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BASIC REGULARITIES OF EJECTION AIR BY FLOW OF FREELY FALLING PARTICLES

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Abstract. Entrained air (ejection process) by flow of freely falling particles of the bulk material is considered by us from the position of the classical laws of dynamics of two-component streams "particulate matter - the air." The nature of this process is determined by the volumetric intercomponent interaction, detected as a result of excessive speed over the speed of the incident particles of ejected air. The research is being supported by the Council for Grants of the President of the Russian Federation (projects NSH-588.2012.8), RFBR (project number 12-08-97500-p_center_a), and Strategic Development Plan of BSTU named after. V. G. Shukhov.

1 INTRODUCTION

Minimizing the output of suction hoods it becomes possible to decrease the volumes of suction emissions and significantly reduce the power consumption of ventilation units.

In order to implement the effective control of air suction process it is required to explain the mechanism of intercomponent interaction and the regularities of formation of directed air flows in a stream of particles in various initial conditions of the stream generation (Fig. 1.). The geometric parameters of the bombarding particles stream are influenced by the consumption (G_M), initial velocity (υ_{init}), fineness (d), humidity (W) and self-adhesion properties of the material particles (σ_{self}). These factors defined the stream behavior and structure: bombarding velocity of particles (υ), cross-sectional area (R) and particle distribution (β).

The dynamic interaction is subject to an individual peculiarity of the aerodynamic resistance of bombarding particles (arbp), that is, a unit particle resistance coefficient (ψ_0), and to the common peculiarity of the arbp when bombarding collectively in the material stream, that is, a reduced particle resistance coefficient (ψ^*).The distance of non-permeable walls from the flow axis (r_0) creates various air leakage conditions and facilitates or complicates the suction process. In lack of any enclosure ($r_0 \to \infty$), the air suction is represented by a free flow of particles. In this case, an accelerated flow stream of induced air occurs in the stream. At the approach of the enclosure walls to the stream the air leakage conditions deteriorate and there may an upward stream (circulating stream) occur in addition to the downward air stream. When $r_0<R$ particles are falling down to the chute and there is a uniform movement of the induced air formed in the uniform section chute.

In practice, a free jet may be observed when pouring particles from the above-stack gallery (Fig. 2) and the most common case of transfer by chutes has combined leakage conditions in general. There are favourable air leakage conditions at the receiving funnel inlet: first, the induced air jet is formed (accelerated suction area), then, at the entry of particles into the straight portion of the small section chute ($r_0 < R$), a uniform flow of the induced air occurs (constant suction area).

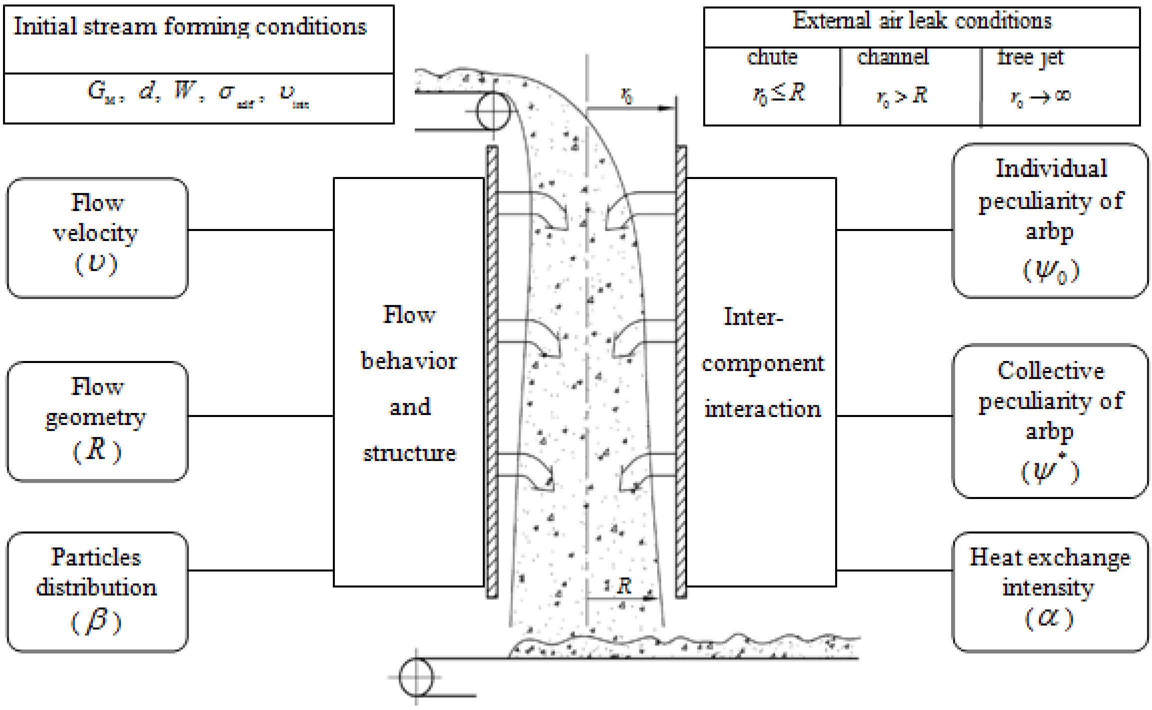

Figure 1: Qualitative structure and key factors defining the process of air suction with a stream of bombarding particles

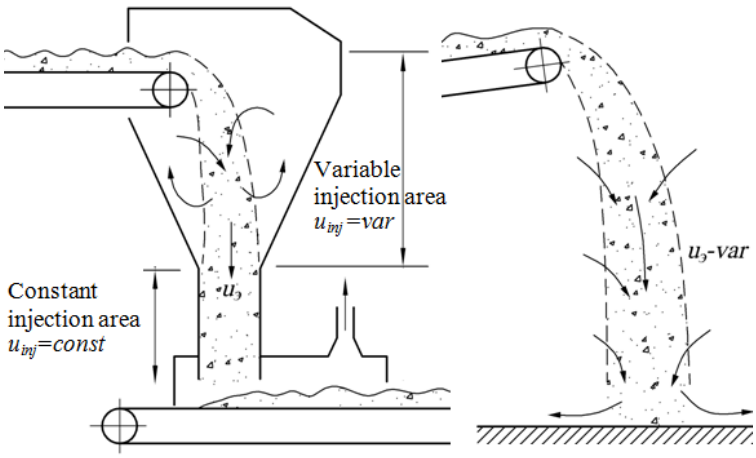

Figure 2: Typical bulk material transfer schemes (the upper scheme illustrates chute transfer; the lower scheme illustrates the free sedimentation)

The large-scale implementation of sintering processes and pelletizing of iron-ore concentrates set a new challenge for the researchers: determine suction properties of a hot stream of particles. On having taken this challenge we had to replace the energy theory model with a more demonstrative dynamic approach that treats movement of air in a chute as the result of forces that we call induction and thermal heads. The first one accounts for a sum of aerodynamic forces of particles currently present in a chute while the second one accounts for buoyancy forces that affect the air heated in the chute in the result of the intercomponent heat exchange. The dynamic theory development enabled both to solve the problem concerning the suction of air with heated particles and to explain many experimental facts: reverse air flow ("anti-suction") in a chute when pouring unheated sand, pressure surges when starting and ending to fill a pressurized vessel with a bulk material [1].

Table 1: Basis stages of studies of solid stream suction properties

Effects, regularities	*Methods, notions*	*Authors*
Experimental estimates		
Air movement in a vertical pipe when pouring sand (suction). Reverse air flow when sand is moving in a chute	Inclined velocity of particles considered $u_э = 0,48 v_k$ Velocity and flow rate of particles as well as the chute cross-section considered All key factors considered	M.K. Altmark. (1941) A.S. Serenko (1953), M.T. Kamyshenko (1955), A.V. Sheleketin (1959), E.N.Boshnyakov (1965), Degner and Futterer (1969)
Mathematical models		
A. Energy theory (based on the equation of the law of variation of kinetic energy of a stream of particles)		
Reduction in volume of the induced air with increase in the material flow rate	Subject to the analysis of the variation of kinetic energy of the uniformly accelerated stream of particles, there was an analytical relation obtained with the aim of determining the induced air flow rate. The same as for powder material, "particle packet" and "nominal diameter" notions were introduced.	S.E. Butakov (1949), O.D. Neykov (1965), V.A. Minko (1969)
B. Dynamic theory (based on the equation of variation of momentum of "solid particles-air" double speed continuum)		
Inhibiting effect on the volume of induced air of a stream of particles at the chute inlet. Reverse air flow in a chute when transferring particles at a high temperature (induction inversion).	There was the dynamic equation of the uniform air flow in a chute accounting bulk forces of the dynamic and thermal interaction of components. The induction head notion was introduced.	I.N. Logachev (1969)

The diversity of factors defining the suction process and a complex mechanism of particles motion as well as the interaction of particles with air predetermined a long history of studies of solid stream suction properties (Table 1.): from an experimental evaluation of that effect in some single conditions of its occurrence to the building and development of mathematical models, initially the simplest ones (an energy theory for uniformly accelerated stream of equidimensional particles in a vertical chute of uniform cross-section), and then more complex models based on classical equations of the multicomponent stream mechanics.

2 AIR INJECTION IN CHUTES

Let us consider a steady isothermal motion of a stream of material particles and air in a straight chute of the uniform cross-section area $S_{жс}$. To this effect, at x distance to the chute inlet (Fig.3) we select a unit prism of Δx length which lateral faces are the chute walls. The origin of coordinates is placed in the entry section; X-axis is directed along the chute centerline towards the bulk material particles motion. With neglect of pulsation instants the obvious equations for mass flow rates of components will look as:

$$G_1 = \int_{S_{жс}} \beta_1 \rho_1 v_1 dS \,, \tag{1}$$

$$G_2 = \int_{S_{жс}} \beta_2 \rho_2 v_2 dS \,. \tag{2}$$

The momentum conservation equation for the material and air confined in the selected element $\Delta x S_{жс} = \Delta V_{жс}$ projected on the chute centerline will look as follows:

$$\Delta\left(\int_{S_{жс}} \beta_1 \rho_1 v_1 v_1 dS \right) = \int_{\Delta V_{жс}} M_1 \beta_1 \rho_1 dV - \int_{\Delta V_{жс}} \frac{\beta_1}{V_ч} R dV \,, \tag{3}$$

$$\Delta\left(\int_{S_{жс}} \beta_2 \rho_2 v_2 v_2 dS \right) = \int_{\Delta V_{жс}} M_2 \beta_2 \rho_2 dV + \int_{S_{\Delta V_{жс}}} \beta_2 \Pi_2 dS + \int_{\Delta V_{жс}} \frac{\beta_1}{V_ч} R dV \,, \tag{4}$$

where $S_{\Delta V_{жс}}$ is the selected element surface $\Delta V_{жс}$; Π_2 is OX-projection of surface forces.

A one-dimensional problem is formulated by substituting the current velocities, bulk concentrations and aerodynamic interaction forces in equations (3) and (4) for the corresponding averaged values.

Herewith the momentum conservation equations will become differential as follows

$$G_1 \frac{d\bar{v}_1}{dx} = \bar{\beta}_1 \rho_1 a_T S_{жс} - \frac{\bar{\beta}_1}{V_ч} \cdot \bar{R} \cdot S_{жс} \,, \tag{5}$$

$$G_2 \frac{d\bar{v}_2}{dx} = \bar{\beta}_2 (\rho_2 - \rho_0) g_x S_{жс} - \bar{\beta}_2 S_{жс} \frac{dP}{dx} - \bar{\beta}_2 \frac{\lambda}{D} \cdot \frac{(\bar{v}_2)^2}{2} \rho_2 S_{жс} + \frac{\bar{\beta}_1}{V_ч} \cdot \bar{R} \cdot S_{жс} \,, \tag{6}$$

Henceforth, the sign of averaging (a hyphen above a value) shall be omitted for the sake of convenience and unless otherwise indicated v_1, v_2, β_1, R are purportedly averaged values.

An averaged velocity and bulk concentration are easily determined from flow equations (1) and (2): $\beta_1 = G_1 / (\rho_1 v_1 S_{жс})$; $v_2 = G_2 / ((1-\beta_1) \rho_2 S_{жс})$.

The third term in the right-hand side of equation (6) was entered on the assumption that $\tau_{cn} = \text{const}$, and then $\beta_2 \tau_{cm} \Pi dx = \beta_2 \dfrac{\lambda}{D} \dfrac{v_2^2}{2} \rho_2 \cdot S_{ж}$, where λ is an aerodynamic drag factor for the chute walls; D is the chute hydraulic diameter: $D = 4S_{ж} / \Pi$.

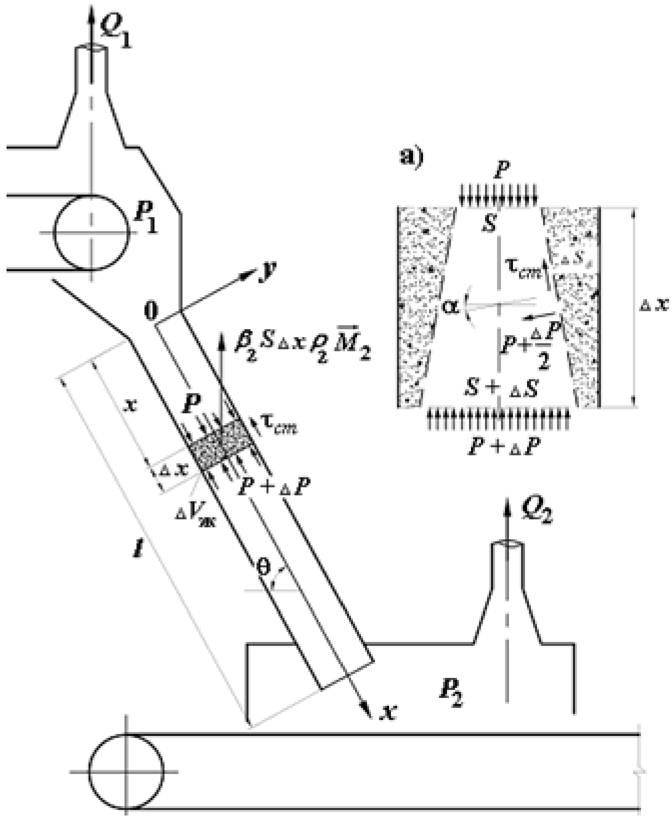

Figure 3: To derivation of dynamic equations of a one-dimensional stream of particles in a tip chute (a represents a conventional diagram of a bulk material flow and vectors of surface forces)

In physical terms a one-dimensional problem thus formulated corresponds to the ca se of a uniform distribution of particles throughout the section. It will be further demonstrated that the solution of one-dimensional equation (5) quite well describes the air injection process for the pseudo-uniform distribution either. An experimental evaluation of a one-dimensional stream and clarification of some of its parameters was performed on the experimental arrangement intended for determination of injective properties of bulk materials (Fig. 4). The principal element of that bench is a chute with a suspended “ceiling” that allows for altering the chute cross-section. The upper bin with a diaphragm ensured the material flow at the specified rate. A sealed bin with a discharge damper was used to receive the supplied material.

The arrangement structure allowed for altering the cross-section height and the chute inclination angle as well as the transfer height. For this purpose the arrangement was mounted on a sectional metal frame. The test section of the arrangement consisted of Venturi tubes installed on air ducts. Air intake or injection to the lower bin was performed with the fan.

The average aerodynamic characteristic of particles is determined from the equation $\beta_1 \Delta V_{ж} \psi^* f_M |v_1 - v_2|(v_1 - v_2)\rho_2 / (2V)_ч = \int\limits_{\Delta V_{ж}} \beta_1 / V_ч R dV$, that defined the meaning of the averaging operation consisted in the substitution of a sum of the aerodynamic forces of particles within the selected chute section for the product of the number of particles and the averaged aerodynamic force. The aerodynamic drag factor ψ^* is determined using the pressure measuring method described above.

Let us refer to the experiment. With the chute outlet pressure measured ψ^* coefficient can be easily determined from formula $\psi^* = P_к \Big/ \left(\kappa_m \varepsilon \left(v_{1к}^3 - v_{1н}^3\right) G_1 / (3S_ж a_T)\right)$, where $P_к$ is an excessive pressure at the chute outlet, Pa.

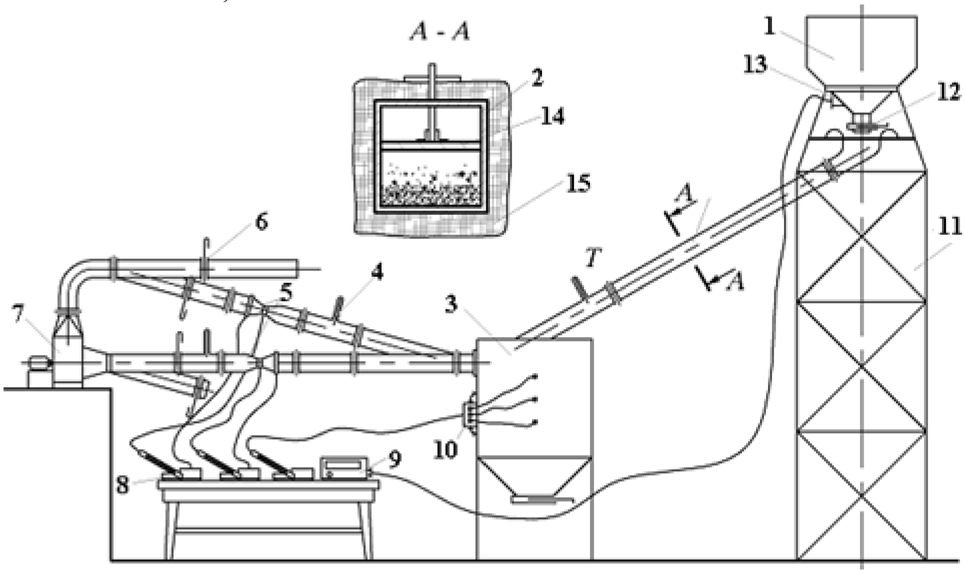

Figure 4: Diagram of the experimental arrangement for the study of injective properties of bulk materials:
1 – upper bin; 2 – chute; 3 – lower bin; 4 – thermometer; 5 – Venturi tube; 6 – damper; 7 – fan; 8 – micropressure gauge; 9 – galvanometer; 10 – blending chamber; 11 – metal frame; 12 – diaphragm; 13 – thermocouple; 14 – chute upper wall; 15 – heat insulation layer

The experiments were conducted with an open entry section of the chute ($P_0 = 0$) and the sealed lower bin. Since no air was removed from the bin ($u_{cp} = 0$) the pressure in the chute outlet section is equal to the bin pressure. An averaged value of the latter was taken for the design value. As it was demonstrated by numerous experiments with various materials and transfer parameters the drag factor is inversely related to the bulk concentration. The following relation was obtained after processing the experimental data

$$1/E^2 = \psi^* / \psi_0 = \exp\left[-1{,}8\sqrt{\beta \cdot 10^3} \Big/ (d_э \cdot 10^3)\right], \tag{7}$$

$$\beta = 2G_1 / \left(S_ж \rho_1 v_{1к}(1+n)\right), \quad n = v_{1н} / v_{1к}, \tag{8}$$

that allows for calculating the averaged drag factor of monofractional material particles within $0.5 < d_э < 20$ mm; $10^{-4} < \beta < 10^{-2}$.Conditions of a polyfractional material stream typically lead to the necessity of determining the mean diameter of particles: $d = \sum_{j=1}^{M} m_j d_j$.

The resulting value of averaged coefficient ψ^* allows for estimating the chute power characteristic in full and analyzing the aerodynamic effects occurring in motion of a bulk material in closed straight tubes (chutes). For this purpose we use equations (5) and (6) which, given that $S_{ж} = const$, will be rewritten as follows

$$\beta_1\rho_1 v_1 \frac{dv_1}{dx} = \beta_1\rho_1 a_T - \psi^*\beta_1\kappa_m \frac{|v_1 - v_2|(v_1 - v_2)}{2}\rho_2 , \tag{9}$$

$$(1-\beta_1)\,\rho_2 v_2 \frac{dv_2}{dx} = (1-\beta_1)(\rho_2 - \rho_0)g_x - (1-\beta_1)\frac{dP}{dx} - \lambda\frac{1-\beta_1}{D}\frac{v_2^2}{2}\rho_2 + \psi^*\beta_1\kappa_m \frac{|v_1 - v_2|(v_1 - v_2)}{2}\rho_2. \tag{10}$$

On having determined the force behavior in the chute and the main element defining that behavior, i.e. the induction head,

$$P_{э_x} = \left(\psi^*\kappa_m\varepsilon G_1/(2a_T S_{ж})\right)\left(|v_1 - v_2|^3 - |v_{1н} - v_2|^3\right)/3 , \tag{11}$$

it is possible to calculate the induced air velocity. Having integrated the dynamic equation

$$dp = -\lambda|v_2|v_2\rho_2 dx/(2D) + dP_{э_x} \tag{12}$$

in the boundary conditions

$$P(0) = P_a - \zeta_н |v_2| v_2\rho_2/2 ; \quad P(l) = P_a + \zeta_k |v_2| v_2\rho_2/2 , \tag{13}$$

we obtain

$$\sum\zeta\rho_2 v_2^2/2 = P_Э \equiv \psi^*\kappa_m\varepsilon(G_1/2a_T S_{ж})\left(|v_{1k} - v_2|^3 - |v_{1н} - v_2|^3\right)/3 , \tag{14}$$

where $v_{1H},\ v_{1k}$ are the material velocities at the chute inlet and outlet, m/s; P_a is the chute outside pressure, Pa; $\zeta_н$, $\zeta_к$ are the local drag factors at the chute inlet and outlet respectively; $\sum\zeta$ is a sum of local drag factors.

As is clear from equation (14), the finite value of $\sum\zeta$ always results in a directional air flow in a chute. The flow direction coincides with the bulk material stream direction. For the sake of convenience of the further analysis transform equation (14) into a dimensionless form

$$\frac{\varphi_k^2}{|1-\varphi_k|^3 - |n-\varphi_k|^3} = \frac{\psi^*\kappa_m G_1 v_{1k}}{\sum\zeta\cdot 3a_T S_{ж}\rho_1} \equiv \frac{Bu}{3}, \quad \varphi_k \equiv \frac{v_2}{v_{1k}}, \quad n = \frac{v_{1H}}{v_{1k}} . \tag{15}$$

The tripled right-hand side of the equation is the Butakov-Neykov criterion $Bu = \psi^*\kappa_m G_1 v_{1k}/\left(a_T S_{ж}\rho_1\sum\zeta\right)$.

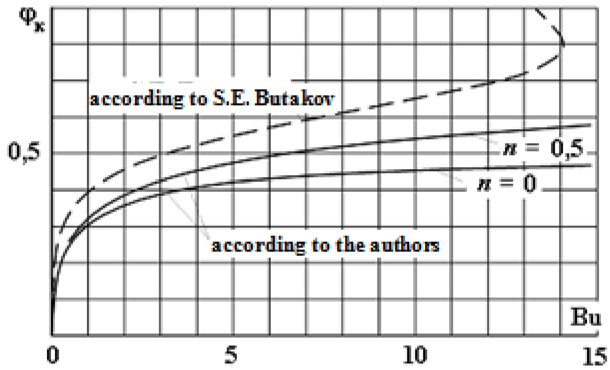

Figure 5: Relation of $\varphi_к$ to Bu. The solid lines are graphs of equation (15)

Analyzing the result is may be noted that the induced air quantity $Q_Э = \varphi_k v_{1k} S_ж$ is increase with the increase in the material flow rate and decrease in size of its particles which agrees satisfactorily with the experimental data, $\varphi_к$ is also significantly influenced by the hydraulic resistance of the chute and the material stream velocity.

Fig. 5 shows the graphs of equation (12) which are indicative of an asymptotic nature of variation in φ_k. The area $Bu > 3$ may be called the self-similarity area. Here φ_k virtually remains unchanged being close to the asymptotic value $\varphi_k = (1+n)/2$. This is explained by the deceleration area at the chute inlet where $v_2 > v_1$ and particles have a decelerating effect on the moving air instead of inducing effect.

This condition was not considered, for instance, in the efforts by the Professor S.E. Butakov who was the first to have analytically studied an inducing effect of a bulk material stream in chutes [2].

The obtained results of the analysis of dynamic equations for a one-dimensional stream correlate very accurately with the experimental data in qualitative as well as in quantitative terms. We verified it both estimating the chute forces and comparing the induced air volumes. Fig.6 shows the results of comparison of extensive experimental data with the estimated data obtained from formula (12) as well as comparisons with the findings of other authors who studied the suction process. The graphs of $\varphi_к$ relations to Bu were plotted at $\sum\zeta = 1{,}5$ according to Hemeon [3]; at $\sqrt[3]{E_Э} = 0{,}4$ according to Hatch [4]; at $\sum\zeta = 1{,}5$; $\rho_1 = 3000$ kg/m^3; $F_H^в = 0{,}2$ м^2; $S_{жс}$ = 0,5 m^2 according to Dennis and Andersen [5]; at $\kappa^3 = 0{,}18$ according to Graschenkov and co-authors [6]; at $\sum\zeta = 1{,}5$; $\rho = 0{,}3$ according to Bagaevskiy and Bakirov [7]; at $d_{cp} = 10$ mm according to Olifer [8].

The experimental data of A.V. Sheleketin [9] for quartzite d = 3-5 mm, M.T. Kamyshenko [10] for granite d = 22 mm and iron ore d = 5.6 mm, E.N. Boshnyakov [11] for iron ore as well as our experimental data correlate very accurately with the theoretical findings concerning a one-dimensional stream. An accurate correlation with the experimental data is also obtained using formulas of V.D. Olifer in $Bu < 1$ and $d \sim 10$ mm and formulas of Graschenkov and co-authors in $Bu > 1$ at introduction of a correction factor $\kappa^3 = 0{,}18$.

Dependences of V. Hemeon, P.I. Kilin and O.A. Bagaevskiy and U.Kh. Bakirov yield the highest deviations.

The induced air pressured is increased affected by the vacuum-gage pressure that occurs in the lower section of the chute due to the local exhaust operation. Indeed, if integrating equation (12) the second boundary condition (13) is substituted for the following relation $P(l) = P_a + \zeta_k v_2^2 \rho_2 / 2 - P_2$, where P_2 is the hood vacuum-gauge pressure under cover, we obtain

$$\sum \zeta v_2^2 \rho_2 = 2(P_Э + P_2) \; . \tag{16}$$

On the assumption that the material flow is uniformly accelerated this equation can be easily transformed into the following criterion relation:

$$\varphi_k^2 = \mathrm{Bu}\left[\left|1-\varphi_k\right|^3 - \left|n-\varphi_k\right|^3\right]/3 + \mathrm{Eu} \, , \tag{17}$$

where $\mathrm{Eu} = 2P_2 \big/ \left(v_{1k}^2 \rho_2 \sum \zeta\right)$ is the Euler criterion equal to.

In this case the comparison of the calculated induced air volumes also agrees satisfactorily with the multiple experimental data (Fig.7).

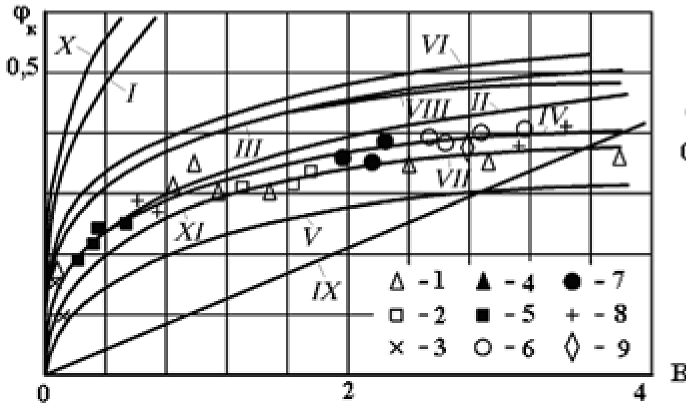

Figure 6: Relation of φ_κ to Bu at n = 0 according to Hemeon (I), Hatch (II), S.E. Butakov (III), authors (IV is by formula (12)), Dennis and Andersen (V), V.A. Minko (VI), N.F. Graschenkov (VII), P.Ch. Chulakov (VIII), O.A. Bagaevskiy and U.Kh. Bakirov (IX), P.I. Kilin (X) and V.D. Olifer (XI); experimental data: 1 is for quartzite, 2,3 is for granite and iron ore, 4 is for iron ore, 5-9 is the authors' data for granite, pellets, agglomerate, charred coal and iron ore respectively

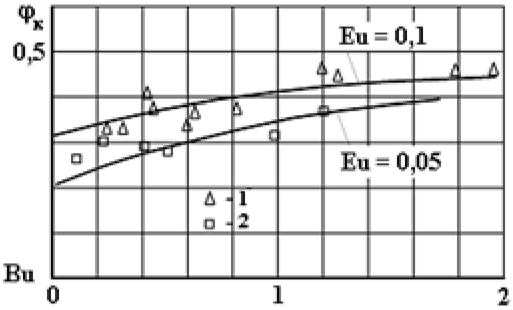

Figure 7:. Relation of φ_κ to Bu and Eu (experimental data: Δ – 1 – at Eu = 0.08-0.12; □ – 2 – at Eu = 0.04-0.06)

3 THE AERODYNAMICS OF A SOLID-PARTICLE JET

Free flows of loose matter comprise the second significant and common class of flows occurring in bulk material handling technology. They are primarily represented by flows of dumped materials in various stockpiling systems. Free flows also occur when open-body railway cars are loaded with concentrate or pellets from feed hoppers. In terms of dynamic interactions between solid matter and air, close approximations of free flows are provided by flows of materials unloaded from rail cars into charging bins of crushers and other equipment.

An equation for the dynamics of such flows can be deduced from general equations describing the mechanics of multi-component flows, ignoring pulsation moments (the latter can be successfully "smoothed out" using experimental coefficients). Concerning ourselves with evaluation of the overall magnitude of values and ignoring minor terms – in a way similar to deducing boundary-layer equations from the general Navier-Stokes equation – we shall end up with the following simultaneous equations for a planar problem:

$$v_{2(1)}\frac{\partial v_{2(1)}}{\partial x_1}+v_{2(2)}\frac{\partial v_{2(2)}}{\partial x_2}=\frac{\beta_1}{\rho_2 V_ч}R(v_{2(1)}-v_{1(1)})-\frac{1}{\rho_2}\frac{\partial P}{\partial x_2}+\nu\frac{\partial^2 v_{2(1)}}{\partial x_2};\quad \frac{\partial v_{2(1)}}{\partial x_1}+\frac{\partial v_{2(2)}}{\partial x_2}=0, \tag{18}$$

These are set apart from the known Prandtl equations for isothermal jet streams by the presence of a volumetric force variable owing to the presence of falling particles in the stream.

The apparent mathematical insignificance of this difference becomes crucial in the physical sense: it is these volumetric forces rather than initial impulse (as would be the case in many problems involving free air jets, for example) that determine the jet flow of air in the class of flows being considered here.

Hence, the following properties are relevant in the physical sense for the two-component free jet in our case. First, the solid component – bulk particulate material – significantly impacts the aerodynamics of boundary layer and is responsible for the formation of this layer as such. Second, owing to the larger mass of particles, the solid component dynamics responsible for the jet flow mode of the gas component remain largely unaffected by airflow, setting this flow mode apart from airflows containing minute solid impurities.

Boundary-layer equations for axially symmetric jets can be expressed as follows:

$$u_x \frac{\partial u_x}{\partial x} + u_r \frac{\partial u_x}{\partial r} = \frac{\beta}{\varepsilon}\left|v-u_x\right|^n (v-u_x) + N_\tau \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_x}{\partial r}\right) - \frac{\partial \mathrm{P}}{\partial x}, \tag{19}$$

$$\frac{\partial \mathrm{P}}{\partial r} = -\frac{\beta}{\varepsilon}\left|v-u_x\right|^n u_r + \frac{\partial}{\partial u_x}\left(N_\tau \frac{\partial u_x}{\partial r}\right). \tag{20}$$

In addition to differential equations, we shall henceforth use an integral relation for changes in the impulse of injected air:

$$\int_0^\infty \frac{\partial u_x^2}{\partial x} r dr = \int_0^\infty \frac{\beta}{\varepsilon}\left(v-u_x\right)^2 r dr - \int_0^\infty \frac{\partial \mathrm{P}}{\partial x} r dr. \tag{21}$$

At smaller viscosity forces air injection is confined within the boundaries of material flow. In this case the longitudinal component of air velocity only sharply changes at the boundary of air current where it becomes virtually equal to zero. Therefore the flow of the injected may be considered devoid of gradient i.e. cross-sectional velocity changes are similar to changes in concentration. For example, consider an axially symmetric jet of radius b with uniformly distributed particles $\beta = \beta_0\gamma(r)/(b^2 v)$, $\beta_0 = G_1/(\pi b^2 \rho_1 v_1)$, where $\gamma(r) = 1$ at $0 \le r \le b$, $\gamma(r) = 0$ at $r > b$. Assuming that air velocity varies similarly to $u_x = \omega(x)\gamma(r)$ let's formulate the one-dimensional problem using the momentum conservation law.

The integral relation (21) could be reduced to the following differential equation, in dimensionless form:

$$u^* du^* / d\upsilon^* = \left(\upsilon^* - u^*\right)^2, \quad u^* = A\omega(x)/c, \quad \upsilon^* = A\upsilon(x)/c, \quad A = G_1/(S\rho_1\varepsilon c). \tag{22}$$

Considering that $u^*/\upsilon^* = \varphi$, the flow rate of injected air can be expressed by means of components' slip ratio $q_Э = \pi b^2 \varphi \upsilon_1$.

Integral curves of the equation (22) become "forgetful" of their initial conditions rather soon, tending toward a "zero-level" integral curve (Fig.8). The equation of the latter may be described with enough accuracy using the equation for inflection points of integral curves: $\upsilon^* = 2\varphi^2 / \left[(1-\varphi)\left(1-\varphi^2\right)\right]$.

A similar situation may be noted in the numerical solution of the equation

$$d\varphi / d\upsilon^* = \left|1-\varphi\right|\left(1-\varphi\right)/\varphi - \varphi/\upsilon^* \tag{23}$$

that results from (22) by replacing $u^* = \varphi\upsilon^*$. Integral curves of the equation rapidly follow the curve passing through coordinate origin (Fig.9). Conspicuously, rapid changes of φ along the "zero-level" curve are confined to short distances from the origin of the jet ($\upsilon^* < 0.1$). Growth of the phase slip ratio consequently slows down, remaining for $\upsilon^* < 3$ within $0{,}4 \div 0{,}6$ (0.5 on average).

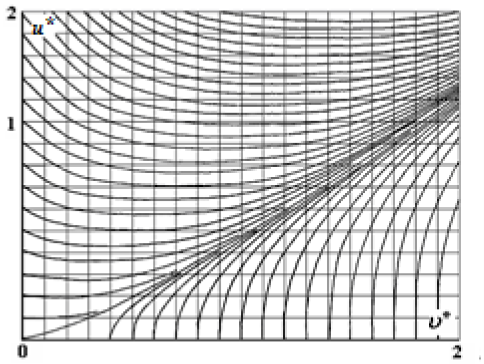

Figure 8: Changes in airflow velocity along the jet of material

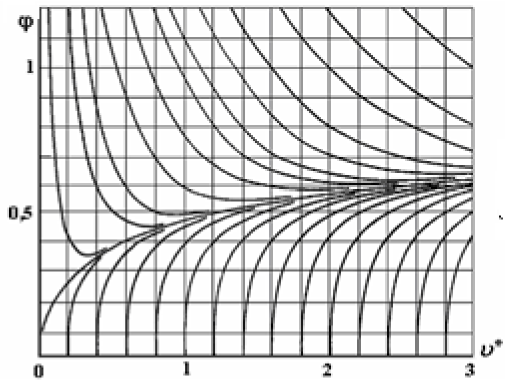

Figure 9: Changes in slip ratios of components along the jet

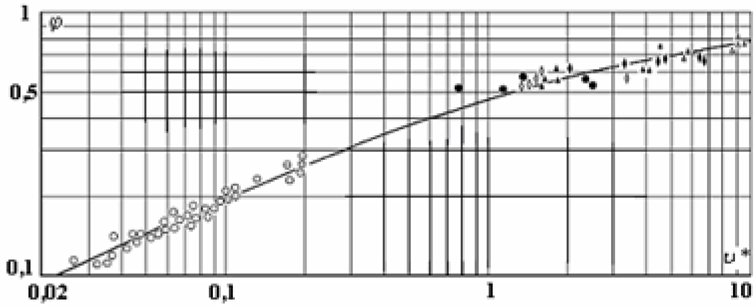

Figure 10: Behaviour of the factor φ along the jet (solid line corresponds to data from (21)): O – water droplets (d=3.4 mm; D_O,=0.8 m; G_1=0.07–0.16 kg/s; H=0.5–3.0 m); Θ – water droplets (d=3 mm; D_O=0.22 m; G_1=0.08–0.14 kg/s; H=1–2.7 m); ● – pellets (d=13.8 mm; D_O=0.8-0.15 m; H=1.5–2,5 m; G_1= 3–19 kg/s); Δ – granite (d=5–10 mm; D_O=0.8–0.1 m; H=1.35–2.5 m; G_1=3.3–5.4 kg/s); ▲ – granite (d=10–20 mm; D_O=0.8–0.15 m; H=1.35–2.5 m; G_1=4.4–23 kg/s); ◊ – iron ore (d=10–20 mm; D_O=0.1–0.15 m; H=1.35–2.5 m; G_1=5.2–18.6 kg/s); ♦– iron ore (d=0.3–20 mm; D_O=0.08–0.15 m; H=1.35–2.5 m; G_1=4.4–23 kg/s)

The zero-level integral curve is described accurately enough by the equation of inflection points

$$\upsilon^* = \varphi^3 / \left((1-\varphi)(1-\varphi^2)\right)\left(1+\sqrt{2/\varphi^2-1}\right), \qquad (23)$$

which tends to yield somewhat higher values although error is moderate, remaining below + 2.4 % at $\upsilon^* \geq 0{,}1$ (and tending toward zero with increasing υ*). A comparison of analytical findings with numerous experimental data published by authors, their disciples and colleagues indicates (Fig.10) that the measured volumes of injected air are in an adequate agreement with calculated values.

4 CONCLUSIONS

Aerodynamically bulk material streams belong to a class of two-component flows in which the carrying medium is a discrete medium of solid particles falling at a growing rate while the carried medium is pseudo-continuous medium of induced air. An accelerated motion of the carrying medium stipulates the asymptotic nature of aerodynamic processes of air induction (Fig.5, 9) which depend on the geometry of transport channels, the stream kinematics, intensity of the dynamic interaction of components, distribution

It was demonstrated that by means of averaging velocities, bulk concentrations and intercomponent interaction forces in the channel section it is possible to formulate a one-dimensional problem concerning the dynamics of a stream of particles (9) and the induced air (10) in closed chutes. The induced air volume is limited at the chute inlet due to a braking effect of a stream of particles. As far as Butakov-Heykov number is growing higher the slip ratio of components (15) is increasing to reach an asymptotic value equal to $\varphi = (1+n)/2$.

It was demonstrated that the dynamics of air flows in a stream of freely-falling particles may be described by the boundary-layer equation where due to a great mass of particles the carrying (solid) component dynamics virtually does not depend on the hydrodynamical field which distinguishes these streams from gas jets carrying solid impurities. The main forces that cause forming of jet flows of air in a stream of freely-falling particles are bulk forces of intercomponent interaction and turbulent viscosity (19) and (20). The intercomponent interaction forces increase the quantity of the inducing jet motion (21) which distinguishes these jets from free gas jets.

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Legend: a_t – acceleration of a stream of particles in a chute, m/s; c – airborne speed of particles, m/s; D – hydraulic diameter of a chute (channel), m; d, $d_э$ – particle diameter (sphere diameter equivalent to a particle in terms of volume), m; $f_м$, – particle frontal area, m^2; G – mass flow (G_1 – particles, G_2 – air), kg/s; k_m – particle frontal area/volume ratio, 1/м; l – chute length, m; M – mass force (M_1 – particles, M_2 – air), N/kg; n – relation of the initial particle speed in a chute to the particle speed in the chute channel; P – pressure ($P_э$ – chute injection pressure, $P_т$ – chute thermal pressure, P_a, P_0 – outside chute, R – aerodynamic drag of bombarding particles, N; S, S_{ch} – cross sectional area of a chute (channel), m^2; V – volume ($V_ч$ – particle volume), m^3; υ – velocity (υ_1 – particles; $\upsilon_{1к}$ – particles at the chute outlet; $\upsilon_{1н}$ – particles at the chute inlet; υ_2, u – air), m/s; β – volume concentration (β_1 – particles, β_2 – air), m^3/m^3; ε – air-to-particles density ratio; λ – hydraulic resistance coefficient; ρ – density (ρ – particle material; ρ_2 – particle stream air, kg/m^3; τ – tangential stress, Pa; φ – component slip ratio (relation of the induced air speed to the particle speed); ψ – particle resistance coefficient (ψ_0 – particles in the area of self-similarity, ψ^* – stream particles).