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NUMERICAL MODELLING OF DIVISION PROCESS
IN THE AIR MULTICASCADE GRAVITATIONAL QUALIFIER

As a result of researches movement of air with firm particles in a new design of the two-level gravitational qualifier is simulated. Cross-section-line character of movement of air and firm particles in the device is investigated. Influence on resistance of the qualifier of average in relation to cross-section section of speed of air and frequency of rotation of a separating wheel is investigated, at approximation of the received dependences by a square parabola value of factor of resistance is received. The boundary size of division of particles is calculated at modelling of classification of quartz sand and compared with results of experimental researches. Satisfactory convergence of settlement and experimental values is received. The developed model can be used for calculation of process of classification of loose polydisperse materials.

Introduction. In industry qualifiers serve for receiving powders of demanded granulometric structure. The technological problem of the process of classification is reduced to the division of the initial polydisperse material into two or more fineness classes.

The authors of the article have developed, patented and experimentally investigated a new design of the air gravitational qualifier with two steps of division: gravitational and chipping-vortex [1, 2]. The experiments proved high efficiency of the developed device at the classification of quartz sand, plaster, sylvinite. However the lack of reliable methods of technological calculation of devices of this type demands carrying out additional experimental studies for adjustment of regime parameters of the qualifier at the change of characteristics of a divided material and the sizes of the qualifier.

Therefore the purpose of further researches was modeling of the air stream movement with polydisperse firm particles in the qualifier for data acquisition about the influence of technological, design characters of the device on the division process as a whole and the boundary size of division in particular.

Main part. Among classical methods of modeling of aerodynamic classification two main are allocated – determined and stochastic.

Stochastic models are based on the use of the theory of probability for calculation of the direction of movement of particles of the various size in working volume of the qualifier. The most essential results in this direction are received by M. D. Barskiy [3] and V. E. Mizonov [4] at the research of gravitational and centrifugal qualifiers.

The determined models are based on the differential equations of the movement of the loose environment and the bearing stream.

For a long time, up to the beginning of the 90s of the last century, the determined models didn't find wide application. It is caused by the fact that in the determined models there was accepted the mass of the assumptions connected with impossibility of the accounting of many random factors, such as turbulent pulsations of a stream, collision of particles among themselves and elements of devices. Besides, mutual influence of a stream of a firm phase and gas phase on each other was ignored, the laminar boundary layer near a motionless wall was difficult to model. As a result the accuracy of the determined models was rather low.

Now the development of scientific approaches of mathematical description of turbulent vortices and the boundary layer, joint movement of firm, liquid and gas phases allows to model with high precision one – and multiphase currents. Computing capacities of modern computers allow to receive the decision in a short time. Therefore the determined models in hydrodynamics find the increasing application, the proof of that is use of the program complexes Ansys Fluent, Flow Vision, etc. by such companies, as Boing, Airbus, Mercedes, BMW, DCNS, and others. The design of the qualifier represents the vertical cylindrical hollow case with loose elements. A shaft with distributive disks is established axially to the case. In the top part of the case the separating wheel is mounted. A detailed description of the device is given in article [2].

When the qualifier is operated air rises in the hollow case from below up, flows round a rotating shaft with distributive disks, penetrates layers of the particles descending from loose elements of the case and distributive disks, picks up small and easy particles, passes through a rotating separating wheel and goes to a cyclone to split small fraction (small class). Under the influence of gravity large particles move down and get to large fraction (large class). Particles of the boundary size or close to it can circulate some time in working volume of

the qualifier and get casually to this or that fineness class. Therefore the separating wheel increases the clearness of division in the qualifier which prevents large particles from getting into small product.

First of all the movement of clean air in the qualifier was simulated. For this purpose there was used the Navier – Stokes equation for viscous fluids which in a vector form registers as

$$\rho \frac{d\mathbf{c}}{dt} = \mathbf{M} - \text{grad}\, p + \mu \Delta \mathbf{c}, \qquad (1)$$

where ρ – the fluid density, kg/m^3; $\mathbf{c}$ – vector of speed; $\mathbf{M}$ – vector of mass forces; p – the pressure, Pa; μ – dynamic viscosity, Pa · s; Δ – Laplacian operator.

The Navier – Stokes equation was supplemented with the equation of contiguity of a stream

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \overline{c}) = 0 \qquad (2)$$

and the equation of condition

$$\rho = \frac{pM}{RT}, \qquad (3)$$

where M – moral mass of gas, g/mol; R – universal gas constant; T – absolute temperature, K.

As the direct numerical modeling at the solution of the equations (1)–(3) demands essential temporary resources to calculate turbulent flows, the standard model of turbulence k-ε was used. Here the Navier – Stokes equation is transformed to the form in which there is added the influence of fluctuation of average speed (in the form of turbulent kinetic energy) and the process of reduction of this fluctuation due to viscosity (dissipation) [5].

In the accepted model the tensor of viscous shift tension is defined as

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij}, \quad (4)$$

where μ – dynamic viscosity, Pa · s; u – speed, m/s; x – coordinate, m; δ – the Kronecker delta; k – kinetic energy of turbulence.

Dynamic viscosity μ is calculated as the sum of the dynamic viscosity coefficient μ_l and the turbulent viscosity coefficient μ_t.

The turbulent viscosity coefficient is calculated on dependence

$$\mu_t = f_\mu \frac{C_\mu \rho k^2}{\varepsilon}, \qquad (5)$$

where f_μ, C_μ – coefficients; ε – dissipation of turbulence energy.

The C_μ coefficient is recommended to accept equal to 0.9 [6]. The f_μ coefficient is calculated by the formula

$$f_\mu = \left(1 - e^{-0.025 R_y}\right)^2 \left(1 + \frac{20.5}{R_T}\right), \qquad (6)$$

where R_y, R_T – the variables determined by the expressions

$$R_y = \frac{\rho \sqrt{k}\, y}{\mu_l}, \quad R_T = \frac{\rho k^2}{\mu_l \varepsilon}, \qquad (7)$$

where y – the distance from local average volume of a current to the wall of the computational domain, m.

The kinetic energy of turbulence k and the dissipation of this energy ε are defined at the solution of two equations:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_k k) = \frac{\partial}{\partial x_k}\left(\left(\mu_l + \frac{\mu_l}{\sigma_k}\right)\frac{\partial k}{\partial x_k}\right) + S_k, \,\,(8)$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_k \varepsilon) = \frac{\partial}{\partial x_k}\left(\left(\mu_l + \frac{\mu_l}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_k}\right) + S_\varepsilon, \,\,(9)$$

where S_k, S_ε – the characteristics of pulsations of kinetic energy and the dissipation of this energy:

$$S_k = \tau_{ij}\frac{\partial u_i}{\partial x_j} - \rho\varepsilon - \mu_l\left(\frac{g_i \partial \rho}{\sigma_B \rho \partial x_i}\right), \qquad (10)$$

$$S_\varepsilon = C_{\varepsilon 1}\frac{\varepsilon}{k}\left(f_1 \tau_{ij}\frac{\partial u_i}{\partial x_j} + \mu_l C_B\left(\frac{g_i \partial \rho}{\sigma_B \rho \partial x_i}\right)\right) - C_{\varepsilon 2}f_2\frac{\rho\varepsilon^2}{k}, \,\,(11)$$

where $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $\sigma_\varepsilon = 1.3$, $\sigma_k = 1$ – empirical coefficients; f_1, f_2 – the variables depending on the coefficients of dynamic and turbulent viscosity, determined by the following formulas:

$$f_1 = 1 + \left(\frac{0.05}{f_\mu}\right)^3, \quad f_2 = 1 - e^{-R_T^2}. \qquad (12)$$

The use of the above-stated equations allowed to simulate the air current in the qualifier, to receive distribution of speeds and to analyse the mechanism of air flow of a rotating shaft with disks and loose cones. One of the characteristic pictures of the air current is presented on Fig. 1.

The modeling showed that in the qualifier there are steady contours of a stream circulation over the rotating disks and the loose elements. The air moves in zigzag fashion, therefore, there is a repeated cross-section-line classification.

Statistical processing of profiles of total pressure at various air flows allowed to receive the schedule of hydraulic resistance of the qualifier

and to calculate the coefficient of resistance $\zeta = 290$ is presented in Fig. 2.
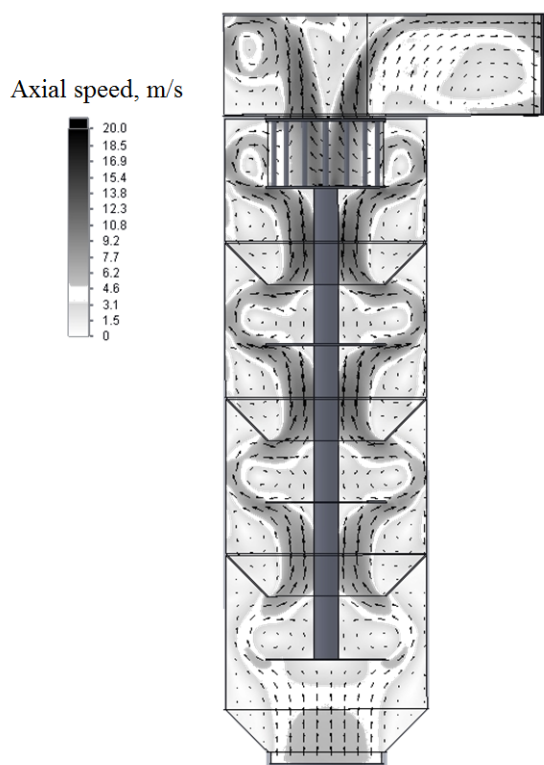

Fig. 1. A profile of axial speeds in the qualifier at the average speed on section of 2 m/s

The results of modeling have high convergence with the experiment. However with the increase in speed the growing divergence is observed. This is explained by the drawback of the model of turbulence $k\text{-}\varepsilon$ which incorrectly counts streams with big anisotropism of turbulence.
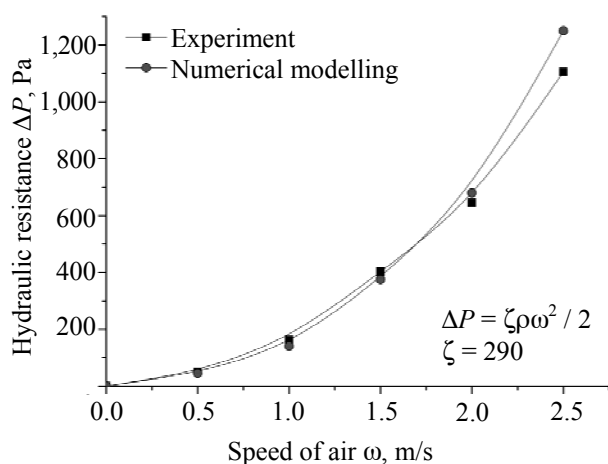

Fig. 2. Hydraulic resistance

Also it was established that the change of rotation frequency of the separating wheel in limits from 200 to 1,500 rev/min has no essential influence on the hydraulic resistance of the qualifier.

To estimate the process of classification formulas (1)–(12) were added the equation of movement of firm particles in a stream [7]:

$$\frac{du_p}{dt} = C_D A \frac{(u-u_p)^2 \rho}{2} + g \frac{\rho_p - \rho}{\rho_p} + F_x, \quad (13)$$

where u_p – speed of a particle, m/s; C_D – coefficient of resistance; A – midsection of a particle, m^2; ρ_p – density of a particle, kg/m^3; F_x – the forces caused by a field of pressure upon surfaces of a particle, N.

The coefficient of resistance is determined by the Henderson formula [8]:

$$C_D = \frac{24}{Re} + \frac{4.12}{1 + 0.03Re + 0.48\sqrt{Re}} + 0.38, \quad (14)$$

where Re – the Reynolds number at a particle flow.

The interaction of particles with the qualifier elements and with each other was considered as the elastic blow. The coefficient of restoration when modeling the classification of quartz sand was accepted equal to 0.5.

The boundary size of division when modeling was defined as follows. The material with particles of various sizes was entered into the estimated volume through a loading branch pipe. The size and quantity of particles passing through the control section were fixed at the exits from the qualifier. If the quantity of particles in small and large classes coincided, their size was boundary for the current parameters of the classification. In Fig. 3 the results of calculation of the boundary size in comparison to the experimental data at sand classification are presented.
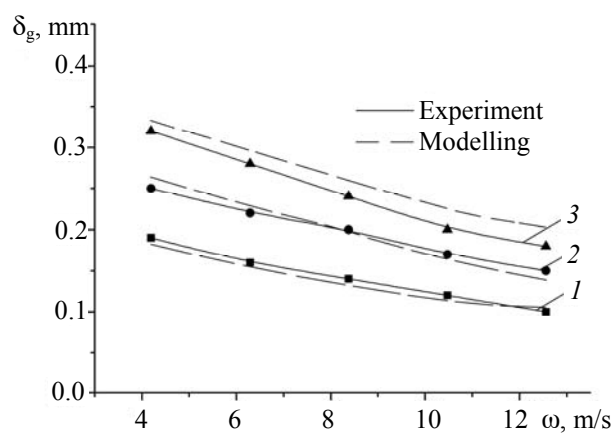

Fig. 3. The dependence of the boundary size of division δ_g from the linear speed of cores ω of the separating wheel at average speed of air:
1 – 0.8 m/s; *2* – 1.6 m/s; *3* – 2.2 m/s

From the diagrams (Fig. 3) it is seen that the results of modeling are well coordinated with the experimental data, especially at small speeds of air

in the qualifier. The increase in speed of air leads to the growth of modeling error. As it has already been noted above, it is connected with limited possibilities of the applied model of turbulence. But as the studied qualifier works generally at average air speeds of 1–3 m/s, this shortcoming has no serious value and it is possible to recognize the results of modeling satisfactory.

Conclusion. As a result of the carried-out researches there was simulated the movement of air stream with polydisperse firm particles in the qualifier. The cross line nature of the movement of air and firm particles in the device was established and studied. The influence on resistance of the qualifier of average in relation to cross section of air speed and the frequency of rotation of the separating wheel was studied; at approximation of the received dependences of square parabola the value of the resistance coefficient was received. The boundary size of particles division was calculated when modeling the classification of quartz sand and compared with the results of experimental studies. The satisfactory convergence of the calculated and experimental values was established. The developed model can be used for the calculation of loose materials classification process.

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