Calculation Scheme of Purification of Industrial Emissions in Separators of Nozzle Type

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Abstract. The article discusses a model of motion of a four-phase continuum that simulates the flow of dusty gas in a nozzle separator. The main design features of such separators are considered, in particular, the rebound of solid particles from the walls of the nozzle is taken into account and their influence on the efficiency of cleaning gas and dust flows in separators of this type is investigated. It is shown that, at high mass contents of the dispersed phase in the inlet section of the nozzle of the first stage, the distribution of the parameters of the dispersed flow in the flow part of the separator has a nonmonotonic character.

1. Introduction
Among the methods of cleaning gas and dust streams from suspended solids, the most common method is dry mechanical cleaning [1-3]. This method is used in most inertial separators and gives a high degree of purification for coarse mixtures. In most works devoted to the calculation of separators, either the motion of solid particles in a given velocity field of the carrier medium is considered, calculated on the basis of either the Euler equations or the equations [4-6]. Failure to take into account the bouncing particles leads to a distortion of the flow pattern, a discrepancy between the calculated and experimental data and, accordingly, to constructive miscalculations in the design of dust collectors. Failure to take into account the bouncing particles leads to a distortion of the flow pattern, a discrepancy between the calculated and experimental data and, accordingly, to constructive miscalculations in the design of dust collectors. In this work, to describe the motion of gas and dust flows, we use the model of interpenetrating continua [7], which allows, with an appropriate choice of the number of phases, to describe all the effects occurring. The calculation scheme in this case is based on the numerical method of large particles [8].

2. Problem statement and mathematical model of the flow
Consider the movement of a gas-dust medium consisting of a carrier gas and solid particles in an axisymmetric two-stage nozzle separator with an inlet radius $R$, a schematic diagram of the operation of a fig.1.
Figure 1. Longitudinal section of a two-stage nozzle separator with a central dust outlet. 
1 – first stage, 2 – second stage, 3 – dust collector, 4 – partition.

The principle of operation of the separator is that all dust particles that have fallen from the inlet section of the nozzle of the first stage into the working area of the separator enter the second stage, and then into the dust collector. The purpose of the calculations is to determine the shape of the outer wall of the separator, at which all particles that have bounced off the outer wall of the first stage separator and the partition are as well as particles entering the separator together with the gas flow from the inlet section of the nozzle of the first stage, fell into the second stage, and then into the dust collector. Since the main separation of flows occurs in the first stage of the nozzle separator, it is of the greatest interest to calculate the phase interaction precisely in this part of the nozzle. To solve this problem, a four-speed model of the motion of a multiphase continuum was considered.

The carrier gas was considered as the first phase, 2nd phase - fraction of particles entering the separator from the inlet section of the nozzle of the first stage, those. particles flying both to the side surface of the nozzles of the first and second stages, and flying through from the inlet section of the first stage nozzle to the dust collector, 3rd phase - fraction of particles bouncing off the side surface of the nozzle of the first stage and the 4th phase - the fraction of particles that bounced off the inner wall of the nozzle (baffle) located along the axis of symmetry of the air cleaner. Only the force interaction of both gas and particles and particles of different fractions with each other was taken into account. We will assume that the axis of symmetry of the nozzle OX coincides with the axis of the cylindrical coordinate system (X, Y, Φ). The equations describing the motion of a given medium within the framework of the model of interpenetrating continua will have the form:

\[
\begin{align*}
\frac{\partial \rho_i}{\partial t} + \text{div}\rho_i \vec{v}_i &= 0 \\
\frac{\partial \rho_i \vec{v}_i}{\partial t} + \nabla \cdot (\rho_i \vec{v}_i \vec{v}_i) &= (\delta - 1) \nabla p + \vec{f}_i \\
\sum_{i=1}^n \left[ \frac{\partial \rho_i E_i}{\partial t} + \text{div}(\rho_i E_i + (1-\delta)p)\vec{v}_i \right] &= 0 \\
\frac{\partial \rho_i e_i}{\partial t} + \text{div}(\rho_i e_i \vec{v}_i) &= q_{ii} + \vec{f}_i (\vec{v}_i - \vec{v}_j)
\end{align*}
\] (1)
\( \delta = \begin{cases} 0, i = 1 \\ 1, i \neq 1 \end{cases} \), subscript \( i \neq j; i, j = 1,2,3,4 \) refers, respectively, to the parameters of the gas and the corresponding fractions of particles; \( \rho_i, \tilde{V}_i, e_i, E_i, p \) – reduced density, velocity vector, internal and total energy of the \( i \)-th phase, gas pressure, \( f_{ij} \) – intensity of force interaction between phases, and \( q_{ii} \) – heat exchange between gas and particles of different fractions. Taking into account the data given in [7-9], the system of equations (1) is closed by the relations:

\[
\tilde{f}_{ii} = \frac{0.75 \rho_i \rho_j G_d (\tilde{v}_i - \tilde{v}_j) \left( \tilde{v}_i - \tilde{v}_j \right)}{\rho_j d^2} \Psi_{\alpha_i}, C_{di} = \frac{24}{\text{Re}_{ii}} + \frac{4}{\sqrt{\text{Re}_{ii}}} + 0.4, \\
\text{Re}_{ii} = \frac{\rho_i \left| \tilde{v}_i - \tilde{v}_j \right| d}{\mu_i}, \Psi_{\alpha_i} = (1 - \alpha_i)^{-2.7}, \alpha_i = \frac{\mu_i}{\mu_j}, \\
q_{ii} = \frac{6 \rho_i \lambda_i \text{Nu}_{ii} (T_i - T_j)}{\text{Re}_{ii}^0 d^2}, \text{Nu}_{ii} = 2 + 0.6 \text{Re}_{ii}^\frac{1}{3} \text{Pr}^\frac{1}{3}.
\]

Here \( \rho_i^0 \) - true phase density; \( C_{d_i}, \text{Re}_{ii}, \text{Nu}_{ii}, \text{Pr} \) – drag coefficient, Reynolds number and Nusselt number of relative flow around a particle of the \( i \)-th phase, Prandtl number, respectively; \( \mu_i, d \) – gas dynamic viscosity coefficient and particle diameter.

\[
\tilde{F}_{sl} = \frac{k^{(F)}}{\beta^{(v)}} \frac{\rho_i \rho_j (\tilde{v}_i - \tilde{v}_j) \left( \tilde{v}_i - \tilde{v}_j \right)}{\beta^{(v)}} = \frac{\rho_i d}{\rho_j R}.
\]

Here the value \( k^{(F)} \) determines the intensity of the force interaction of the phases, \( \beta^{(v)} \) – the degree of inertia of the particles. It was shown in [10] that for gas velocities \( v_i \cong 10 \text{ m/s}, k^{(F)} \cong 0,1 \).

Also, the equations of state of the phases were used as closing relations for system (1):

\[
p = \rho_i^0 (\gamma - 1) e_i, e_1 = c_0 T_1, e_2 = c_2 T_2,
\]

where \( \gamma \) – gas adiabatic index; \( c_1, c_2 \) – specific heat capacity of gas at constant volume and specific heat capacity of particles; \( T_i \) – phase temperature.

The system of equations (1) was written in new variables

\[
\xi = \xi(x, y), \eta = \eta(x, y),
\]

in which the considered curvilinear region becomes rectangular [11,12]. By replacing independent variables \( x = x \),

\[
\xi = \frac{y - G(x)}{F(x) - G(x)}.
\]

where \( F(x) \) и \( G(x) \) –equations of the upper and lower boundaries of the channel, the curvilinear region turns into a rectangular

\[
N \ (0 \leq x \leq 1, \ 0 \leq \xi \leq 1)
\]

Equations of motion written in variables \((x, \xi)\) look like:

\[
\rho \frac{\partial u_i}{\partial t} + \frac{\partial \rho u_i}{\partial x} + \frac{\partial \rho U_i}{\partial \xi} = -\frac{\rho U_i^\xi}{\varepsilon \xi} - \frac{\partial p}{\partial x} + \frac{\xi}{\partial \xi} \left( -\frac{\partial p}{\partial \xi} + \frac{\partial p}{\partial \xi} \right) + \frac{\rho \mu_i U_i^\xi}{\varepsilon \xi} + f_i^\xi
\]
The calculation results shown in Fig. 2.3 showed that starting from $m_{20} = 0.2$, where $m_{20}$ – concentration of the dispersed phase in the inlet section of the nozzle of the first stage, the particles have a significant effect on the movement of the gas and dust flow in the flow path of the first stage nozzle. So, for example, with an increase $m_{20}$ under the influence of particles of the 2nd phase, particles of the 3rd phase, more intensively drift towards the outlet section of the nozzle of the first stage, thereby...
reducing the concentration of particles in the annular gap of the outlet section of the nozzle of the first stage of the separator.

**Figure 2.** Gas and particle trajectories in the flow path of the first stage nozzle.

Solid lines and dashed lines - trajectories and lines of the gas level, points – second particle phase, circles – third particle phase, asterisks – fourth particle phase; \( m_{20} = 0.2; \, \, M_0 = 0.05; \, \, d = 200 \text{mkm} \).

**Figure 3.** Gas and particle trajectories in the flow path of the first stage nozzle.

Solid lines and dashed lines - streamlines and gas level lines, points – second particle phase, circles – third particle phase, звездочки – fourth particle phase; \( m_{20} = 0.5; \, \, M_0 = 0.05; \, \, d = 200 \text{mkm} \).

The figures show that the mass concentration of particles in the inlet section of the separator significantly affects the distribution of the characteristics of the dispersed flow in the working zone of the nozzle of the first stage, in particular \( m_{20} \) both streamlines and streamlines of particles of all phases
are significantly deformed. Due to the forceful interaction of the gas with particles of all fractions, the gas level lines are curved (dashed lines), which fixes the fact of significant deceleration of the gas phase (the velocity of the carrier medium decreases by a factor of 2.5 with an increase in the mass concentration of particles in the incoming flow) dispersed particles.

3. Conclusions
The developed mathematical model and calculation method made it possible to find the distribution of characteristics of gas-dispersed flows in nozzle-type separators. It was revealed that when the gas suspensions move in the flow path of the first stage nozzle, at high contents of the dispersed phase in the inlet section of the separator, dispersed particles significantly affect the structure. In particular, the streamlines of the gas phase are deformed, on which inflection points appear that change the curvature of these lines, and the deformation of the streamlines manifests itself most noticeably in the outlet of the nozzles. It can also be noted that there are local extrema in the distribution of the characteristics of the gas and dust flow in the flow part of the separator. The calculation results made it possible to determine the profile of the outer wall of the separator, which makes it possible to use this type of air cleaner for cleaning industrial emissions with a high degree of efficiency.

4. References
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