Application of low-temperature plasma in steel-making converters

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With the use of numerical modeling an investigation of the process of the jet guniting of the walls of a steel-making converter is considered. By the jet guniting is meant the process of making an additional protective refractory coating on the basic lining of the walls of the steel-making converter with the aid of a system of two-phase jets transporting a softened refractory material (magnesite) to the converter wall. The results of numerical modeling agree quite satisfactorily with the experimental results in terms that the highest penetration rate of particles takes place in the region of high temperatures near the nozzle block axis into which the particles migrate under the action of turbulent fluctuations of the carrying gas flow.
Keywords: jet guniting, converter, magnesite, plasma torch.

The process jet guniting of the walls of a steel-making converter is considered. By the jet guniting is meant the process of making an additional protective refractory coating on the basic lining of the walls of the steel-making converter with the aid of a system of two-phase jets transporting a softened refractory material (magnesite) to the converter wall. This process is organized immediately after the steel unloading from the converter, carried out in a semi-automatic regime, and enables one to increase a refractory coating layer by several dozens of millimeters during several minutes.

1. Model description and governing equations

The converter is then ready for a new loading of the original raw material. The application of jet guniting enables one to increase substantially the number of meltings on the same converter without replacing its basic refractory lining and thereby reduce significantly the converter downtimes, which gives a significant economical effect [1]. To ensure the sticking of magnesite particles to the wall the particles must have the corresponding velocities when they approach the wall and be in a viscoplastic state. To achieve such a state the coke particles are fed additionally into the jet, and oxygen is supplied for coke combustion. The heat released at the coke particles combustion heats up the magnesite particles, which partially undergo a passage to viscoplastic state. Both the coke particles and the magnesite particles have different sizes and move in a turbulent jet in conditions of a nonuniform distribution of parameters over the cross section. This results in three possible states of magnesite particles: solid state, viscoplastic state with solid core, and viscoplastic (penetration) state. We will define the phase state of the i-th particle in the following by its penetration rate $\alpha = 1 - r_{is}/r_i$, where r_{is}, r_i are the radius of the solid core in the i-th particle and the particle radius. The particles carried by the carrying gas jet to the converter wall (magnesite and the non-burnt coke) have sufficiently small sizes (of the order 50–100 μm) and at the impact on the wall they can both stick to the wall and reflect from it forming the screening layer, which hinders the particle sedimentation on the wall.

The complexity of the control of the basic characteristics of the process, including the quality of the produced refractory coating, is the main shortcoming of the considered jet guniting process. One of the reasons for that consists of using the heat from the coke combustion for heating of the magnesite particles. The coke quality, the sizes, and disperse composition may differ significantly from one jet guniting procedure to another. This affects both the quantity of the heat released and the distribution of the heat release capacity along the jet length and cross section. The use of oxygen combined with a finely dispersed coke represents a certain explosive medium. This should also be taken into account when implementing the measures on improving the safety aids an labor conditions. It is, therefore, of interest to consider a possibility of using the plasma technologies, which are widely applied in various technological schemes for making the protective coatings with the aid of a low-temperature jet, for the purpose of jet guniting (cf., for example, the work [2] and the references therein). The low-temperature plasma represents a gaseous medium (air, nitrogen, helium, etc.) heated up to the temperatures o the order $5000 \div 10000$ K. The heating is performed with the aid of an electric arc created and maintained in a special device called the electric arc plasma torch. Varying the electric power of the plasma torch one can vary within rather wide limits also the temperature of the exhausted jet of low-temperature plasma. The dissociation processes occur intensely in the gaseous media heated up to so high temperatures, and this gives rise to the particles active in chemical respect (atoms, ions, radicals) with a rather high concentration. This makes such a plasma to be a very attractive means for intensification of various technological processes related to chemical conversions. For technological problems which are considered in the present work the use of low-temperature jets is attractive for the following reasons:

— the jet of such a plasma is first of all a well controlled heat source for heating of magnesite particles;

— the jet length no longer plays the main role in the jet guniting technology because there are no combustion processes whose completion requires a certain time;

— there is no need to use high-pressure pneumotransport for transporting the particles to the converter wall because the nozzle exit may be located at a small distance from the wall;

— the velocity at which the magnesite particles approach the wall as well as the regime of their heating may be controlled within wide limits, which will enable one to increase the efficiency and quality of the layer formed by jet guniting, and also at the expense of the absence of non-burnt coke particles.

It is clear that for an actual application of plasma technology for jet guniting it is necessary to carry out a large amount of research of both technological and economic character. There are, however, no significant reasons hindering their application and, therefore, an attempt has been undertaken in the present work within the framework of mathematical modeling at showing the possibility of the application of plasma technologies here.

The main purpose of the conducted research was the study of the specifics of magnesite particles heating under the action of a jet of low-temperature plasma exhausting from the plasma torch, and the determination of their penetration rate. The simplest technological

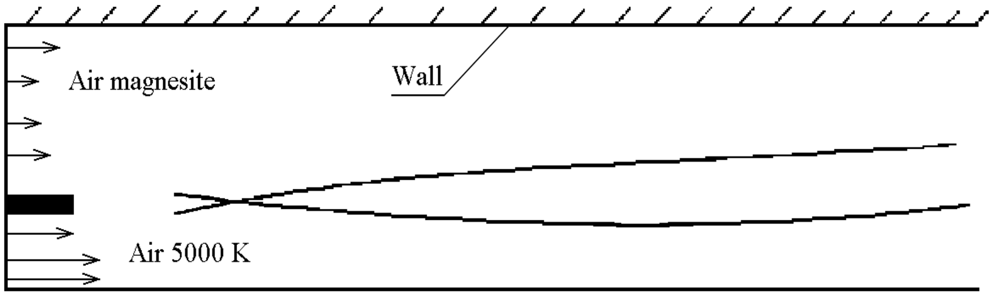

Fig. 1. Scheme of nozzle block

scheme of the unit for mixing and heating of particles (the nozzle block) shown in Figure 1 was chosen.

The nozzle block represents a circular coaxial pipe through the central part of which a jet of low-temperature plasma heated in the plasma torch up to the temperature of 5000 K flows into the nozzle block from the nozzle head of the plasma torch. The air was used as the plasma forming gas. The mixture of air and magnesite particles was supplied through the central part of the pipe at the temperature of 1200 K, which was close to the temperature inside the converter after the steel was discharged from it. In this way the most favorable situation was modeled when during the pneumotransport of guniting mass the latter is dried and preliminarily heated at the expense of using as the carrying gas a partially or completely hot air from the internal converter volume, which is technologically quite feasible. This enables one to use a plasma torch with a relatively small capacity and to apply a nozzle block with small dimensions by mounting it in the immediate vicinity of the converter wall.

At the computation of flow in gaseous phase we have taken into account the processes of nonequilibrium reversible chemical reactions of dissociation and recombination as well as the exchange reactions occurring in low-temperature plasma in accordance with recommendations of work [3] for the above temperature intervals:

$$\mathrm{O_2} \leftrightarrow \mathrm{O} + \mathrm{O}, \quad \mathrm{N_2} \leftrightarrow \mathrm{N} + \mathrm{N}, \quad \mathrm{NO} \leftrightarrow \mathrm{N} + \mathrm{O}, \tag{1}$$

$$\mathrm{O_2} + \mathrm{N} \leftrightarrow \mathrm{NO} + \mathrm{O}, \quad \mathrm{N_2} + \mathrm{O} \leftrightarrow \mathrm{NO} + \mathrm{N}, \quad \mathrm{N_2} + \mathrm{O_2} \leftrightarrow \mathrm{NO} + \mathrm{NO}. \tag{2}$$

The rates of these reactions were determined on the basis of the Arrhenius law.

A feature of the flow under study is that the particles are fed into the peripheral part of the nozzle block, and, therefore, the region of low-temperature plasma jet near the nozzle head is free of particles. As the particles move, they then get, however, gradually into this region at the expense of the turbulent diffusion mechanism. At some distance from the nozzle exit the particles can even cross the symmetry axis, which results in certain difficulties at the description of their motion within the framework of continual approach. Therefore, the motion of particles was considered in the present work within the framework of a stochastic Lagrangean—Eulerian approach [4].

Since the particles get into the region of mixing the plasma jet with co-flow, where the flow is close to a stratified one, besides the aerodynamic drag forces, also the Suffman force as well as the rotation of particles, which were assumed to be spherical, were taken into account. Both the convective and radiation heat exchange between the gas and particles were considered, and the latter was determined at the present research stage by the simplest technique via the mean radiation temperature of the medium taking into account also the thermal radiation from plasma jet. The system of equations for particles motion written along the trajectory of the ith particle has the form:

$$\frac{du_i}{dt} = C_{R_i}(u - u_i) - \frac{3}{4}\frac{\rho}{\rho_{b_i}}(v - v_i)\left[\omega_i - \frac{1}{2}\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right)\right] \equiv F_1, \tag{3}$$

$$\frac{dv_i}{dt} = C_{R_i}(v - v_i) + \frac{3}{4}\frac{\rho}{\rho_{b_i}}(u - u_i)\left[\omega_i - \frac{1}{2}\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right)\right] + $$
$$+\frac{9.69}{\pi\rho_{b_i}d_i} sign\left(\frac{\partial U}{\partial y}\right)(u - u_i)\sqrt{\rho\mu|\frac{\partial U}{\partial y}|} \equiv F_2, \tag{4}$$

$$\frac{d\omega_i}{dt} = C_{\omega_i}\left[\frac{1}{2}\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right) - \omega_i\right], \tag{5}$$

$$c_i m_i \frac{dT_i}{dt} = \pi d_i^2[\alpha_i(T - T_i) + \varepsilon\,\sigma(T_{av}^4 - T_i^4)] + q_c J_c - q_v J_v \equiv Q, \tag{6}$$

$$C_{R_i} = \frac{18\mu}{\rho_{b_i}d_i^2}\left[1 + 0.179\ \mathrm{Re}_{p_i}^{0.5} + 0.013\,\mathrm{Re}_{p_i}\right], \quad C_{\omega_i} = \frac{60\mu}{\rho_{b_i}d_i^2}, \quad \mathrm{Re}_{p_i} = \frac{\rho|\mathbf{U} - \mathbf{U}_i|}{\mu},$$
$$u = U + u^{'}, \quad v = V + v^{'},$$

where ω_i and T_i are the angular velocity and temperature of particle; $U,\ V,\ u^{'},\ v^{'}$ are the mean and fluctuation parameters of the flow of carrying gas (components of the velocity vector); T is the mean gas temperature; T_{av} is the mean radiation temperature over the cross section; $\rho_{b_i},\ d_i$ are the density of the particle material and the particle diameter.

The quantities $u^{'},\ v^{'}$ were determined as random with the Gaussian distribution and mean-square deviation equal to $(2/3)k$.

To describe the carrying gas motion we have used the Reynolds averaged system of the Navier—Stokes equations closed by a standard $k - \varepsilon$ turbulence model, in which the interphase interactions were taken into account at the level of both the mean and fluctuation motions. The system of such equations was written for the axisymmetric flow case as follows:

$$\frac{\partial}{\partial x_k} y\rho U_k = 0, \tag{7}$$

$$\frac{\partial}{\partial x_k} y\rho U_i U_k + \frac{\partial}{\partial x_k} yp = \frac{\partial}{\partial x_k} y[\mu\,\tau_{ik} - \rho < u_i^{'}u_k^{'} >] + y\,n_p << F_i >>, \tag{8}$$

$$\frac{\partial}{\partial x_k} y\rho H U_k = U_k\frac{\partial}{\partial x_k} yp = \frac{\partial}{\partial x_k} y\left[\lambda\frac{\partial T}{\partial x_k} + (\mu\,\tau_{ik} - \rho < u_i^{'}u_k^{'} >)\frac{\partial U_i}{\partial x_k} - \rho < h^{'}u_k^{'} >\right] + $$
$$+y\,n_p(<< Q >> + << (\mathbf{U}, \mathbf{F}) >>), \tag{9}$$

$$\frac{\partial}{\partial x_k} y\rho U_k C_j = \frac{\partial}{\partial x_k} y\left[\left(\rho D_j + \frac{\mu_t}{Sc_t}\right)\frac{\partial C_j}{\partial x_k}\right], \tag{10}$$

$$\frac{\partial}{\partial x_k} y\rho U_k k = \frac{\partial}{\partial x_k} y \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_k} \right] - y \left(\rho < u_i^{'} u_k^{'} > \frac{\partial U_i}{\partial x_k} - \rho\varepsilon - k\, n_p << \varepsilon_s >> \right), \quad (11)$$

$$\frac{\partial}{\partial x_k} y\rho U_k \varepsilon = \frac{\partial}{\partial x_k} y \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_k} \right] -$$

$$-y \left(C_{\varepsilon 1} \frac{\varepsilon}{k} \rho < u_i^{'} u_k^{'} > \frac{\partial U_i}{\partial x_k} - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} - C_{\varepsilon 3} \varepsilon\, n_p << \varepsilon_s >> \right), \quad (12)$$

$$p = \rho R_0 T \sum_j (C_j / M_j), \quad (13)$$

$$\tau_{ik} = \left(\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} - \frac{2}{3} \frac{\partial U_m}{\partial x_m} \delta_{ik} \right), \quad \rho < u_i^{'} u_k^{'} >= \frac{2}{3} \rho k \delta_{ik} - \mu_t \tau_{ik},$$

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}, \quad \rho < h^{'} u_k^{'} >= -\frac{\mu_t}{\mathrm{Pr}_t} \frac{\partial H}{\partial x_k},$$

where ρ, $\mathbf{U} = \{U_1, U_2\} \equiv \{U, V\}$, H, p, T, C_j, M_j are the mean flow parameters (the density, the velocity vector, the enthalpy, the pressure, the temperature, the concentrations of chemically reacting mixture components and their molecular weights $j = \{\mathrm{O}, \mathrm{O}_2, \mathrm{N}, \mathrm{N}_2, \mathrm{NO}\}$); $u_1^{'}$, $u_2^{'}$, $h^{'}$ are the corresponding fluctuation parameters; $\mathbf{F}$ is, the vector of the force interaction between the gas and particles.

2. Some numerical and practical results

Only the initial conditions in the inlet section of the nozzle block were specified for system of equations (3)–(6). As the particles move they can reflect from the pipe wall and cross the symmetry axis. The boundary conditions for system (8)–(13) were typical for internal turbulent flows: the no-slip condition on the pipe wall, the symmetry conditions on the axis, and the "soft" boundary conditions in the outlet section. It was assumed that in the inlet section there takes place a developed turbulent flow with the profile of the streamwise component of the velocity vector varying near the solid walls according to the "1/7 law".

An implicit A-stable second-order difference scheme was used for the solution of the system of equations (3)–(6) belonging to the class of the "stiff" systems. The system (8)–(13) was solved by the control volume method SIMPLE [6]. The interphase interactions were taken into account by iterations at a sequential solution of the systems of equations (3)–(13) [5].

The flow computations were carried out at the following values of the basic flow parameters: $T_0 = 5000$ K, $T_b = 1200$ K, $R_0 = 0.015$ m, $R_b = 0.075$ m, $d_p = 100$ μm, $w_p = 0.3$, $U_0 = 300$ m/s, $U_b = 20$ m/s, where T_0, T_b are the temperatures of the low-temperature plasma jet and co-flow in the inlet section; R_0, R_b are the radii of the outlet sections of the plasma torch and the nozzle block duct, respectively; d_p, w_p are the particle diameter and the relative weight fractions of particles; U_0, U_b are the gas velocities in the jet and in co-flow. The force and thermal interactions between the particles were not taken into

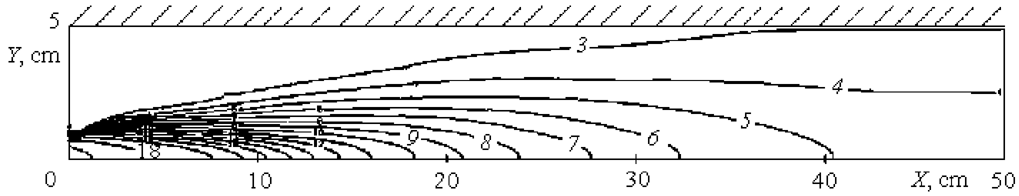

Fig. 2. Isotherms in flow field

account. Figure 2 shows the isotherms of the flow field (the lines were drawn with the step $\Delta T = 200$ K, all linear dimensions were referred to the radius of the outlet section of the plasma torch nozzle).

It is seen that near the nozzle exit the temperature of the plasma jet rapidly drops at the expense of a heat exchange with the co-flow. This is typical for turbulent jets, therefore, the region of high temperatures does not interact directly with the magnesite particles, and there is no danger of their rapid penetration or even evaporation. Since the plasma jet in the present technology of jet guniting plays only the role of an adjustable heat source, the investigation of the concentration distribution of atomic oxygen in the flow field is of considerable interest since the presence of its even relatively low concentrations at the interaction with magnesite particles may result in the alteration of the physical properties of particles surface.

Figure 3 shows the picture of the distribution of atomic oxygen concentration (the isolines were drawn with the step $\Delta C = 0.05$), on the basis of the analysis of which one can draw a conclusion that in the technological scheme of the nozzle block under study practically the entire atomic oxygen is spent in the recombination reactions near the plasma torch nozzle exit in the zone free of particles, and there is no its interaction with magnesite particles.

The behavior of the magnitude of penetration rate of magnesite particles as the move along the nozzle block is naturally of the main interest. Figure 4 presents the distributions of the mean value of the penetration rate α over the radius in three cross sections of the nozzle block. The dashed lines correspond to a computation with no regard or radiation heat transfer.

It is seen that the highest penetration rate of particles takes place in the region of high temperatures near the nozzle block axis into which the particles migrate under the action of turbulent fluctuations of the carrying gas flow field. The velocity of this migration is, however, small, and the fraction of completely penetrated particles is relatively small. The fact of increase in the penetration rate of particles under the effect of radiation heat exchange is of considerable interest. This enables one at the expense of its intensification to increase

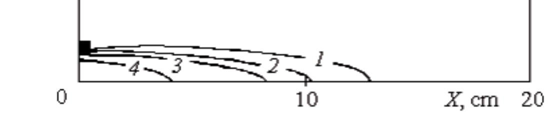

Fig. 3. Isolines of atomic oxygen concentration

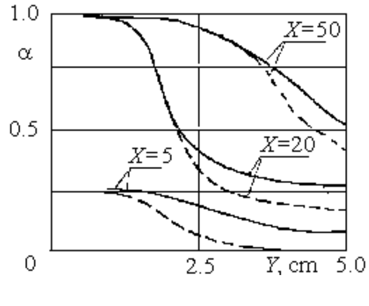

Fig. 4. Penetration rate of particles

the uniformity of the distribution of quantity α along the section and thereby to improve the quality of the gunited coating. For this purpose one can, for example, introduce in the plasma forming gas the water vapor whose molecules as well as the products of its dissociation increase the emissive power.

Conclusion

1. Results of numerical modeling are showing that plasma technologies can use for the process of the jet guniting of the walls of a steel-making converter as alternative of traditional technology.

2. The refractory coating contains the particles of magnesite only and the quality of coating will be improving.

3. The plasma technologies provide more wide range of work parameters of the jet guniting coating.

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