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Influence of heat supply on the hydrodynamics of gas suspension motion in shotcrete – variable-delivery tuyere

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Abstract
The results of numerical calculations of the equilibrium two-phase flow into shotcrete - tuyere with output of the gunite - mass at different levels along its length are given. It is defined that at such constructive solution of pressure, velocity, density of the gas suspension change abruptly. It is shown that if the tuyere body becomes heat exchanger, the energy potential of gas-dispersed flow increases significantly.To reduce the potential loss of compressed gas suspension flow, it is recommended to build a pipe of tuyere pit of steplike type.
Keywords: SHOTCRETE – TUYERE, ENERGY POTENTIAL, THE FLOW OF GAS SUSPENSION.

Statement of the problem. Reduction of energy - and resource consumption with introduction of high metallurgical technologies is a problem of a national scale. During production of steel in oxygen converters one of the key objectives is to increase the resistance of the lining. The cost of relining during hot repair of 350 t converter reaches $ 1 million.

The works [1 – 3] show that for a radical increase of converter lining resistance, the best is to use one of two technologies of industrial operations - blowing of prepared final slag and flare shotcrete. Nonwater-colling gas-powder tuyere was applied in these works during experimental-industrial testing of lining slagging; during motion in its body nitrogen was being heated. Authors' researches [1 – 3] have also proved that if gas suspension is heated, it is reasonable to use gas-cooled tuyere, the body which acts as heat exchanger. Relevance of technology is obvious – in a new technical solution, previously lost heat can be used for warming the gas suspension in the gunning tuyere and thus increase energy potential at the end of the dust-gas flow into the cavity of the vessel. If only torchlight gunning is used for hot relining (PJSC «Mariupol Ilyich»), then this process may be combined with the heating of scrap. In this case, the empty converter is loaded by scrap, and coal on the top. Coal enters into a shapeless mass of scrap because of the heat of shotcrete flame there appears ignition and volume combustion. Usage of a portion of previously lost heat of the flame for heating scrap intensification improves the thermal balance of the next smelting.

In this paper we consider the steady flow of the equilibrium velocity and temperature of the gas suspension phase in a long annular channel at a constant temperature of gas-cooled wall.

The aim of this work while solving the equations of motion and energy of gas-powder flow, as well as a number of closure relations, to show how the heat input from the heated wall gunning lance with variable flow of gas suspension affects the distribution of pressure *p* and velocity of the mixture w_{12} on the length *l* of lance, and the density ρ_{12}, speed w_{12}, the volume fraction ε_1 of the gas phase in a cross sectional view of the lance with a concentration of μ and diameter δ of powder particles.

Physical model. Plant layout for flare shotcrete is presented in the work [4]. Figure 1 shows an element of gas cooled gunning lance, from which one may see how the nozzles for supplying powder mixture and oxygen in the gas-cooled lance with different levels of consumption are located. In such construction gas suspension is heated from the body wall of

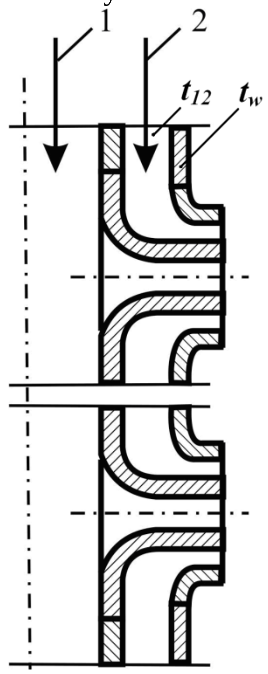

Figure 1. Arrangement of nozzles in gunning tuyere with two levels of consumption; 1 - oxygen; 2 - gas suspension

the tuyere due to convective heat flow transmitted by the wall to the carrier gas. Because of thermal resistance temperature of the gas suspension t_{12} will always be lower than the temperature of the body wall of the tuyere t_w (see fig. 1). Given that the oxygen is $\left(V_{\textit{н}0_2} \approx 300\ m^3/\min\right)$ ~ 40 times higher than the carrier nitrogen $\left(V_{\textit{н}N_2} = 480\ \textit{м}^3/h\right)$, there is no danger of its heat through the partition wall of the pipe, but it is desirable to increase the temperature of O_2. To prevent deterioration of the oxygen nozzle tube at the moment of turning gas-powder flow at 90º degrees, ceramic inserts should be fitted.

Mathematical model. Let us write the equations of gas-dispersed flow in single-speed and single-temperature approximation taking into account the reduction of the flow of a gas suspension G_{12} along the channel

– motion equation

$$\frac{d}{dx}\left(G_{12}w_{12}\right) = -\frac{dp}{dx} - F_w + \rho_{12}g - \chi w_{12} \qquad (1)$$

– the energy equation

$$\frac{d}{dx}\left(G_{12}c_{p_{12}}T\right)=w_{12}\frac{dp}{dx}+Q_w-\chi c_{p_{12}}T\,. \qquad (2)$$

During motion of the mixture past the nozzles in the channel

$$\chi=n_iG_i/D\,, \qquad (3)$$

In the equations (1) – (3), and further there accepted the following notation parameters of the equilibrium gas suspension flow (pseudo gas): G_{12} – reduced flow rate, kg/(s · m^2); w_{12} – flow velocity, m/s; p – static pressure, Pa; F_w – friction force of pseudo gas on the pipe wall of tuyere body, N / m^3; ρ_{12} – density, kg/m^3; χ – intensity of cost reduction of the mixture along the channel, kg/(s·m^3); $c_{p_{12}}$ – Heat, kJ / (kg·K); T – the static temperature, K; V_H – gas flow rate under normal physical conditions, m^3 / min; m_2 – gunning mass flow rate, kg/s; Q_w – quantity of heat transmitted by convection from the wall of the tuyeres to the gas suspensions, W/m^3; n_i – the number of nozzles on the *i*-th level; D – inner hydraulic diameter of gunning tuyere, m.

In the equations (1) – (3) and further indices denote parameters: 1 – carrier gas; 2 – solid phase; 12 – equilibrium of gas suspension (pseudo gas); *w* – the walls of the tuyere; *p* – constant pressure; *i* – the level of the expiration of the gas suspension; 01 - isentropic gas diddusion.

The intensity of heat exchange of carrier medium with the wall of the channel was determined by the equation

$$Q_w=4St\rho_{12}c_pw_{12}\left(T_w-T_1\right)/D \qquad (4)$$

where the Stanton's criterion $St=Nu/(\mathrm{Re}\,\mathrm{Pr})$ for high-speed subsonic flows was calculated by the Gukhman's formula

$$St=0{,}0167\left(\mathrm{Re}_{12}\,\mathrm{Pr}_{12}\right)^{-0{,}18}\left(T_{01}/T_w\right)^{0{,}35},\ T_{01}\approx T_1$$

(5)

The calculation were conducted under the condition that the pipe wall temperature t_w was set and throughout the length *l* of the tuyere it remained constant. Naturally, the temperature of the gas suspension t_{12} along the length *l* of non-water-cooled body of tuyere grows. This temperature was calculated in the work.

Force F_w, characterizing friction against the wall during the flow of a gas suspension in the tube was determined according to the formula of Darcy-Weisbach [5]

$$F_w=\zeta_{12}\rho_{12}w_{12}^2/(2D)=\zeta_{12}G_{12}w_{12}/(2D)\,;$$

$$\zeta_{12}=\zeta_1+\zeta_2\,. \qquad (6)$$

The coefficient of hydraulic losses ζ_1, taking into account the friction of gas against the walls of the channel, was calculated with the help of Altshul's formula

$$\zeta_1=0{,}11\left(\Delta/D+68/\mathrm{Re}_{12}\right)^{0{,}5}$$

$$\mathrm{Re}_{12}=Dw_{12}\rho_1/\eta\,, \qquad (7)$$

where Δ – height of roughness, m; *D* – diameter of the pipe, m; ρ_1 –density of the carrier gas, kg / m^3; η – coefficient of dynamic viscosity of the gas - carrier, Pa·s.

To find the coefficient of hydraulic losses ζ_2, conditioned by dispersed phase, the best results are obtained with the help of Mihaelidisa's formula [6], where the calculation is carried out through the Froude number

$$\zeta_2=K\mu/Fr_{12}^{0{,}5}\,,$$

$$Fr_{12}=w_{12}^2/(gD)\,. \qquad (8)$$

Empirical loss factor of Mihaelidisa *K* depends on the material of the particles and wall. In [6] there represented the results of experiment (~ 600 tests) and there found the values of the coefficient *K* for steel pipes, which depending on the lubricity of the material (glass, carbon, etc..) varies within the limits of *K* = 0,041 – 0,194. For the system "steel pipe - carbon powder" *K* = 0.058.

While solving the system of equations (3) – (5) there were set the boundary conditions: in input of the tuyere (x = 0) –costs of both phases $G_{12}=G_1+G_2$, the temperature of T_{01}; in the output (x = l) – backpressure $p_{o.c}$.

Original data. A numerical experiment was conducted in relation to gunning tuyere of 160 t converter of «Mariupol Ilyich». Calculations were performed according to the following initial data: internal hydraulic diameter of gunning tuyere tube *D* = 98 mm, length of tuyere located in the high temperature region *l* = 12 m, the flow rate of the carrier gas (N_2) was V_n = 480 m^3/min, powder consumption varied in the range of m_2 = 200 – 800 kg/min, to which mass concentration μ = m_2 / ($\rho_n V_n$) = 40 – 80 kg /kg (except fig. 2 – 4) corresponded. It was taken that the specific heat of the particles c_2 = 0,8 kJ / (kg · K), equivalent particle diameter and their density were equal to δ_2 = 0,05 mm, ρ_2 = 1900 kg /m^3, the number of nozzles on the same level *n* = 2, the number of levels z_1 = 3, the inner nozzle diameter D_0 = 39mm, the distance up to the upper level of the nozzles l_1 = 1,5 m, equivalent roughness of the tuyere tube Δ= 0,06 mm, Mihaelidisa's loss coefficient *K* = 0,058, end portion of the tuyere coefficient ζ_k = 0,4. If the housing is water-cooled, the wall temperature of the tuyere was assumed to be t_w = 30°C, and the temperature of the dust and gas flow in the input t_{01} = 27°C. Number of calculated nodes is N_l = 600. If the housing of shotcrete – tuyere is gas cooled, i.e. it serves as a heat exchanger, then the intense heat transfer from the hot flame cavity of converter to gas-dispersed flow through the partition wall of the tuyere itself with set temperature t_w of housing takes place. In this paper, heat transfer between the high-temperature gas of cavity vessel and the outer wall of the tuyere body was not calculated, but it was taken as t_w = 30 – 700°C.

The results of calculation and analysis. Using the above mentioned methodology let us show the influence of the determining factors, including difficult-to-forecast ones, on the example of flow with heat supply to the gas suspension (fuel-refractory powder + nitrogen) in gunning tuyere of 160 t converter.

The length l of the tuyere. From the figure 2, it follows that with increase of the temperature t_w *of the* wall gas suspension is intensely heated, its density ρ_{12} falls. Since there is an additional pseudo-heating, the so-called thermal resistance, for the overcoming of which it is required higher pressure. For example, increase of the temperature t_w from 30°C to 700°C leads to the necessity of increase of pressure p in the input into the tuyere from 0.46 MPa to 0.82 MPa.

Confirmation of the correctness of calculations with application of mathematical model are the results shown in the figure 2. So, if the tuyere is made with multiple layers of discharge for flow rate of gas suspension, then the parameters in the nozzle block with several horizons of powder output will not obey the known laws for the case of constant-flow m_{12}. For example, when t_w = 700°C, in the area of the entrance (l = 0) to l = 10,3 m gas-dispersed mixture accelerates, and then in the area l = 10,3 – 12 m, there is a sharp decrease of maximum speed – 64,4 m/s to 44,7 m/s and at the second level which is spaced from the previous one in 61 mm, the rate falls from 48 m/s to 12.1 m/s, etc. (figure 2). If the temperature of the wall decreases t_w up to 30°C, the drop in velocity occurs from only 29,2 m/s to 18,4 m/s.

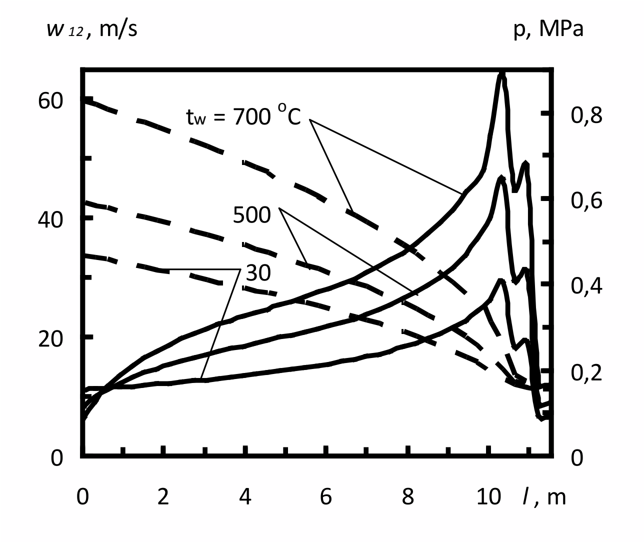

Figure 2. Influence of temperature t_w of pipe wall on the distribution of velocity w_{12} (—) and the static pressure p (- -) of gas suspension along the length l of gunning tuyere with three levels of consumption.

Calculated data: D = 98 mm, l = 12, m, δ = 0,05 mm, ρ_2 = 1900 kg / m^3, m_2 = 400 kg / min, V_n = 480 m^3/h, z = 3, n = 2, μ = 40 kg / kg, D_0 = 39 mm, h = 0,058, Δ = 0,06 mm.

This is the value of the model. Any integral calculation methods, e.g., with usage of Bernoulli's equation, would not allow to fix a sharp decrease in the rate of the gas suspension w_{12} through the output of its side on the 2 – 3 levels (fig.2, 3).

For the tuyere with variable flow the most interisting processes flow in its end part, where gas suspension is outputted on several horizons. In contrast to the values given in the figure 2, let us consider the nature of the flow on the length of the tuyere l = 8,5 – 12 m, which could be represented in a more detailed form at the previous sections.

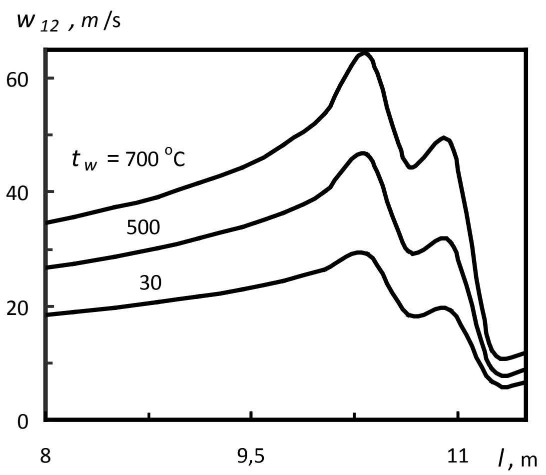

Figure 3. Changing of the speed w_{12} along the length l of the pipe with variable flow of powder m_2 on 3 levels at different temperatures t_w of gunning tuyere wall.

Calculated data: D = 98 mm, l = 12, m, δ = 0,05 mm, ρ_2 = 1900 kg/m^3, m_2 = 400 kg/min, V_n = 480 m^3/h, z = 3, n = 2, μ = 40 kg / kg, D_0 = 39 mm, h = 0,058, Δ = 0,06 mm.

From the figure 3 it is clear that the heating of gas suspension changes the flow pattern of gas-powder flow in the tuyere. Thus, increase of the temperature of wall from t_w = 30°C to t_w =700°C due to a significant increase of thermal resistance to the flow of pressure p. Under these conditions, for example, before the first level of output of flow rate (l = 10,3 m) w_{12} pseudogas speed increases from 26 m/s at t_w = 30° C to 65 m/s at t_w = 700°C. This rate increase, on the one hand, is conditioned by action of the law of circulation effects – with heating subsonic flow is accelerated, and on the other – corresponds to the continuity equation $m_{12} = \rho_{12} w_{12} f$ = const, when ρ_{12} is reduced, and the area f = const, then the velocity of the gas suspension w_{12} grows.

Let us consider how the parameters are changed in one, the most typical control section of the lance – in front of a nozzle unit (l = 10,3 m) (figure 4 – 6).

Equivalent diameter of δ particles. Influence of size of δ powder on the distribution of thermogasdynamic parameters during flow of gas suspension in gunning tuyere. From figure the 4 one may see that with increase of δ speed w_{12} increases. For example, if the tuyere housing wall is heated to t_w = 700°C, then the increase of δ in 10 times with 0,01 mm to 0,1 mm, the rate w_{12} increases almost twice from 46 m/s to 91 m/s. This is explained by the fact that if m_2 = const, μ = const with increasing of δ, for example, 10 times, interfacial surface friction decreases 100 times!

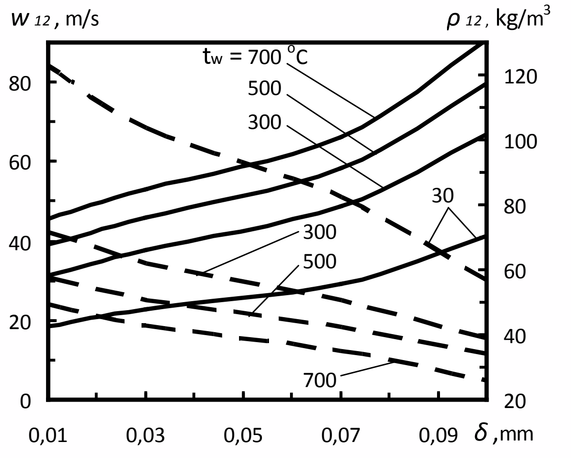

Figure 4. Change of the speed of gas suspension w_{12} and its density ρ_{12} depending on the diameter δ of the powder particles at a different temperatures t_w of housing wall of gunning tuyere.

Calculated data: D = 98 mm, l = 10,3 m, ρ_2 = 1900 kg /m^3, m_2 = 400 kg /min, V_n = 480 m^3/h, z = 3, n = 2, μ = 40 kg/kg, D_0 = 39 mm, h = 0,058, Δ = 0,06 mm.

At one and the same diameter δ temperature increase t_w leads to acceleration of the flow. Thus, when δ = 0,07 mm and wall temperature t_w increase from 30°C to 700 °C, flow accelerates from w_{12} = 30 m/s to w_{12} = 65 m/s and the density of the gas suspension ρ_{12} thus reduces from 82 kg/m^3 to 34 kg/m^3. This follows from the equation of condition for the pseudogas $\rho_{12} = (p_1/RT_1)(1+\mu)$ – the higher $t_1 = t_{12}$ of carrier gas, the lower the ρ_{12}.

The concentration of gunning mass μ. From the figure 5 it follows that with increase of concentration of the powder μ, pressure p of gas suspension in front of the tuyere grows at any temperature t_w. Thus, when t_w = 500°C, increase of μ from 20 kg/kg to 70 kg/kg leads to increase of pressure in front of the tuyere p from 0,41 MPa to 0,71 MPa. At the same time with heating of the gas suspension the pressure in the input into the tuyere increases substantially at any μ. For example, when μ = 70 kg/kg with increasing t_w from 30°C to 700°C the pressure p in the input into the tuyere increases from 0,58 MPa to 0,9 MPa.

From the figure 5 it is seen that with increase of μ, volume fraction of gas phase ε_1 reduces at any wall temperature t_w. For example, if t_w = 700 ° C, then μ increases

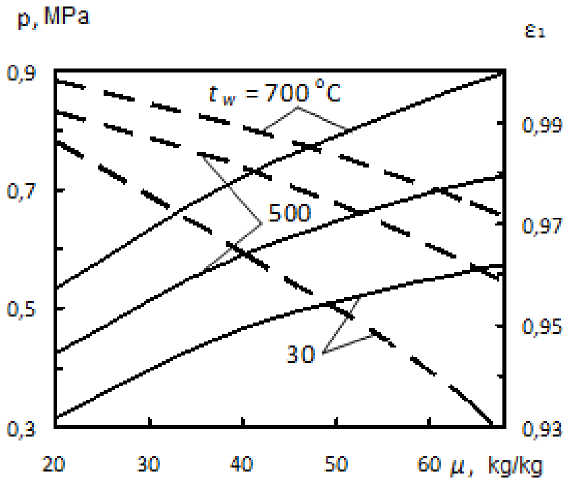

Figure 5. Influence of wall temperature t_w and concentration μ of powder on the change of pressure p (—) in front of the tuyere, (l = 0) and volume concentration ε_1 (- -) in front of the nozzle array (l = 10,3 m).

Calculated data: D = 98 mm, l = 12, m, δ = 0,05 mm, ρ_2 = 1900 kg/m3, m_2 = 200 - 800 kg/min, V_n = 480 m^3/h, z = 3, n = 2 , μ = 20 - 80 kg/kg, D_0 = 39 mm, K = 0,058, Δ = 0,06mm.

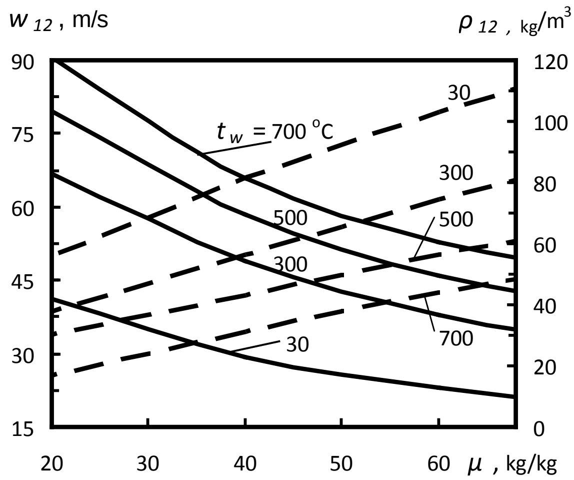

Figure 6. The influence of mass concentration μ of powder on the change rate w_{12} (—) of gas suspension and its density ρ_{12} (- -) before the first level of flow m_{12} (l = 10,3 m) at different temperatures t_w tuyere wall.

Calculated data: D = 98 mm, l = 10,3 m, δ = 0,05 mm, ρ_2 = 1900 kg/m^3, m_2 = 400 kg /min, V_n = 240 - 960 m^3/h, z = 3, n = 2, μ = 20 - 80 kg / kg, D_0 = 39 mm, h = 0,058, Δ = 0,06 mm.

from 20 kg/kg to 70 kg/kg, gas phase volume fraction ε_1 decreases from 0,999 to 0,97. This is due to the fact that, as follows from the equation $\varepsilon_1 = \left(1 + \frac{\mu}{\psi}\frac{\rho_1}{\rho_2}\right)^{-1}$ with increase of μ and all other equal conditions, the ratio ε_1 only reduces.

Peculiarity of the flow, which is discussed below – use the so-called second method of controlling the concentration of the gas suspension μ, in which the powder flow rate remained constant (m_2 = 400 kg/min), and the carrier gas flow rate varied within the range of V_n = 240 – 960 m^3/h (μ = 20 – 80 kg/kg).

From the figure 6 it is seen that the velocity of the gas suspension w_{12} with the increase of concentrations μ decreases at any temperature t_w of housing wall of tuyeres. For example, increase of μ from 20 kg/kg to 70 kg/kg at t_w = 500°C leads to speed reduction w_{12} from 80 m/s to 40 m/s. As follows from the conditions for pseudogas $\rho_{12} = \rho_1(1+\mu)$ – at the same temperature t_{12} the greater μ, the higher ρ_{12}. Thus, if μ increases from 20 kg/kg to 70 kg/kg, then at t_w = 700°C, density ρ_{12} is increased from 61 kg/kg to 112 kg/kg. If, for example, μ = 50 kg/kg t_w temperature increases from 30°C to 700°C, then ρ_{12} falls from 95 kg/m^3 to 40 kg/m^3.

Note once again that shown in the fig. 2 – 6 results were obtained by numerical solution of differential and algebraic equations (1 – 12), which allows to gain an insight into the considered problem.

Checking the results of numerical studies. As it is difficult to conduct physical experiment in the tuyere, which is in the cavity of the converter, let us check the correctness of the numerical calculations using the method of testing. Thus, if:

- Gas carrier is heated, its density ρ_1 reduces, and hence it is required higher pressure p to provide the same flow rate (m_{12} = const) of a less dense gas through a pipe of constant cross section (f = const) (figure 2, 5);
- Gas carrier is heated, according to the law of circulation effects of subsonic flow (our case) in a tube of constant

cross section at m_{12} = const only accelerates (figure 2 – 4, 6);

- Along the pipe mixture flow m_{12} on each of three levels decreases, from the continuity equation for the mixture follows that the rate of flow of gas suspension along the length *l* of tuyere pipe should be reduced, rather than increased, as it was till the first level of output flow (see fig. 2, 3);
- Diameter δ of powder increases, then at m_2 = const, the flow accelerates due to reduction of the number of particles in gas suspension (see fig. 4), which is obvious.

Test analysis showed that obtained gas-dispersed flow patterns in the gunning tuyere correspond to the well-studied laws of motion of gas-powder flow in pipes, and the results of given studies are representative.

Further in the tuyere with variable flow it should considered the movement of two-speed gas-powder flow.

Conclusions

1. Used differential equations of motion and energy are highly information – they allow to consider threshold character both of gas suspension flow and heat transfer in several tuyere horizons with variable flow.
1. 2 If the body of gunning tuyere serves as a heat exchanger, the energy potential of gas-powder flow before nozzle unit of gunning tuyere significantly increases, aerodynamic characteristics of gaspowder torch are improved, and the absence of moving with tuyere flexible hoses for supply and discharge of cooling water simplifies the design of the blast unit.
2. To prevent the reduction of energy of compressed gas powder flow before nozzle unit, tuyere tube must be of stepwise form reducing cross section with decreasing of flow rate.

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