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Modelling of Two-Phase Turbulent Flows in Subsonic Jets with Burning Particles and Phase Transition in Core

Abstract:

The numerical modelling of two-phase flow in subsonic turbulent jets with a mixture of combustible (coke) and non-combustible (magnesite) particles is considered. The following basic processes were taken into account: momentum and heat transfer interaction between phases; ignition and combustion of coke particles; phase transition in particles of magnesite; radiative heat transfer.

Motion of two-phase medium is considered within the framework of stochastic Lagrangian-Eulerian approach, when the model of continual medium is used for the carrier gas, and the disperse phase is described by the trajectory model of trial particles. The influence of the carrier gas turbulence to the particles is considered through the process of their random walk.

On the basis of numerical simulation the conditions of particles ignition, the distribution of particles concentration, and the structure of burning zone have been investigated.

1 INTRODUCTION

A process of jet guniting (making a fire-proof protective coating) of the walls of steel-melting converters allow to increase the number of the steel meltings in several times without the replacement of the converter's base fire-proof walling. This method gives a large commercial profit. A problem of numerical modelling of this process within the framework of technological scheme with coaxial jets is considered in this paper. This technological scheme of the jet guniting is shown in Fig. 1.

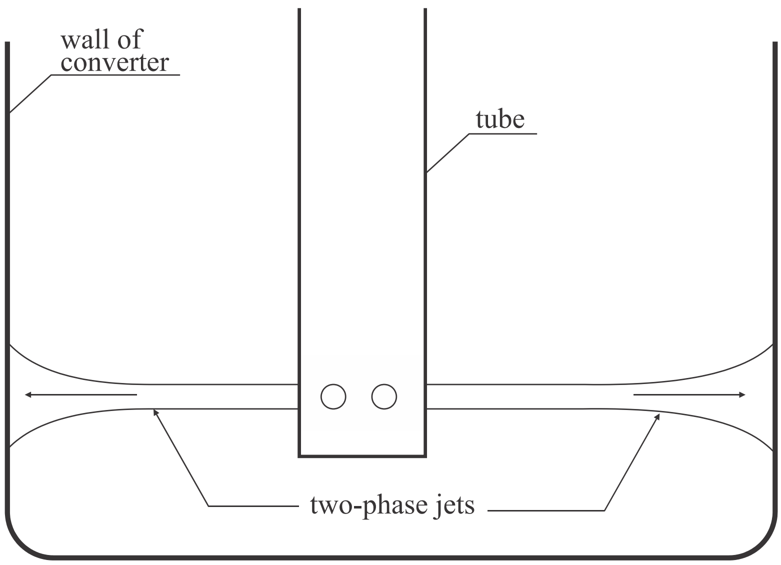

Figure 1. Technological scheme of the jet guniting

Two-phase mixture of burning (coke) and non-burning (magnesite) particles and nitrogen (carrier gas) is fed into the central jet and the peripheral (annular) jet of the oxygen is used for combustion of the coke. The heat releasing from the burning of coke particles results in the increasing of the magnesite particles temperature.

Phase transition in the magnesite particles takes place when heating, and the formation of the viscous liquid layer on their surface ensures the particles sticking on the converter walls. The dynamics of this process of heating is very important for the improvement of the jet guniting results.

The sketch of computational region of such flow is shown in Fig. 2.

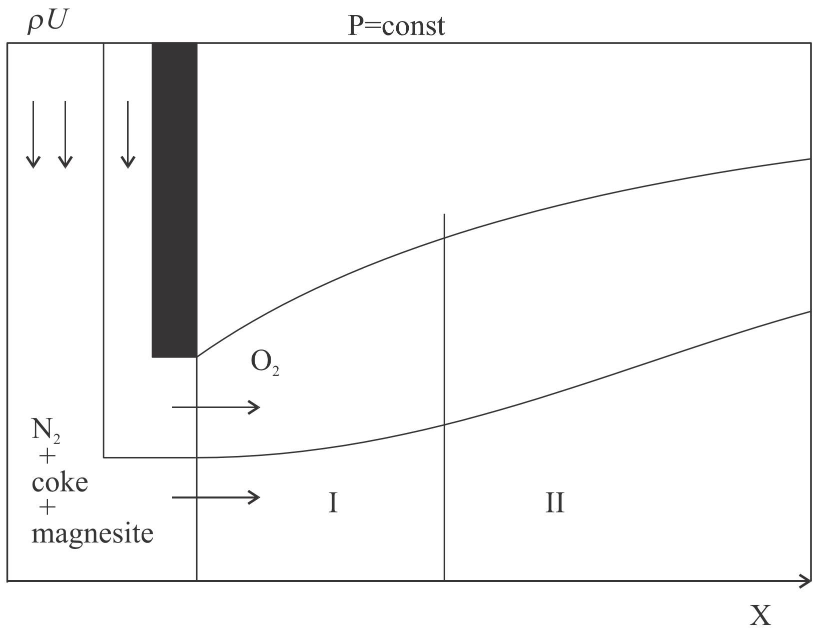

Figure 2. Diagram of computational region

The peripheral oxygen jet is a high-speed jet, and the central two-phase jet is a low-speed jet. The jet outflowing from this device has a sufficiently large extension (100 - 200 calibres), therefore the overall flow region was subdivided into two regions: the first one is the non-isobaric flow region in and near the nozzle device, and the second is the region of isobaric jet. The computations in these regions were carried out sequentially. The values of flow parameters obtained at the right boundary of the first region were taken as the initial data for the computation in the second region.

2 MATHEMATICAL MODEL

The simulation of the turbulent two-phase flow was performed within the framework of "$k-\varepsilon$" model. The Lagrangean - Eulerian approach proposed in the works of Crowe [2] is used for the description of such flows, when the continual model is used for the carrier gas, and the trajectory model of trial particles is used for the disperse phase. The influence of the carrier gas turbulence to the particles motion and the heat transfer from the gas to particles is considered through the process of their random walk, according to Mostafa works [4], Process of heat transfer in a magnesite particle is considered within the framework of Stephan's problem.

In addition, the following simplifying assumptions were used:

- the flow is stationary and axisymmetric;
- the carrying medium consists of the oxidizer (O_2), reaction products (CO_2) and the inert gas (N_2). The ambient space is filled by a hot air;
- the second phase consists of spherical particles of two kinds
- the combustible particles (coke) and non-combustible particles (magnesite). The dimensions of magnesite particles are constant, those of coke are variable because of the coke combustion. The reaction between the coke particles and oxygen is one-stage and is described by the equation $C + O_2 = CO_2$.
- the reaction takes place only on the surface of a coke particle, and the heat produced thereby is consumed for the heating of the particle itself, then this heat is transferred to the carrier gas. The magnesite particles are heated by the interphase heat exchange with the gas. The temperature throughout the volume of the coke particle is the same; in the process of combustion a particle preserves its spherical shape;

The system of equations governing the two-phase stationary flow has the following form.

$$\frac{\partial}{\partial x_k} y\rho U_k = yJ, \tag{1}$$

$$\frac{\partial}{\partial x_k} y\rho U_i U_k + \frac{\partial}{\partial x_k} yP = \frac{\partial}{\partial x_k} y\left[\mu\tau_{ik} - \rho < u_i^{'} u_k^{'} >\right] + y\left(n_p << F_i >> + U_i J - J << UU_i >>\right), \tag{2}$$

$$\begin{aligned} \frac{\partial}{\partial x_k} y\rho H U_k &= U_k \frac{\partial}{\partial x_k} yP + \frac{\partial}{\partial x_k} y\left[\lambda \frac{\partial T}{\partial x_k} - \rho < h^{'} u_k^{'} >\right] + \\ &+ y\left(\mu\tau_{ik} - \rho < u_i^{'} u_k^{'} >\right)\frac{\partial U_i}{\partial x_k} + y n_p \left(<< Q >> + << S >>\right) \end{aligned}, \tag{3}$$

$$\frac{\partial}{\partial x_k} y\rho U_k C_j = \frac{\partial}{\partial x_k} y\left[\left(\rho D_j + \frac{\mu_T}{Sct}\right)\frac{\partial C_j}{\partial x_k}\right] + yJ_j, \quad \left(j = 1, 2\right), \tag{4}$$

$$\frac{\partial}{\partial x_k} y\rho U_k k = \frac{\partial}{\partial x_k} y\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_k}\right] + y\left(-\rho < u_i^{'} u_k^{'} > \frac{\partial U_i}{\partial x_k} - \rho - k << \varepsilon_s >> - Jk\right), \tag{5}$$

$$\frac{\partial}{\partial x_k} y\rho U_k k\varepsilon = \frac{\partial}{\partial x_k} y\left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_k}\right] + y\left(-C_{\varepsilon 1 \frac{\varepsilon}{k}\rho} < u_i^{'} u_k^{'} >\right)\frac{\partial U_i}{\partial x_k} - C_{\varepsilon 2\rho\frac{\varepsilon^2}{k}} - C_{\varepsilon 3^{\varepsilon}} << \varepsilon_s >> - J\varepsilon, \tag{6}$$

$$P = \rho R_0 T \sum_{j=1}^{3}\left(C_j / M_j\right) \tag{7}$$

$$\tau_{ik} = \left(\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} - \frac{2}{3}\frac{\partial U_l}{\partial x_l}\delta_{ik}\right),$$

$$\rho < u_i^{'} u_k^{'} >= \frac{2}{3}\rho k \delta_{ik} - \mu_T \tau_{ik},$$

$$\mu_T = C_\mu \rho k^2 / \varepsilon, \qquad \rho < h^{'} u_k^{'} >= -\frac{\mu_T}{Pr_T}\frac{\partial H}{\partial x_k},$$

$$C_1 + C_2 + C_3 = 1, \qquad J =<< n_1 W >>,$$

$$J_1 = -\frac{M_1}{(M_1 + M_2)} J, \qquad J_2 = -\frac{M_2}{(M_1 + M_2)} J$$

$$<< UU_1 >>=<< U_1 - u_1 >>,$$

$$<< UU_2 >>=<< U_2 - v_1 >>$$

The motion of carrier gas is considered within the framework of averaged Navier - Stokes model, where J_1, J_2 are the mass rates of O_2 consumption and forming CO_2, and k and e are the turbulent kinetic energy and the rate of its dissipation. The tensor of turbulent stresses $< u_i^{'} u_k^{'} >$ is expressed via the averaged parameters of flow, the terms in the double angular brackets describe the interaction between carrier gas and particles.

The terms in double angular brackets take into account the interphase interactions and are determined by a spatial/temporal averaging of the quantities between the brackets over the segments of the trial particles trajectories intersecting the boundaries of a computational cell of the difference grid $V_{m,l}$

$$n_p = \frac{\sum_k \eta_k \tau_k}{V_{m,l}}, \qquad << \varphi >>= \frac{\sum_k \eta_k \int_0^{\tau_k} \varphi_k dt}{},$$

$$<< \varepsilon_s >>= 2\sum_{i=1}^{2} F_i \left(1 - \frac{\tau_L}{\tau_L + 1/C_{Ri}}\right) >>,$$

$$k \in (m,l), \qquad \tau_L = 0,35k/\varepsilon,$$

where n_p is the concentration of particles in a cell, η_k is the number of particles in a "packet" of trial particles along the *k*-th trajectory determined from the conditions specified in the initial section, φ is any quantity from the set F_i, UU_i, ε_s, *Q*, *S* in (3)-(6).

The motion of particles along its trajectory is described by a system of ordinary differential equations:

$$\frac{du_i}{dt} = C_{Ri}(u - u_i) - \frac{3}{4}\frac{\rho}{\rho_{bi}}(v - v_i)\left[\omega_i - \frac{1}{2}\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right)\right] \equiv F_1, \qquad (8)$$

$$\frac{du_i}{dt} = C_{Ri}\left(v - v_i\right) + \frac{3}{4}\frac{\rho}{\rho_{bi}}\left(u - u_i\right)\left[\omega_i - \frac{1}{2}\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right)\right] + \frac{9,69}{\pi\rho_{bi}d_i} sign\left(\frac{\partial U}{\partial y}\right) \times \left(u - u_i\right)\sqrt{\rho\mu\left|\frac{\partial U}{\partial y}\right|} \equiv F_2, \quad (9)$$

$$\frac{d\omega_i}{dt} = C_{\omega i}\frac{1}{2}\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right) - \omega_i, \quad (10)$$

$$c_1 m_1 \frac{dT_1}{dt} = Q_1 = \pi d_1^2\left[\alpha_1\left(T - T_1\right) + \varepsilon_1\sigma\left(T_{cp}^4 - T_1^4\right) + QWn_1\right], \quad (11)$$

$$\frac{dm_i}{dt} = 4\pi W = \frac{-4\pi\beta C_{O_2}}{1/\alpha + d_1/\left(DNu_{O_2}\right)}, \quad (12)$$

$$\frac{\partial c_2\rho_2 T_2}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\alpha_2\frac{\partial T_2}{\partial t}\right), \quad (13)$$

$$0 \le r \le R_m: \qquad \frac{\partial T_2}{\partial r} = 0\Big|_{r=0},$$

$$\lambda_2\frac{\partial T_2}{\partial r}\Big|_{r=R_m-0} = \lambda_2\frac{\partial T_2}{\partial r}\Big|_{r=R_m+0} + L_m\rho v_m, \qquad T_2\left(R_m, t\right) = T_m;$$

$$\left(R_m \le r \le R_2\right): \qquad T_2\left(R_m, t\right) = T_m,$$

$$\lambda_2\frac{\partial T_2}{\partial r}\Big|_{r=R_2} = Q_2 = \pi d_2^2\left[\alpha_2\left(T - T_2\right) + \varepsilon_2\sigma\left(T_{cp}^4 - T_2^4\right)\right],$$

$$C_{Ri} = \frac{18\mu}{\rho_{bi}d_i^2}\left[1 + 0,179 Re_{pi}^{0,5} + 0,013 Re_{pi}\right],$$

$$C_{\omega i} = \frac{60\mu}{\rho_{bi}d_i^2}, \qquad Re_{pi} = \frac{d_i\rho\left|\vec{u} - \vec{u_i}\right|}{\mu},$$

$$u = U + u', \qquad v = V + v'$$

The value of superscript i equal to one corresponds to coke and value equal to two corresponds to magnesite. We take into account a rotation of the particles (ω_i) and Magnus force and Safmen force and the convective and radiative heat transfer between gas and particle. C_R and C_α are the coefficients of particle aerodynamic drag and the heat transfer from particle to the gas, respectively.

Calculation of radiative heat transfer was realized within the framework of the averages radiative temperature [6] when it was took into account a radiation from burning coal particles. For the description of complex process of the coke combustion, the expression for its mass rate W according to Khitrin formula was used, which works sufficiently well in both kinetic and diffusive regimes of combustion [3],

We consider the unsteady process of the heat transfer into the magnesite particles within the framework of Stefan's problem. For the solution of this problem the approximate analytical methods of work [7] was used. In this case the velocity of the phase transition surface motion from the solid state to the liquid state was calculated and the mass of melting part of particles was also defined.

The approach of the random walk process was used to take into account the influence of the carrier gas turbulence on the motion of particles and on the process of the heat transfer. In this case the velocity vector of carrier gas was defined as the sum of their averaged values and the pulsation components which were supposed to be random values with the normal Gauss distribution, with mean square of deviations to be k respectively.

As the boundary conditions in the inlet section of the nozzle device, for the gas we have specified the values of the mass flux (ρu), the enthalpy and the direction of the velocity vector. For the particles we have specified here the values of all the parameters under the assumption on the absence of their lag in velocity and temperature. On the device wall the sticking conditions were specified for the gas, and the slip conditions were specified for the particles. The conditions typical for the ambient space were specified in the upper boundary and the non-reflecting condition was specified in the outlet boundary.

In the region (I) the system (l)-(7) was replaced by a nonstationary system and was solved by the pseudo- unsteady method with the aid of Patankar's method SIMPLE [5], and for the solution of the equations for particles motion the implicit A-stable second-order scheme [1] was used. In the region (I) in the nozzle device the well-known method of near-wall functions was used to determine the values of k and ε near the walls. Also it was used the Rodi correction [?] for the free jet modelling in the region (II). Here the pressure was assumed to be constant, and the parabolized system (l)-(7) was considered, which was solved by a marching method.

3 SOME NUMERICAL RESULTS

The turbulent two-phase flows were calculated with following values of main parameters. All linear dimensions are referred to the radius of the exit section of the annular nozzle (r_* =0,015 m), the velocities of gas and particles are referred to the critical sound speed in the oxygen (α_* =298 m/s), their temperatures are referred to the stagnation temperature, the densities are referred to the stagnation density (ρ_0 =1,28 kg/m). The diameters of the coke and magnesite particles in the inlet section were assumed to be the same ($d_1 = d_2 = 100$ μm), the relation of the mass flow rate of the second phase to the mass flow rate of the carrier gas $W_s / W_g = 10\left(W_s = W_1 + W_2\right)$, and the weight fraction of coke $q = W_1 / W_2$ was varied. The stagnation temperature T_0 for both gases in the inlet section was equal to 300 K, the air temperature in the ambient space was 1700 K.

The computations have shown that under the same conditions the intensity of the two-phase jet expansion is significantly less than in the case of a monophase jet, which is related to the back influence of particles on the gas flow field. In Fig. 3 the flow parameters distributions along the jet axis are shown (the curves 1 correspond to the parameters of the pure gas, and the curves 2 correspond to the two-phase flow, the dashed lines refer to the magnesite particles velocity). It may be seen that the central jet is accelerated by the viscous interaction with the high-speed peripheral jet, and the presence of the second phase reduces the intensity of acceleration. However, in the main region of the jet flow the particles velocity exceeds the gas velocity, and the particles begin to carry the gas along, thus increasing the "range" of the two-phase jet. The increasing of the gas temperature due to the particles combustion occurs at a sufficiently large distance from the mouthpiece. This indicates to a considerable lag of the coke particles ignition process. Filming of the industrial guniting process confirms the obtained results.

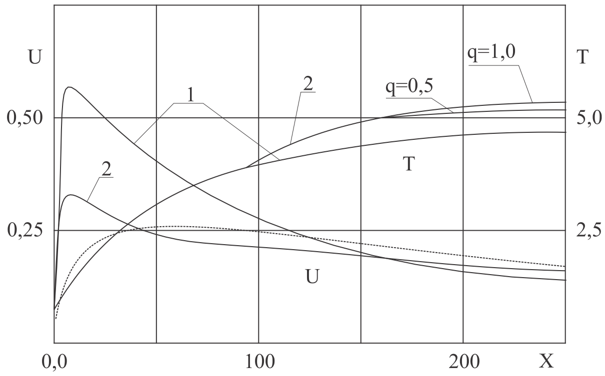

Figure 3. Flow parameters along the jet axis.

In Fig. 4 we depict the distribution of the magnesite particles density along tire jet axis for the different regimes of flow (solid lines and dashed lines) and q. The solid lines and dashed lines denote high-speed and low-speed jet of oxygen, respectively. A sharp increase of the particles density at the initial part of the high-speed jet is related to the effect of the "lacing" of the particles jet, which is expressed by the reduction of the cross dimension of their jet. This effect is conditioned by the influence of turbulent pulsations of the carrier gas on the particles motion.

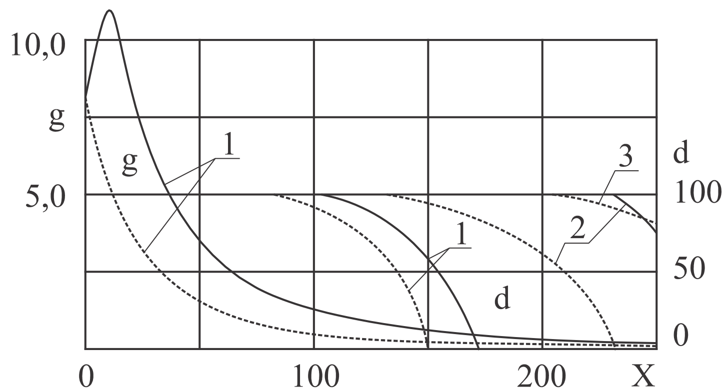

Figure 4. Density of magnesite particles and the coke particles diameters along the jet.
1) *q*=0.5, 2) *q*=1.0, 3) *q*=1.5

In the case of low-speed jet the mixing of the jets occurs considerably faster with less intensive generation of k. The consequence of this is the absence of the "lacing" effect. We show in the same Figure the change of tire coke particles diameter along the jet axis for three values of the coefficient q, from which it follows that the "lacing" effect reduces the intensity of the coke combustion process.

The dispositions of the zones of the beginning and ending of the coke combustion in the jets are presented in Fig. 5.

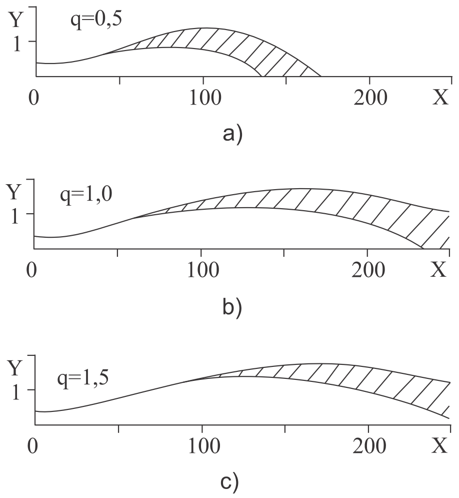

Figure 5. Zones of the beginning and end of the coke combustion.

It may be seen that tire increase of Ore relative fraction of coke in the gunit mass leads to a substantial lag of the combustion process, the intensity of which is limited by a turbulent diffusion of oxygen from the peripheral jet.

Some computational results for the evaluation of the melting part of the magnesite particles are presented in Fig. 6 and Fig. 7. We show here the distribution of the melting part of magnesite particles along the jet axis and in its cross section at *X*=250. It can be seen that the dependence of the melting part of particles from parameter q is not monotone. This fact is very important for the improvement of the jet guniting results.

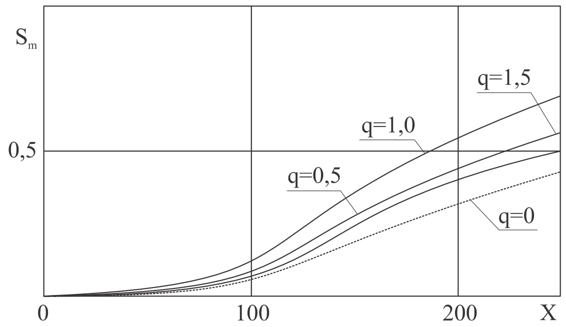

Figure 6. Distribution of melting part of particles along the jet axis

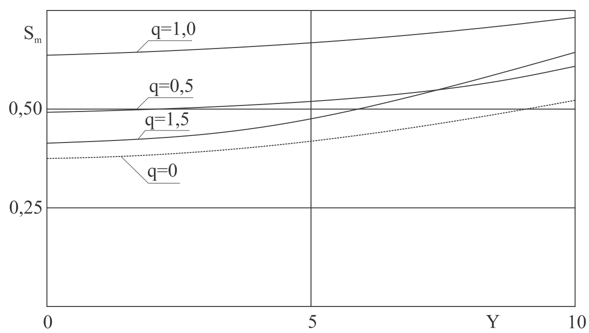

Figure 7. Distribution of melting part of particles in the cross section of the jet (*X*=250)

4 CONCLUSION

The analysis of computational results shows that in the given scheme of guniting it is reasonable to provide sufficiently high velocity of the central two-phase jet as well as to intensify in some way the process of the turbulent transfer of the oxygen to the central part of a jet in order to ensure a more complete combustion of coke particles.

ACKNOWLEDGEMENTS

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