Journal of Machine Construction and Maintenance
QUARTERLY ISSN 1232-9312 1/2018(108)

p. 111–117

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ANALYSIS OF THE FLOW OF GAS/POWDER MIXTURE IN THE OXYGEN CONVERTER LANCE NOZZLES

Key words: nozzle, numerical calculations, gas/powder mixture flow, slag splashing method.

Abstract: A numerical solution of mathematical equations for the carrier gas and powder flow and numerical variables were used for establishing the effect of carrier gas pressure at the nozzles on the change of the thermodynamic flow of gas parameters of gas/powder mixture and pure gas in the nozzles at different operation modes. The calculations were based on the author's computer program worked out from a mathematical model consisting of equations and parameters of thermodynamic flow of gas conditions. The results of simulations revealed that the change of entry pressure significantly affects the static pressure, gas velocity in the nozzles, the temperature of the carrier gas, and the velocity of *i*–th solid particle of the expelled powder. Apart from it, the effect of entry pressure before the nozzle on the density and velocity of *j*-th particle was also analysed. Similar results were obtained in works [1, 4]. Accordingly, the optimum conditions of pure gas jetting in the analysed converter are reached when the jetting out pressure is 1.7 MPa (during each "slag splashing"). The temperature before the nozzles should increase every second as this stabilizes the drop of power due to the pressure drop in the manometer. In this case, the lance has to be cooled with water [3].

Badania przepływu mieszaniny gaz/proszek w dyszach lancy konwertora tlenowego

Słowa kluczowe: dysza, obliczenia numeryczne, przepływ mieszanki gaz/proszek, metoda rozpryskiwania żużla.

Streszczenie: Numeryczne rozwiązanie równań matematycznych dla przepływów gazu nośnego i proszku oraz wielu zmiennych pozwoliło ustalić, jak ciśnienie gazu nośnego wpływającego do dysz wpływa na zmianę termo-gazodynamicznych parametrów przepływu mieszaniny gaz/proszek oraz czystego gazu w dyszach przy różnorodnych trybach pracy. W obliczeniach zastosowano własny program komputerowy opracowany na podstawie modelu matematycznego zawierającego równania i parametry związane z termo-gazodynamicznymi warunkami przepływu. Wyniki symulacji pokazały, że zmiana ciśnienia wstępnego istotnie wpływa na ciśnienie statyczne i prędkość gazu w dyszach oraz na temperaturę gazu nośnego i prędkość *i*-tej cząstki fazy stałej – wdmuchiwanego proszku. Oprócz tego pokazano wpływ ciśnienia wstępnego przed dyszą na gęstość oraz prędkość *j*-tej cząstki. Podobne wyniki otrzymano w pracach [1, 4]. Na tej podstawie ustalono, że dla badanego konwertora tlenowego optymalne warunki wdmuchiwania czystego gazu osiąga się przy parametrach procesu, kiedy moc wypływającego strumienia jest na poziomie 1,7 MPa (w każdym czasie „slag splashing"), natomiast temperatura przed dyszami musi zwiększać się w każdej sekundzie, ponieważ to niweluje spadek mocy w rezultacie spadku ciśnienia na manometrze, ale przy tym lanca musi być chłodzona wodą [3].

1. The state of the question

In the splashing method involving specially prepared post-processing slag in an oxygen converter, the resistance of the refractory lining can be radically increased (5–7 times) [1–3]. The bigger the efficiency of the pneumatic spraying of slag onto the hot refractory lining, the bigger is the power of the splashing gas jet. When working out mathematical models of gas flow, attention should be paid to the specific character of the technological conditions of the splashing itself. During "slag splashing," constant pressure should be maintained before nozzles of the same size, which is technically impossible; the pressure drops on the manometer from ~ 1.7 MPa at the beginning of splashing to 1.1 MPa at the end, but the jet remains supersonic. The character of the supersonic jet that entered the converter is commonly known. When the pressure in the lance differs from the pressure in the converter, the gas jet leaving the nozzle assumes the form of a shock wave (1) [4]:

$$n = p_a / p_g > 1 \text{ or } < 1 \tag{1}$$

where

n – the abnormal parameter characterizing the ratio of the pressures,

p_a – pressure in the nozzle cross-section [*Pa*],

p_g – pressure in the converter [*Pa*].

Figure 1 illustrates the structure of ultrasonic air jet entering the atmosphere for *a)* $n = 1.3$, and *b)* $n = 6.9$.

The analysis of the figure reveals that, at the same consumption of air introduced to the nozzle, the structure of jets discharged off the nozzles significantly differs.

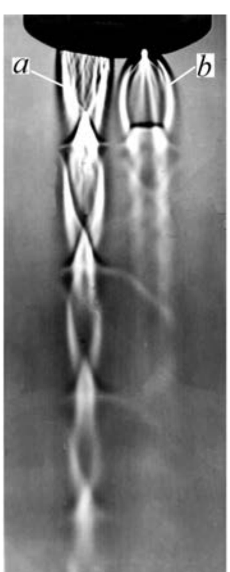


Fig. 1. Structure of supersonic air jets introduced to the atmosphere for *a)* $n = 1.3$, and *b)* $n = 6.9$. Critical diameter of the nozzle $d_{cr} = 6$ *mm*, gas consumption by each nozzle $V_n = 3.6$ m^3/min

Additional broadening of the gas jet behind the nozzle is always less efficient than inside of it. In the system of straight and slanting jumps of the supersonic sealing jet, a significant dissipation of mechanical energy takes place. The higher *n* is different from 1 and the higher the temperature is in the converter, the greater are energy losses behind the nozzle. The loss of efficiency in one step of flow of pure carrier gas was evaluated for the following parameters of the process:

Gas consumption in normal conditions by an oxygen converter nozzle of capacity 350 Mg, – V_n = 210 m^3/min, consumption at direct step – V_{1n} = 0.75 V_n, Mach number before step – M_1 = 1.7, nitrogen adiabatic – $k = 1.4$, gas constant – R_{N2} = 0.297 *kJ/kg·K)*, density of nitrogen ρ_N = 1.25 kg/m^3, temperature $T_{atm.}$ = 300K.

When the pressure before the nozzle p_o = 1.2 *MPa,* and gas consumption V_n = 210 m^3/min, the power of one of the nitrogen jets will equal to 550 kW. In the tables of gas dynamics functions and tables for calculating parameters with direct gas flow steps, the velocity before and after the step totals to: $\lambda_1 = 1.48$, $\lambda_2 = 0.68$, and the pressure to density ratio before and after the step is $p_2/p_1 = 3.2$; $\rho_2/\rho_1 = 2.2$. The change of entropy directly during the step equals the following:

$$\Delta S = \frac{R}{k-1} \ln\left[\frac{p_2}{p_1}\left(\frac{\rho_1}{\rho_2}\right)^k\right] \tag{2}$$

$$\Delta S = \frac{0.297}{1.4-1} \ln(3.2 \cdot 0.455^{1.4}) = 0.045 \ kJ/(kg{\cdot}K)$$

The energy loss (anergy) on direct step of gas flow was determined with equation [1]:

$$\Pi = \rho_n V_n T_{atm} \Delta S \tag{3}$$

Hence $\Pi = 1.25 \cdot 0.75 \cdot 210 \cdot 300 \cdot 0.045 / 60 =$ $= 44{,}3$ *kW.*

The velocity ratio before and after the step equals the following:

$$w_1/w_2 = \lambda_1/\lambda_2 = 1.48/0.68 = 2.2$$

For the assumed conditions, the kinetic energy of gas behind the direct step drops $2.2^2 = 4.84$ times. The character of mechanical energy losses, with the lesser degree of irreversibility, repeats 8–10 times in a series of straight and slanting jumps of gas jet. Therefore, at the existing slag splashing technology, serious irreversible losses are observed in the jet only during the operation on anormal modes of outflow. This signifies that the condition of $n \approx 1$ should be met, which cannot be realized in practice.

In work [5], technology was presented of improving slag splashing by adding a nitrogen jet containing powder obtained from unbaked dolomite. The powdered magnesia material consumption equals to 500–600 *kg/min*. However, it is technically difficult to quickly introduce refractory powder, because nozzles of significant size are required. Therefore, after introducing powder, the same nozzles cannot be efficiently used for pure nitrogen. It is better to lower the amount of refractory additive:

$$\mu = m_2 / m_1$$

where
m_1 – mass consumption of nitrogen by a nozzle,
m_2 – powder consumption,

and slightly elongate the time of spraying of gas/powder mixture onto slag. This promising technology spurred the development of a new method of calculating the work of nozzles in the lances to be used for charging gas/powder mixtures.

In the present model, the work of nozzles can be modelled numerically for a vast range of powder content (μ = 0–30); however, bearing in mind the problems presented above, the authors assumed that the powder content should not exceed μ = 1.5. The calculations were aimed at using a two-rate flow model for determining the influence of entry pressure p_o on the change of thermodynamic parameters of gas of single – or two-phase flows in the area of nozzles.

2. Mathematical model

The gas dynamics of two-phase flow is based on physical laws: mass conservation, pulse conservation, and energy conservation laws. Analogous to polydispersive powder particles, which move at various rates, the interphase exchange between particles of different size should be taken into account.

This model relies on the ideas presented in works [6] and [7]. In the case of axis-symmetrical two-phase stationary flow, the system of differential equations of motion can have the following form [1]:

– for gaseous phase

$$\frac{d}{dx}\left(\varepsilon_1 \rho_1 w_1^2 f + \varepsilon_1 p f\right) - p\frac{d(\varepsilon_1 f)}{dx} = -F_{1w} - \sum_{i=1}^{N} F_{1i} \tag{4}$$

– for *i*-th fraction of particles

$$\frac{d}{dx}\varepsilon_{2i}\rho_2 w_2^2 = -\varepsilon_{2i} f\frac{dp}{dx} + \varepsilon_{2i}\rho_2 C_{Ri}(w_1 + w_2) + \varepsilon_{2i}\rho_2 f\sum_{j=1}^{N}(w_{1j} - w_{2i})k_{ij}^{/} \tag{5}$$

In equations (4), (5) and further in this paper, the following denotations were made: p – absolute static pressure, *Pa*; ρ – density, kg/m^3; w – velocity in *i*-th phase, m/*s*; ε_i – participation of *i*-th phase; F_{1w}, F_{2w} – force of friction of gas and powder against the nozzle wall, *N*; F_{1i} – force of interphase interaction, *N*; C_{Ki} – friction coefficient of particles; k_{ij} – function of interaction of particles of *i*-th fraction with particles of *j*-th fraction; η – dynamic viscosity, [*Pa·s*]; $\psi = w_i/w_1$ – coefficient of dynamic delay of *i*-th fraction from carrier gas; ζ_1 – friction losses coefficient; k – adiabatic coefficient; $\mu_i = m_i / m_1$ – mass participation of *i*-th fraction in the gas suspension, *kg/kg*; *D, l, f* – diameter *m*, length *m* and cross-sectional area of nozzle m². The indices denote the following parameters: 1 – carrier gas; 2 – powder particles; *i* – *i*-th phase; 1_w – at the carrier gas/wall interface; 2*w* – at the particle/wall interface; 1*i* – at the gas/particle interface; *min, cr*, *a* – minimum, critical and entry cross section of nozzle, *n* – in normal physical conditions.

In equation (5) we have C_{Ri} – resistance coefficient, which equals to:

$$C_{Ri} = \frac{18\eta}{\rho_2 \delta_1^2}\varphi_1 \tag{6}$$

$$\varphi_1 = \left[1 + \sqrt{\frac{k}{2}}\frac{M_{1i}}{Re_{1i}}\left(4.33 + \frac{3.65 - 1.53\frac{T_{2i}}{T_1}}{1 + 0.353\frac{T_{2i}}{T_1}}exp\left(-0.247\frac{Re_{1i}}{M_{1i}}\sqrt{\frac{2}{k}}\right)\right)\right]^{-1} + \tag{7}$$

$$+\frac{Re_{1i}}{24}\left\{\left[\frac{4.5 + 0.38\left(0.03\,Re_1 + 0.48\sqrt{Re_{1i}}\right)}{1 + 0.03\,Re_{12} + 0.48\sqrt{Re_{1i}}} + 0.1M_{12}^2 + 0.2M_{1i}^8\right]exp\frac{M_{1i}}{2\sqrt{Re_{1i}}} + \right.$$

$$\left. +0.6\sqrt{\frac{k}{2}}M_{1i}\left[1 + exp\left(-\frac{M_{1i}}{Re_{1i}}\right)\right]\right\}$$

The interaction function was determined with the following equation:

$$k'_{ij} = \frac{6\varepsilon_{2j}k_{ij}}{\pi\left(\delta_i^3 + \delta_j^3\right)} \tag{8}$$

Equations (3) – (7) can be solved if the condition of common movement of phases is met:

$$\varepsilon_1 + \sum_{j=1}^{N} \varepsilon_{2j} = 1 \tag{9}$$

If above parameters are changed, the correctness of the solution is determined with Equation (9).

When continuity equations for gaseous phase and *i*-th fraction of solid phase are solved, the participation of *i*-th fraction equals the following [5–6]:

$$\varepsilon_i = \left(1 + \frac{\psi_i\,\rho_i}{\mu_i\,\rho_1}\right)^{-1} \tag{10}$$

The force of friction between the nozzle wall and carrier gas was determined with Equation (11) [1]:

$$F_{1w} = \zeta_1\varepsilon_1\rho_1 w_1^2 f/(2D); \quad \zeta_1 = 0{,}11\left(\frac{\Delta}{D} + \frac{68}{\mathrm{Re}}\right)^{0.25} \tag{11}$$

where
Reynolds number for gas: $\mathrm{Re} = Dw_1\rho_1/\eta$.

The equation of state for gaseous phase equals the following [1]:

$$p = \rho_1 R T_1 \tag{12}$$

The thermal capacity of nitrogen was calculated with Equation (13):

$$c_p = 965 + 0.212T - 12.067\ 10^{-6}T^2 \tag{13}$$

The calculations were performed using a computer program developed at Pryazovskyi State Technical University in Mariupol (Ukraine).

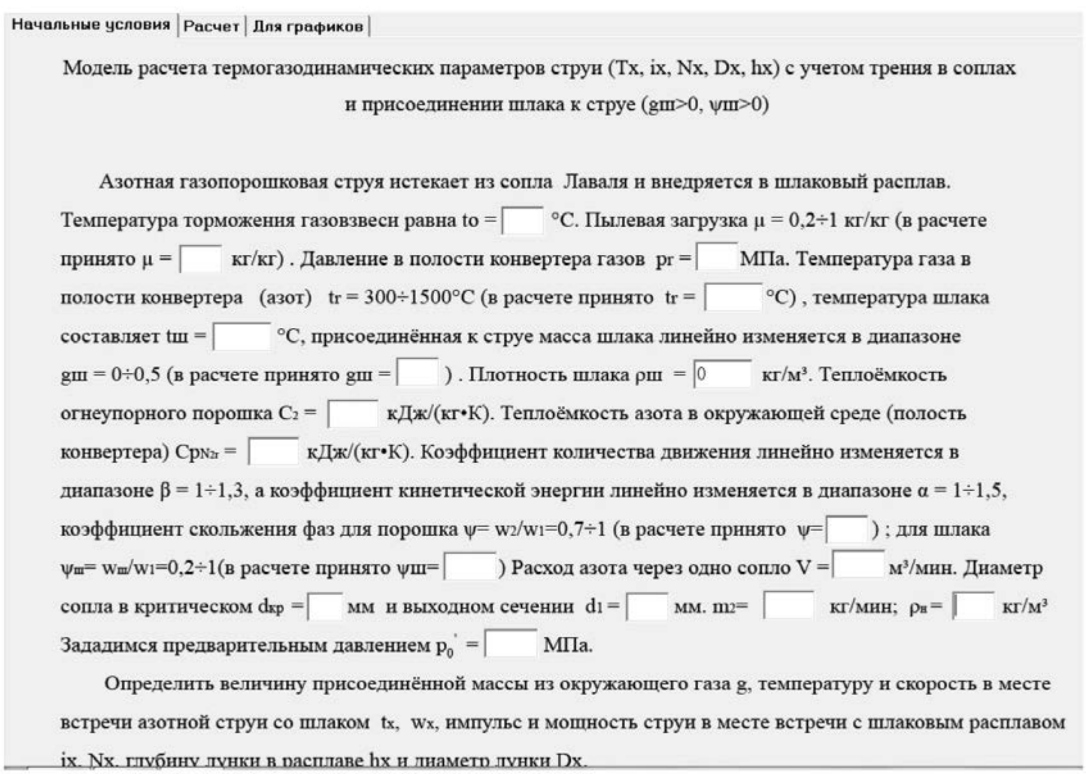


Fig. 2. Program window for calculating parameters of the process

3. Calculation data

Calculations were performed for a lance, for spraying nitrogen on slag in a converter 350 Mg of volume. In all calculations, the nitrogen consumption by one nozzle in normal physical conditions was V_n = 210 m^3/min. Refractory powder consumption was about m_2 = 79 − 395 *kg/ min* with the corresponding mass participation of powder in carrier gas

$m = m_2 / m_1 = m_2 / r_n V_n = 0.3 – 1.5\ kg / kg$.

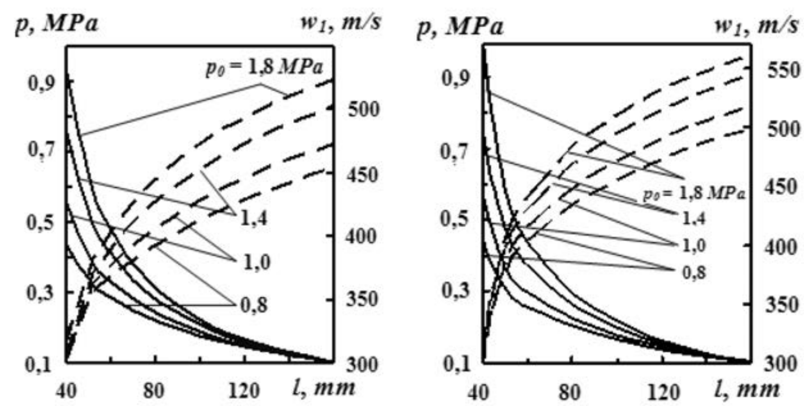
Pressure before the nozzle changed: $p = 0.8 – 1.8$ *MPa*, and the pressure behind the nozzle in all operation modes equalled atmospheric pressure ($p_2 = p_g = 0.1MPa$) (boundary condition). Temperature before the nozzle was $t_o = 20 - 600°C$. The assumed length of the contracting (confusor) and broadening (diffuser) part of the nozzle was $l_1 = 40$ *mm*, $l_2 = 120$ *mm*, and the roughness of nozzle wall $\Delta = 0.07$ *mm*. The corresponding diameter of particles was assumed for considerably differing dimensions, $\delta_i = 0.07$ *mm* and $\delta_j = 0.5$ *mm*, and their mass participation in the gas/powder mixture was $g_i = 0.3$, $g_g = 0.7$, respectively, and the shape factor $f = 1.2$. The assumed thermal capacity of powder $c_2 = 0.6$ *kJ/(kg·K)*, density of particles $\rho_2 = 2200$ *kg/m*^{3}. The particle delay to the velocity in the entry nozzle diameter ratio equalled $\psi = w_2/w_1 = 0.8$. Coefficients accounting for thermophysical parameters of nitrogen (thermal capacity c_p, thermal conductivity λ and kinematic viscosity v) changed depending on gas temperature.

In this model, when a great number of parameters were changed in each of the discussed modes, the entry nozzle diameter d_{we}, diameter in minimum cross-section $d_{min,,}$ *in* critical cross-section d_{cr}, in discharge cross-section d_a, were determined, provided that the attenuating single – or two-phase jet in all variants approximately equals n ≈ 1. Only if the condition $p_a = p_g$ ($p_g = 0.1$ *MPa*) $n = 1$ holds true, no shock wave occurs in the resulting supersonic jet. The entry nozzle diameter d_{we} was calculated for each variant; however, these results were not given in this paper, because this parameter is not important for the final results.

4. Results of calculations

The computer simulations were performed for over 30 variants and the characteristic nozzle diameters (d_{min}, d_{cr}, d_a). The flow characteristics in the w subsonic part of the nozzle presented in works [6–7] change insignificantly. Therefore, the division of basic parameters was presented in the form of plots only for the broadening part of the nozzle (at a length of $l = 40 - 160$ *mm*), which is technologically more important.

The analysis of Fig. 3 reveals that, with the increase of entry pressure p_o, both static pressure p and gas velocity w_1 increase in each nozzle diameter during gas flow. For instance, at a distance $l_1 = 100$ *mm* from the entry nozzle cross-section at a pressure growth p_o from 0.8 to 1.8 *MPa,* static pressure p increases from 0.18 to 0.22 *MPa*, and velocity w_1 increases from 455 *m/s* to 511 *m/s*.



a) b)

Fig. 3. Effect of pressure p_0 on static pressure distribution p (—) and gas velocity w_1 (---) in a function of length l of the broadening part of the nozzle. Source data: a) $\mu = 1.5$; b) $\mu = 0.3$

The plot in Fig. 4 shows that, with the increase of entry pressure p_o before the nozzle, temperature t_1 decreases, but the velocity of *i*-th particle increases. At the distance of $l = 120$ *mm* from the entry nozzle diameter, at the pressure increase from 0.8 to 1.8 *MPa,* the carrier gas temperature t_1 decreases from – 85 to –115°*C*, and the velocity of particles w_i increases from 125 *m/s* to 268 *m/s*.

When entry pressure p_o before the nozzle is increased, density ρ_1 and velocity of *j*-th particle increases in each cross-section (Fig. 5). For instance, when the pressure increases from 0.8 to 1.8 *MPa* (at a distance $l = 120$ *mm* from the entry nozzle cross-section d), density ρ_1 increases from 2.5 *kg/m*^{3} to 3.5 *kg/m*^{3}, and velocity of particles w_j increases from 106 *m/s* to 237 *m/s*.

With the increase of pressure p_o before the nozzle, density ρ_1 and the velocity of *j*-th particle also increase (Fig. 6). For instance, with the increase of pressure from 0.8 to 1.8 *MPa* in the discharge cross-section of the nozzle ($l = 160$ *mm*), ρ_1 increases from 0.7 *kg/m*^{3} to 1.0 *kg/m*^{3}, and w_j increases from 60 *m/s* to 165 *m/s*.

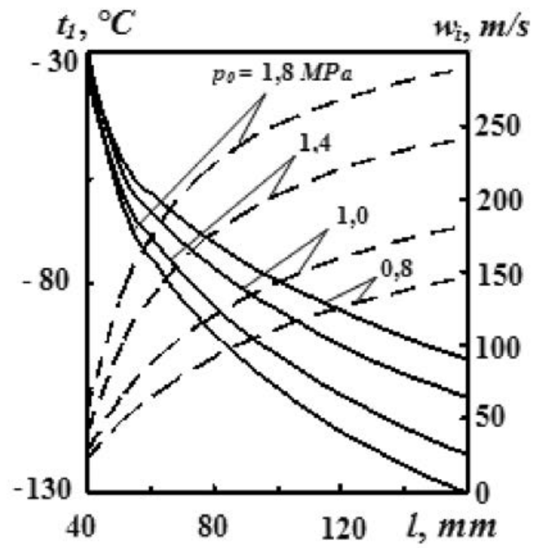


Fig. 4. Effect of pressure p_0 on a change of temperature t_1 (—) and velocity of i-th particle w_i (---) at length l of broadening part of the nozzle. Source data: $\mu = 0.3$

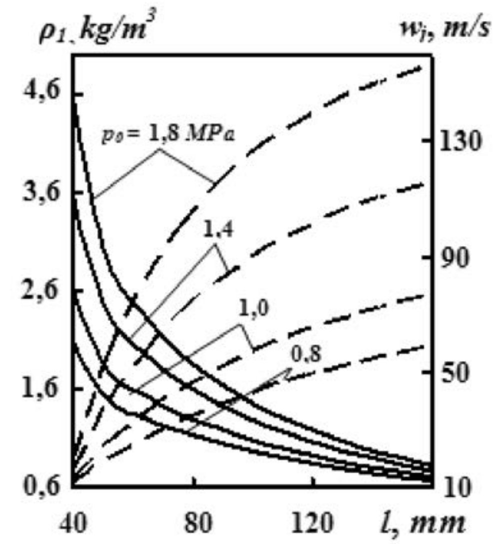


Fig. 6. Distribution of density ρ_1 (—) and velocity of i-th particle w_j (---) at length l of broadening part of the nozzle at various entry pressure p_o

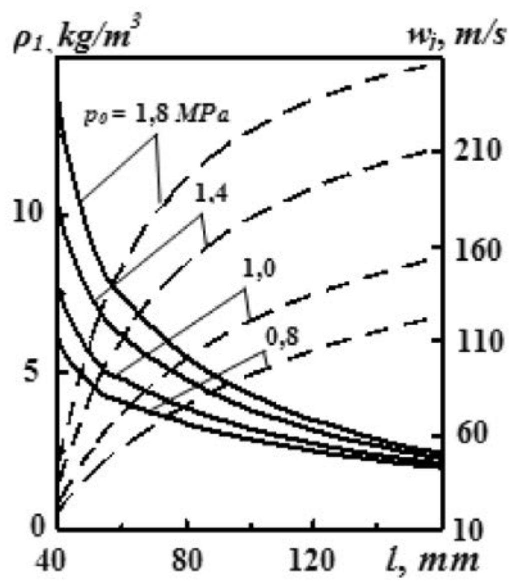


Fig. 5. Distribution of density ρ_1 (—) and velocity of i-th particle w_j (---) at length l of broadening part of the nozzle at various entry pressure p_o

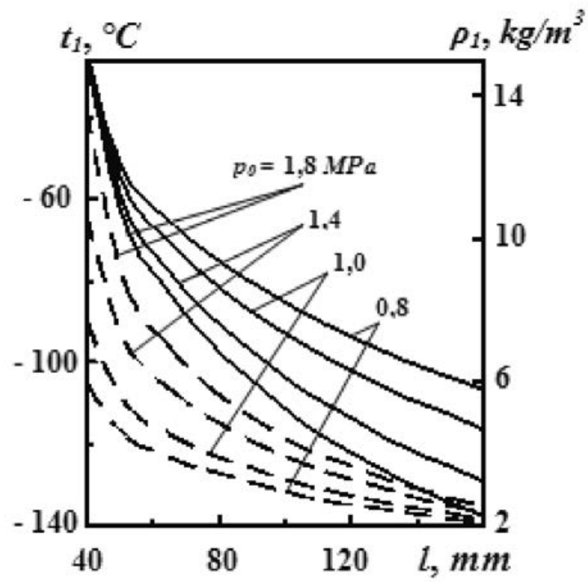


Fig. 7. Change of static temperature t_1 (—) and density ρ_i (---) at length l of the broadening part of the nozzle at different pressure p_o

It follows from Fig. 7 that with the increase of pressure p_o before the nozzle, static temperature t_1 decreases, whereas density ρ_1 increases. For instance, at a distance $l = 120$ *mm* from the entry nozzle cross-section, with the increase of pressure from 0.8 to 1.8 *MPa,* temperature t_1 decreases from –94°*C* to –126°*C*, whereas density ρ_1 increases from 2.6 kg/m^3 to 3.5 kg/m^3.

Importantly, parameters and source data in the numerical model were not variable (Figs. 3–7), i.e. only pressure before the nozzle p_o was changed for all analysed variants of nozzle diameters $d_{min,}$ $d_{cr,}$ and d_a for established p_o.

Conclusions

1. The presented calculation method accounts for changes of thermodynamic parameters of gas along the nozzle at entry pressure p_o, only for nozzles operating in variant in which $n = 1$.
2. With this method, one may easily select the appropriate shape of the nozzle in the lance that will be used for slag splashing in an oxygen converter, which provides optimum jetting of gas/powder mixture in each gas pressure variant, where no dissipation of the jet takes place. Consequently, the parameters of the process can be selected as to increase the power of the jet splashing liquid slag at the same amount of consumed powder and pressure.

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