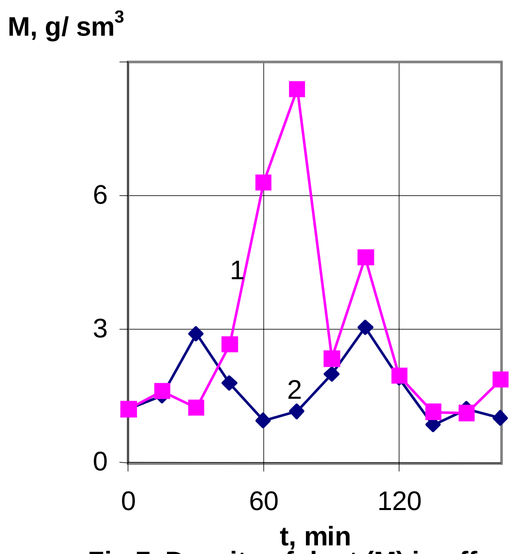


Fig.7. Density of dust (M) in off-gases from 100-ton EAF during heat (t). 1- conventional roof, 2- experimental roof.

According to reduced data, realization of a hydraulic grid of a roof with parameter calculated on the basis of a mathematical model, provides 4-5 times lowering of a scatter of sucking air flow rates by series of roof panels. Thus, the realization of panels of a roof with a variable parameter of a hydraulic grid ensures largely uniform suction of gas by a significant part of the roof working surface.

Industrial examinations

In 100-ton EAF of a Donetsk metal works is installed and there is in maintenance since August 1998 a prototype of a roof with components of distributed off-gas suction system. For examination of effectiveness of its operation from a point of view of a decrease of materials flow-out from the furnace working space by gas stream industrial test was carried out. It comprises examination of a dust content in off-gases, sucking from experimental and conventional water-cooled roofs on comparable heats from the positions of energy consumption and technology. Sampling produced from the chamber of post-combustion behind suction elbow during melting phase of the heat. The analyses provided in institute «Ukrecology». The outcomes, reduced in a fig. 7, testify about 2-times (in average) decreasing of dust particles density in furnace off-gases on an experimental roof in matching with traditional one.

Summary

A mathematical model of heat exchange between working space of operating EAF and water-cooled panel elaborated. By aid of the model a new generation of multi-layer panels with slag renewable coating is designed. A new panels provide 10-12% lowering of heat loss with cooling water in comparison with conventional 2-rows panels. Initiated a new solution of roof panels with matched function of gas suction through gas-distribute grid. New design solutions provide energy and materials saving.