Second International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
6-8 December 1999

MODELING OF THE TOP BLOW-DOWN PROCESS IN OXYGEN STEEL-MAKING CONVERTERS

Jurii I. SHOKIN, Hranislav MILOSHEVICH and Alexander D. RYCHKOV

Institute of Computational Technologies, Siberian Branch of Russian Academy of Sciences
pr. Lavrentyeva 6, Novosibirsk 630090, RUSSIA

ABSTRACT

Mathematical modeling of the interaction process of high velocity oxygen jets with the surface of liquid metal in a steel-making converter is considered. A cavity in the metal will be generated by penetration of the gas jets into the metal. A simplified scheme of chemical reactions and a dispersion mechanism of metal drops from the interface has been offered for the correct description of gasdynamic flow pattern in the area of the cavity.

The modeling of two-phase turbulent flow in the cavity is considered within the framework of a continuum model with the help of systems of averaged Navier – Stokes equations. The modified $k-\varepsilon$ model turbulence is used for their closure taking into account the presence of the second phase. The research of the flow structure was carried out in the cavity and on this basis practical recommendations for increasing the efficiency of the reburning process of CO are offered.

NOMENCLATURE

x, y	spatial variables [m]
p	pressure [Pa]
$\vec{U}, \vec{u}'$	average and instantaneous velocities [m/s]
ρ	density [kg/m^3]
μ	dynamic viscosity [kg/(m.s)]
C	mass fraction of species
M	molecular weight [kg/kmol]

INTRODUCTION

Top blowing of a bath of liquid pig-iron in oxygen steel-making converters is performed with the purpose of burning out carbon dissolved in the metal - the basis process of transformation of pig-iron into steel (Baptizmansky and Ochotsky, 1984). The blow-down is carried out making use of a system of high-head supersonic and subsonic jets of oxygen interacting with the surface of the metal and by their action a gas cavity is formed in the metal with a hydrodynamically unstable interface. An intense dispersion of finely divided drops of metal is formed in the volume of the cavity from this surface and this process results in a many-fold increase in the surface of oxygen-metal interaction. The basic gaseous products of such interaction are CO and CO_2 and it is necessary to increase the degree of reburning CO to CO_2 in the working space of the converter through improving the technology of the upper blow-down for better effectiveness of the converter process and reduction of harmful ejections.

As a whole, the problem of reburning carbon monoxide in the cavity of a converter has been the subject of a large number of researchers. However, up to now there has been no satisfactory solution of this problem because of the complexity and relatively poor understanding of processes taking place under the interaction of oxygen with liquid pig-iron.

In the present paper only the gas-dynamic aspect of this problem is considered, including the process of the cavity formation and the study of the structure of a two-phase flow taking into account the nonequilibrium chemical reactions.

MODEL DESCRIPTION

The typical technological scheme of the process for upper blow-down is shown in figure 1.

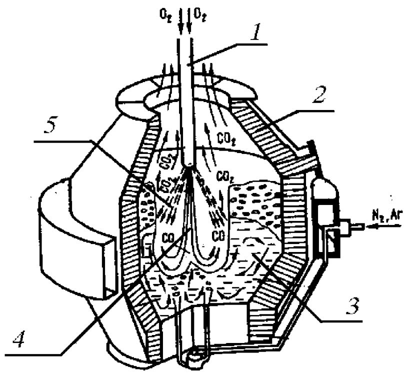

Figure 1: Scheme of blow-down process

Industrial oxygen is supplied through a lance (1) as a system of subsonic (5) and supersonic (4) jets with adjustable intensity of their action on the surface of the metal bath (Chernjatevich and Protopopov , 1995). It is possible to assume (Baptizmansky and Ochotsky, 1984) that the refining of metal by oxygen takes place as a two-stage process:

- the oxidation of metal with the formation mainly of ferrous oxides (primary zone of reactions);
- their interaction with chemical elements dissolved in the metal bath (the secondary zone).

Thus the basic gaseous product of reactions in the secondary zone is carbon monoxide which evolves from a reaction layer and passes to the gas cavity where it partially burns due to its interaction with the jets of oxygen. Generally, the process of pig-iron transformation into steel is described by a system of several dozen chemical reactions (Baptizmansky and Ochotsky, 1984). However, to study the gas-dynamic structure of flow in a cavity the following simplified scheme of the process can be used:

1. The fluid phase is a melt containing 4% carbon and 96% metal.
2. One generalized reaction of carbon combustion takes place on the interface:
$$2C + O_2 \rightarrow 2CO \quad (1)$$
3. The after-burning of carbon monoxide occurs in the cavity as a gaseous reaction:
$$2CO + O_2 \rightarrow 2CO_2 \quad (2)$$
4. The formation of drops of liquid metal happens on the hydrodynamically unstable "gas - metal" interface of the cavity. The reaction (1) is also assumed to proceed on this surface.
5. The process of formation of a slag-metal emulsion above the surface of the metal bath is not considered.

Mathematical Model

As has been mentioned above, the basic purpose of this research is to understand the gas-dynamic aspect of the process considered and we shall use a simplified scheme of the upper blow-down shown in figure 1.

Suppose that the flow is axisymmetric and accordingly we shall simplify the calculated scheme of the multinozzle lance tip. Namely, assume that at the end of the lance there is a hemisphere and from its surface there flows out two jets of industrial oxygen. The central jet is supersonic (figure 2) and the lateral one is subsonic with variable inclination to the lance axis.

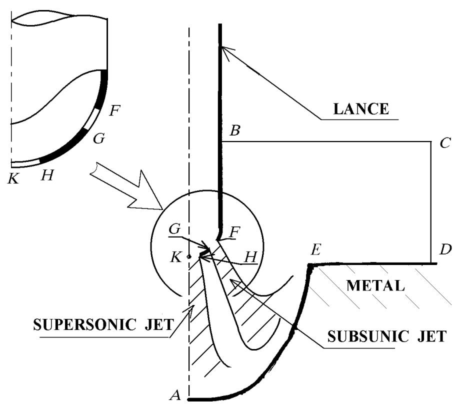

Figure 2: Simplified scheme of the blow-down process.

This axisymmetric formulation with a fan lateral jet provides a good model of multinozzle construction of the lance tip (Chernjatevich and Protopopov, 1995).

Let us further assume that the regime of the jet outflow is stationary and the basic purpose of the calculations is research of the gas-dynamic structure of two-phase flow in the cavity of the cavern taking into account the chemical reactions and dispersion of metal particles from the hydrodynamically unstable interface and their behaviour in the cavity. We have no prior knowledge of the shape of the interface, and so it is obtained from the condition of equality between the pressure in the gas phase and the hydrostatic pressure in the molten metal at each point of this surface. The flow in the gas cavity contains the subsonic and supersonic zones, shock waves and it is two-phase and turbulent.

In addition to the simplifying assumptions formulated above it was also taken that:

- the problem is axisymmetric and stationary;
- movement of the liquid phase is neglected. Only the hydrostatic pressure is taken into account;
- the gas phase consists of five components O_2, CO, CO_2, N_2, H_2O and the chemical reaction (2) proceeds in it;
- the mass fraction of carbon in metal is assumed to be constant since the characteristic time of gas-dynamic processes in a cavity is less by some orders of magnitude than the time of steel melting in the converter.

The chemical components N_2 and H_2O are considered neutral. The presence of molecular nitrogen is due to its presence in air which can be entrained into the supersonic jet from the ambient space. The presence of water vapour is necessary for the reaction (2) to proceed, as it is emphasized in (Pomeranzev, 1986). However, the complete scheme for its formation in the cavity is complicated and its concentration does not exceed 0.1% reactions (Baptizmansky and Ochotsky, 1984) . Therefore it was assumed that mass flow of H_2O from the interface takes place with the above-mentioned concentration.

The description of such a two-phase flow was carried out within the framework of the continuum approach using the set of averaged Navier-Stokes equations written in tensor form:

$$\frac{\partial}{\partial x_k} y\rho U_k = yJ \quad (3)$$

$$\frac{\partial}{\partial x_k} y\rho U_i U_k + \frac{\partial}{\partial x_k} yp = \frac{\partial}{\partial x_k} y[\mu\tau_{ik} - \rho < u_i' u_k' >] + y\rho_p C_R (U_{pi} - U_i) \quad (4)$$

$$\frac{\partial}{\partial x_k} y\rho H U_k = U_k \frac{\partial}{\partial x_k} yp + \frac{\partial}{\partial x_k} y[\lambda \frac{\partial T}{\partial x_k} - \rho < h' u_k' > + (\mu\tau_{ik} - \rho < u_i' u_k' >) \frac{\partial U_i}{\partial x_k}] + y\rho_p \{C_\alpha (T_p - T) + C_R U_{pi} (U_{pi} - U_i) \quad (5)$$

$$\frac{\partial}{\partial x_k} y\rho k U_k = \frac{\partial}{\partial x_k} y[(\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_k}] - \rho < u_i' u_k' > \frac{\partial U_i}{\partial x_k} - \rho\varepsilon - k\Phi_S \quad (6)$$

$$\frac{\partial}{\partial x_k} y\rho\varepsilon U_k = \frac{\partial}{\partial x_k} y[(\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_k}] - C_{\varepsilon 1} \frac{\varepsilon}{k} \rho < u_i' u_k' > \frac{\partial U_i}{\partial x_k} - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} - C_{\varepsilon 3} \varepsilon \Phi_S \quad (7)$$

$$\frac{\partial}{\partial x_k} y[\rho C_i U_k - (\rho D_i + \frac{\mu_t}{Sc_t}) \frac{\partial}{\partial x_k} C_i] = yJ_i, \quad (i = 1, ..., 5) \quad (8)$$

$$p = \rho R_0 T \sum_{i=1}^{5} C_i / M_i \tag{9}$$

$$\tau_{ik} = (\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i} - \frac{2}{3}\frac{\partial U_l}{\partial x_l}\delta_{ik}),\ \mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$

$$\rho < u_i^{'} u_k^{'} >= \frac{2}{3}\rho k \delta_{ik} - \mu_t \tau_{ik},\ \rho < h^{'} u_k^{'} >= -\frac{\mu_t}{Pr_t}\frac{\partial H}{\partial x_k}$$

$$\frac{\partial}{\partial x_k} y(\rho_p U_{p_k} + < \rho_p^{'} u_{pk}^{'} >) = y J_p \tag{10}$$

$$\frac{\partial}{\partial x_k} y \rho_p U_{pi} U_{pk} = \frac{\partial}{\partial x_k} y[-U_{pi} < \rho_p^{'} u_{pk}^{'} > - \rho_p < u_{pi}^{'} u_{pk}^{'} >] + y \rho_p C_R (U_i - U_{pi}) \tag{11}$$

$$\frac{\partial}{\partial x_k} y \rho_p U_{pi} H_p = \frac{\partial}{\partial x_k} y[-H_p < \rho_p^{'} u_{pk}^{'} > - \rho_p < h_p^{'} u_{pk}^{'} >] + y \rho_p C_\alpha (T - T_p) \tag{12}$$

$$\Phi_S = 2\rho_p C_R (1 - \frac{\tau_L}{\tau_L - 1/C_R}), \qquad \tau_L = 0.35\, k/\varepsilon$$

$$J = J_2 - J_1, \quad J_p = -J, \quad J_3 = J_4 = J_5 = 0$$

where: the indexes 1 - 5 refer to components of a gas phase O_2, CO, CO_2, N_2, H_2O respectively, index p refers to particles. Values of coefficients C_R, C_α and correlations of the fluctuating quantities of particles were defined from averaged quantities of the carrying gas as suggested by (Shraiber, Gavin and Naumov, 1987). The modification of the $k-\varepsilon$ model was used in the area of jet flow stagnation (Kato and Launder, 1993) and the Rodi correction (Knowles, 1996) for the flow region of the free-jet.

The influence of turbulence in the carrier gas on the burning rate of the carbon monoxide was taken into account therefore the burning rate was defined from the expression

$$J_1 = \min\{J_{ch}, J_{tb}\}, \quad J_{tb} = A\rho \frac{\varepsilon}{k} \min\{C_1, \frac{C_2}{s}\} \tag{13}$$

$$J_{ch} = 1.3 \cdot 10^{14} \exp(-30000 / R_0 T) \cdot C_2 \sqrt{C_1 C_5} \tag{14}$$

where J_{ch} is the generalized chemical reaction rate of combustion of CO, taken from (Mitchrill and Tarbell, 1982) and taking into account the influence of the water vapour concentration (C_5) on the process of combustion; J_{tb} designates the reaction rate from the eddy breakup model which relates the rate of reaction to the dissipation rate of the reactant and product containing eddies (Magnussen and Hjertager, 1976); s is stoichiometric coefficient; A denotes an empirical constant.

Solution of equations (3)-(12) was considered in the area shown in figure 2 which then was covered with a rectangular irregular difference grid. The following boundary conditions were specified on the boundaries of the area:

- mass flow of oxygen, inclination of the jets to the axis of symmetry and the stagnation temperature as the temperature of ambient space were established in the output section of nozzles on the lance tip (KH, GF, see Figure 2);
- pressure equal to the hydrostatic pressure of liquid metal and the normal mass flow of CO from the surface were set on the interface for the gas phase. The boundary conditions for mass fractions were $\partial C_i / \partial n = 0$, (i=1,3,4,5) (AE, ED) and $\rho C_2 - \rho D_2 \partial C_2 / \partial n = J_{CO}$, where n is normal to the surface and the mass flow J_{CO} was defined from the combustion rate of carbon monoxide $J_{CO} = M_{CO}/M_C \rho_C \rho C_1 2 \cdot 10^5 \exp(-158000 / R_0 T)$ where ρ_C is mass fraction of carbon in metal. Mass flow of particles from surface of the cavity was $\rho_p v_{pn} = G_p$, where v_{pn} is normal velocity.
- the symmetry conditions were specified on the axis (AK) and "soft" boundary conditions were prescribed in the exit section (CD, BC).

In order to describe the dispersion process of metal drops from the interface it was assumed that this surface "on the average must be stable ". The size of the particles and the intensity of their mass flow from the interface are determined by the dynamic characteristics of the gas flow under this surface and the physical properties of both phases. To define them we will consider the process of the phase-boundary interaction resulting from the gas flow along a curvilinear impermeable surface with a liquid film of metal, which can be divided into drops because of the Taylor instability. Behavior of the film is unstable when the transversal velocity of the outflow of the vaporizable mass film from the surface becomes comparable with the value of the tangent mass flow velocity of the gas phase to the "average" interface (Gogonin and Lazarev, 1990). The criterion of destruction is determined from the inequality obtained in this work:

$$\left(\frac{\rho^{"}}{\rho}\right)^{1/2} \frac{U^{"}}{\sigma} \mu Ar_*^{1/3} Re^{1/6} > 1.75 \tag{15}$$

$$Ar_* = \left(\frac{\sigma^3}{\upsilon^2 \rho^3 (1 - \rho^{"}/\rho) |(\vec{g}, \vec{\tau})|} \right)^{1/2} \tag{16}$$

where $U^{"}$ is the absolute value of a vector of the gas velocity along the interface outside the boundary layer; $\rho^{"}$ stands for the gas density; σ is the coefficient of surface tension of the film; υ denotes the coefficient of the kinematic viscosity of the liquid; $(\vec{g}, \vec{\tau})$ is a projection of the gravity acceleration vector on the tangent to the surface. Processing of the experimental data has allowed us to obtain the connection between the size of drops and the velocity head of the gas flow:

$$\frac{U^{"2} \rho^{"} d_0}{\sigma} \geq 10 \tag{17}$$

where d_0 is the drop diameter at the moment of breakage. Therefore it is possible to define from expressions (15)-(17) the point position of the beginning the breakup of the film and the value of drop sizes. To define the mass flow rate of particles of metal from the interface the practical recommendations given by (Baptizmansky and Ochotsky, 1984) were used. They found that the mass output of metal drops G_p is approximately three/five times greater than the mass flow rate of oxygen G_1 through the lance.

Therefore the following parametric dependence was used:

$$G_p = \alpha G_1 \tag{18}$$

where the parameter α was set by a series of its values and then the values of all parameters of particles on moving boundary (AE) were determined from the relationships mentioned above. The conditions of the particles absence on (CD) and "soft" boundary conditions on boundaries (AB) and (BC) were set.
Numerical solution of the given problem was carried out making use of the method ELAFINT (mixed Euler - Lagrangian method for account of incompressible flows) with mobile boundaries (Udaykumar, Shyy and Rao,1996) which was modified for compressible flows. The procedure of smoothing the "stable on the average " interface using B-splines was also applied .

RESULTS

The numerical modeling of the upper blow-down process was carried out for its initial stage when the concentration of carbon in metal was maximal. The central jet had Mach number $M_0 = 1.2$ (figure 2) and the lateral jet had $M_1 = 0.5$. The angle of its inclination to the lance axis was 45°. Three parameter values α in (18) were set $\alpha = 2, 4, 6$. The structure of the flow field in the cavity of the cavern is shown in figure 3 as vectors of the gas velocities and position of isolines of Mach numbers for $\alpha = 2$. At other values of this parameter essentially only the shape of the cavity changes. It is shown by dotted curves for $\alpha = 4, 6$ on figure 4. At the same time the structure of the flow field is not changed essentially. It can be seen that stagnation of the supersonic jet takes place near the surface of the metal without penetration into the cavern. Temperature of the gas phase and its density in the cavity are essentially non-uniform owing to the large temperature difference between the jet and the liquid metal. A zone with high values of gas velocities occurs near the interface which can exceed the speed of sound near the output section. Profiles of particle particles in different cross-sections of the cavern are shown in figure 5. It can be seen that the interaction of particles with the carrying gas increases their density near the interface. The consequence of this nonuniformity for the density distribution is that the main mass inflow of CO takes place near the surface of the cavern and most of the oxygen delivered to this zone by convective and diffusive transposition is consumed here. However, such transposition does not ensure sufficiently complete burning of CO as follows from figure 6, and a considerable proportion is carried out of the cavern cavity. The complete absence of carbon monoxide near the center of a jet is due to the fact that the temperature here is low and water vapour does not reach the center of the axis of the oxygen jet hence reaction (2) does not proceed. If the concentration of the water vapour is increased by an order of magnitude, the completeness of combustion of CO increases substantially as is depicted by dotted curves in figure 6. Therefore by carrying out the measures aimed at increasing the intensification of the oxygen transposition to the interface and a rise in the concentration of water vapour in the cavern, it is possible to consider practical recommendation for enhancing the effectiveness of the process of CO reburning.

CONCLUSION

The technique of numerical modeling the top blowing process in steel-making converters, taking into account the carbon monoxide reburning in the cavity, is developed.

Structure of a two-phase flow in the cavity taking into account nonequilibrium chemical reactions is investigated.

On the basis of the analysis of the flow structure and the details of the process of carbon monoxide reburning some practical recommendations for the improvement of the effectiveness of this process have been suggested.

REFERENCES

ALEKSEENKO, S.B., NAKORJAKOV, V.E. and POKUSAEV, B.G. (1992),"Wave flow of liquid films", (in Russian), *Nauka,* Novosibirsk.

BAPTIZMANSKY, V.I., and OCHOTSKY, V.B. (1984), "Physical-chemical fundamentals of oxygen converter process", (in Russian), Kiev-Donetsk.

CHERNJATEVICH, A.G., and PROTOPOPOV, E.V., (1995) "Development of tips for double-loop lances for oxygen converters", (in Russia), *Izvestja VUZov. Ferrous metallurgy*, 12, 13-17.

GOGONIN, I.I. andLAZAREV,S.I. (1990), "Experimental research of heat exchange and surface of the horizontal cylinder", (in Russian), *Engineer-physical journal*, **58**, 2, 181 - 188.

KATO, M. and LAUNDER, B.E., (1993), "The modeling of turbulent flow around stationary and vibrating square cylinders", *Proc. 9th Symposium on Turbulent Shear Flows*, Kyoto, Japan, 10-14 .

KNOWLES, K., (1996), "Computational studies of impinging jets using $k-\varepsilon$ turbulence models", *Int. J.Numer. Meth. Fluids***,** **22**, 799-810.

MAGNUSSEN, B.F. and HJERTAGER, H.(1976),"On mathematical modeling of turbulent combustion with special emphasis on soot formation and combustion", *Proc. 16th Int. Symp. on Combustion,* 747-753.

MITHEL, J.W. and TARBELL, J.M. (1982)"A kinetic model of nitric oxide formation during pulverized coal combustion", *AIChE Journal*, **28**, No.2, 302-311.

POMERANZEV, V.V., (1986), "Fundamentals of the practical theory of combustion", (in Russian), *Energoatom izdat*, Mockow.

POURAHMADI, F., HUMPHREY, J.A.C., (1983), "Modeling solid-fluid turbulent flows with application to predicting erosive wear", *Phys.-Chem. Hydrodynamics*, **4**, 3, 191-219

SHRAIBER, A.A., NAUMOV, V.A., GAVIN, L.B., (1987), "Turbulent flows of suspension of matter in gas", (in Russian), *Naukova Dumka*, Kiev.

UDAYKUMAR, H.S., SHYY, W. and RAO, M.M., (1996), "ELAFINT: A mixed Eulerian-Lagrangian method for fluid flows with complex and moving boundaries", *Int. J. for Numer. Methods in Fluids*, **22**, 691-710.

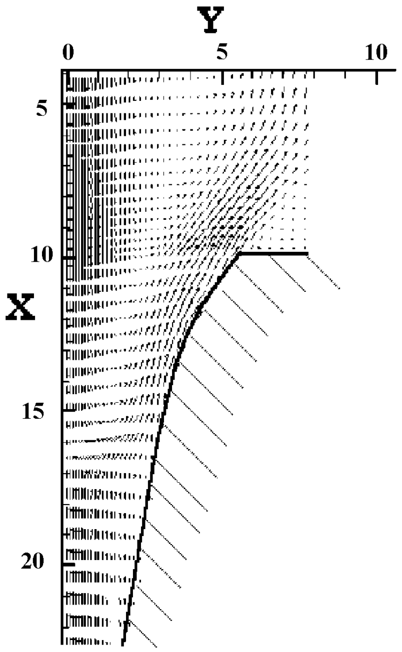

Figure 3: : Structure of field flow in the cavity of the cavern

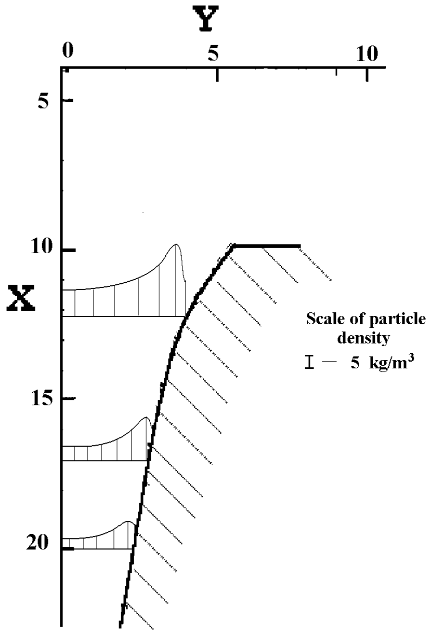

Figure 5: Distribution of density of particles in the cavity

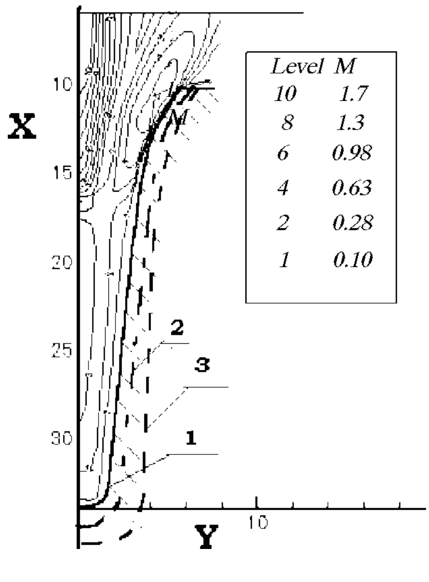

Figure 4. Max isolines in the cavern

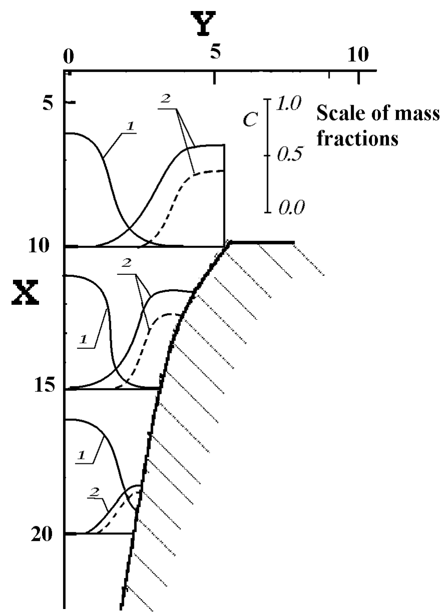

Figure 6. Distribution of mass fraction of oxygen (1) and carbon monoxide (2) in cavity.