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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ГИДРАВЛИЧЕСКОГО СОПРОТИВЛЕНИЯ В КЛАССИФИКАТОРЕ С СООСНО РАСПОЛОЖЕННЫМИ ТРУБАМИ

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Аннотация: рассмотрена проблема классификации мелкодисперсных сыпучих материалов с граничным зерном равным 30 мкм на промышленных предприятиях. Авторами работы предлагается новая конструкция классификатора, принцип действия которого основан на возникновении упорядоченной завихренной структуры в межтрубном пространстве. Представлена упрощенная трехмерная модель классификатора. Целью работы является сравнение экспериментальных данных с результатами численного моделирования по потери давления в классификаторе с соосно расположенными трубами на расчетной сетке с различным количеством ячеек. Показано, что потери давления в классификаторе изменяются от 173 до 972 Па при входной скорости газа от 7,34 до 22,21 м/с. Допустимое количество итераций для выхода на квазистационарный режим составляет от 120 и зависит от входной скорости газового потока. Погрешность между лабораторным экспериментом и численным моделированием составляет не более 16, 15 и 10% при количестве ячеек в расчетной сетке 1131031, 2813963 и 6749250 шт, соответственно.

Ключевые слова: сепарация, мелкие частицы, вихри, гидравлическое сопротивление, расчетная сетка.

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Numerical simulation of pressure loss in a classifier with coaxial pipes

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Abstract: The paper deals with a pressing problem of classification of fine particulate materials with a cut size of 30 μm at industrial plants. A new design of the classifier with coaxial pipes is developed. The principle of operation of the classifier is based on the formation of a stable vortex structure in the inter-pipe space. A simplified 3D model of the classifier is presented.

The work aims to compare experimental data and simulation results to calculate pressure losses in the classifier with coaxial pipes when the number of elements in the mesh is changed. It is found that the pressure loss in the classifier varies from 173 to 972 Pa at a gas velocity at the inlet from 7.34 to 22.21 m/s. The permissible number of iterations to reach a quasi-stationary regime starts from 120, depending on the gas velocity at the inlet. The error between the laboratory experiment and the numerical simulation is not more than 16, 15, and 10% with the number of the elements in the mesh 1131031, 2813963, and 6749250 pcs, respectively.

Key words: separation, fine particles, vortices, pressure drop, computational mesh.

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1. Introduction

Many solid mixtures often need to be purified or classified to obtain products with desired properties. The separation of solid mixture components can be carried out by various methods and technologies [1,2]. The selection and calculation of classifiers are an important task in modern particle technologies, such as the production of catalysts and adsorbents in chemical industry, mining, food and pharmaceutical industries [3,4]. Classifiers are designed to separate particles into desired fractions. This is a vital process since the dispersion of powders directly affects the efficiency of chemical and physical processes [5–8]. However, as a rule, the use of standard classifiers for different branches of material processing is difficult due to the variation of physical and thermophysical parameters of particles and technological parameters, which can deviate the cut size, which leads to non-compliance with the technical requirements [9–12]. Therefore, in most cases, a real classifier is usually upgraded or reconstructed based on an old model for a particular technological system [13,14]. However, the modernization or development of a new classifier requires certain financial and time costs, including the development of new devices [15,16].

The use of computer technologies is the most common way to solve these problems [17–19]. Ansys Fluent, FlowVision, SolidWorks Flow Simulation, and other programs are some of the most well-known tools that allow the calculation of fluid dynamics and sepapration of gas and solids in two- and three-dimensional apparatus geometry. In these programs, the numerical simulation of gas dynamics is usually based on the finite element method, the mesh method [20,21]. Depending on the chosen turbulence model, the partial differential equations (Navier-Stokes equation) are set:

$$\frac{\partial \vec{v}}{\partial t} = -\left(\vec{v} \cdot \nabla\right)\vec{v} + \nu\Delta\vec{v} - \frac{1}{\rho}\nabla p + \vec{f}, \quad (1)$$

where $\vec{v}$ is the velocity vector field; t is the time, s; ∇ is nabla; ν is the kinematic viscosity coefficient, m^2/s; ρ is the density, kg/m^3; p is the pressure, Pa; $\vec{f}$ is the vector field of mass forces.

The Navier-Stokes equation is combined with the continuity equation as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho\vec{v}\right) = 0. \quad (2)$$

These equations can be solved using initial and boundary conditions. The essential task of numerical experiments is to adequately simplify the computational model, reducing the overall simulation time without distorting the results [22] or creating a pseudo-volume model [23]. Thus, the most important factor directly affecting the simulation time is the number of elements (cell size). It is recommended to increase the number of elements in zones where geometry changes, vortices occur, etc. At the same time, it is possible to reduce the number of elements in local places of the simulation model with constant and simple geometry by increasing their size.

The purpose of the work is to compare experimental data and simulation results for pressure loss calculation in the classifier with coaxial pipes under changing the size of the mesh cells.

2. Classifier design and simulation conditions

The Salavat catalyst plant a classifier with coaxial tubes to classify silica gel particles with a cut size of 30 μm. Centrifugal forces cause the classification of particles from gas due to the formation of stable vortices in the inter-pipe space [24]. Fig. 1 shows a simplified three-dimensional model of a full-scale experimental sample of the developed classifier.

Structurally, the classifier can be made according to the pipe-in-pipe principle and is provided with outer and inner cylindrical pipes. The lower part of the inner pipe has six rows with seventeen holes in each row. There is a perforated plate between the pipes at the top of the device and a closed bottom at the bottom of the device. When assembling the device, the inner pipe is inserted into the central opening of the perforated plate in the outer pipe, forming the inlet tube 1. The structural strength of the device is provided by the condition that the external part of the inner cylindrical pipe is fixedly connected to the perforated plate (Fig. 1).

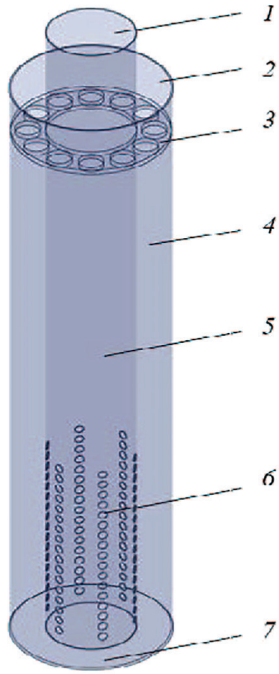

Fig. 1. 3D model of the classifier with coaxial pipes: 1 – inlet, *2* – outlet; *3* – perforated plate; *4* – outer cylindrical pipe; *5* – inner cylindrical pipe; *6* – rows of circular holes on the inner cylindrical pipe; *7* – bottom

The principle of operation of the device is as follows: the gas flow enters the device via inlet 1, then it moves along the inner cylindrical pipe 5. When the gas reaches circular hole 6 drilled in the inner cylindrical pipe 5, it moves in the direction of the holes in an axisymmetrical direction. As the gas flow passes through each circular hole 6, it enters the inter-pipe space of the device. Furthermore, after passing through each circular hole, the gas flow splits into 2 equal vortices, oppositely rotating in the inter-pipe space. Since the inter-pipe space is limited by the inner wall of the outer cylindrical tube 4 and the outer wall of the inner cylindrical tube 5, as well as circular holes 6 made with a certain pitch, stable vortices appear in the inter-pipe space of the classifier. As a result, vortices with

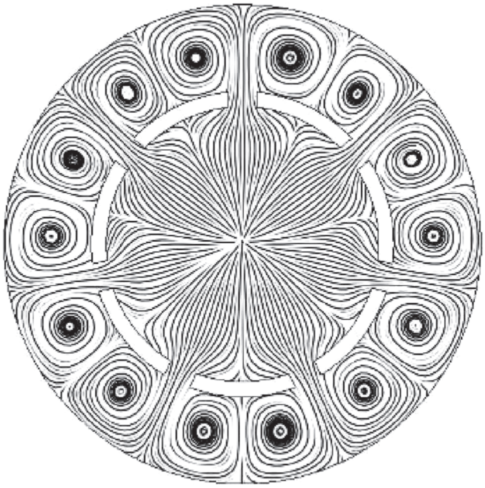

Fig. 2. Vortex structure in inter-pipe space (cross-section view of the lower part of the classifier)

large centrifugal force are formed when the gas rotates [25]. Moreover, each vortex has two contact zones with adjacent ones, which allows the vortices to maintain rotation along the height of the inter-pipe space (Fig. 2).

It should be noted that in the experimental classifier instead of bottom 7 there is a container for collecting particles, outlet 2 (Fig. 1) is covered by a plate. The outlet cylindrical branch pipe is mounted on the side of the device behind the perforated plate 3. Inner cylindrical pipe 5 does not reach the bottom of device 7. It has a tapered narrowing with an opening for pouring larger particles through it into the hopper by gravity when moving to the inner cylindrical pipe. In addition, simplification of the geometry to the form shown in Fig. 1, does not significantly affect the formation of vortices in the inter-pipe space. Thus, the real design of the classifier provides that particles larger than 30 μm are knocked out of the flow under the action of centrifugal forces during rotation of vortices in the inter-pipe space and poured into a hopper, while particles smaller than 30 μm go out of the classifier to the fine cleaning devices. In this study, only gas dynamics in the device was calculated.

The 3D model of the classifier has the following dimensions: the height of the inner cylindrical pipe is 400 mm, the height of the outer cylindrical pipe is 440 mm, the inner pipe diameter is 50 mm, the outer pipe diameter is 100 mm, the plate with 12 holes of diameter 7 mm is located at a height of 370 mm from the bottom of the device, the diameter of the circular holes in the inner cylindrical pipe is 5 mm, the wall thickness is 2 mm. Numerical simulation was performed using Ansys Fluent software. Based on the 3D model, a gas passage zone was created and exported into the Mesh module. As noted above, the calculation time increases or decreases depending on the number of elements, but the accuracy of the results can also increase or decrease. Therefore, the number of elements varied in the study was 1131031, 2813963, and 6749250 (Fig. 3).

The results of the numerical simulation were compared with experimental results to validate the model. During the laboratory experiment, the feed gas was supplied through inlet 1 (Fig. 1), and the gas flow rate was varied. The gas flow rate at the inlet to the classifier was measured with an anemometer (TESTO 405i), the inlet pressure was measured with a smart probe (TESTO 510i), and the pressure at outlet 2 of the classifier (Fig. 1) was equal to atmospheric 101325 Pa. Also in the experimental studies, several upper rows of circular holes 6 in the inner cylindrical pipe 5 were overlapped . During testing and numerical studies, pressure loss Δp was determined by the following equation:

$$\Delta p = p_1 - p_2, \qquad (3)$$

where p_1 is the pressure at the inlet branch pipe, Pa; p_2 is the pressure at the outlet branch pipe, Pa.

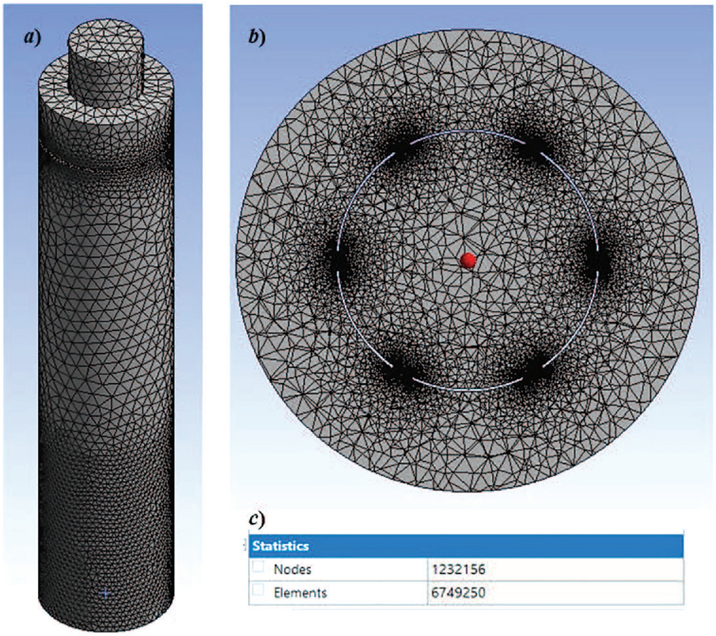

Fig. 3. Meshing scheme: a) gas passage zone of the classifier; b) thickening of elements in the area of circular holes made in the inner cylindrical pipe; c) the number of nodes and elements

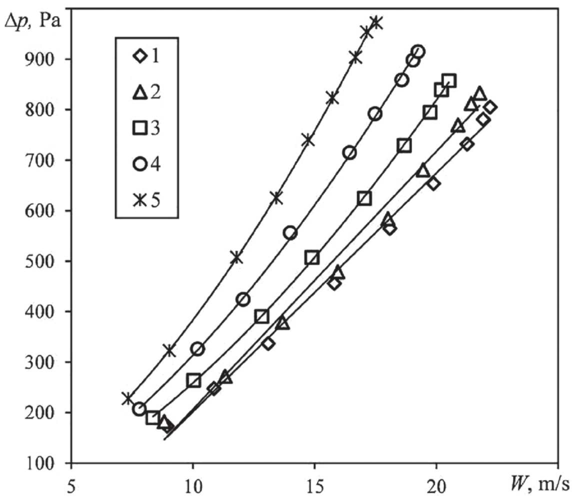

Fig. 4. Dependence of the pressure loss in the classifier on the gas velocity at the inlet for different overlapping holes in rows: 1 – 0; *2* – 2; *3* – 4; *4* – 6; *5* – 8

3. Results and discussion

The results of the experimental studies are presented in Fig. 4. It was found that the pressure drop in the classifier with coaxial pipes increases with increasing gas velocity from 7.34 to 22.21 m/s. Pressure losses in the classifier calculated by the formula (3) ranged from 173 to 972 Pa. It should be noted that the pressure loss increased as the rows of circular holes in the inner pipe overlapped for each inlet velocity. This is due to the fact that the total area of the flow sections decreases as the gas flows from the inner pipe to the inter-pipe space.

For comparison with the results of numerical simulation, the experimental dependence of the pressure loss in the classifier on the gas velocity at the inlet at the lowest values Δp was chosen line 1 in Figure 4, where all rows of circular holes are open. Thus, in numerical simulation, the gas velocity at the device inlet was set to 8.94, 10.86, 13.09, 15.81, 18.09, 19.88, 21.26, 21.92, and 22.21 m/s, according to the results of laboratory experiments (Fig. 4). The k-w SST turbulence model was used since previous studies showed good convergence between experimental and simulation data.

At the first stage of numerical simulation, the required number of iterations for each test velocity was determined. It should be mentioned that for our case, the steady-state mode is characterized by a constant value of pressure loss or its small deviation, so the line characterizing this dependence becomes straight or close to it. In this study, the calculation model was divided into 6749250 elements. For each inlet gas velocity, the dependences of the pressure loss on the number of iterations were obtained. The results showed that the number of iterations should be increased with increasing values of the gas velocity at the inlet, since the vortex center oscillation frequency also increases several times, leading to the violation of the vortex structure (Fig. 2). At gas velocities of 8.94, 10.86, 13.09, 15.81, 18.09, 19.88, 21.26, 21.92 and 22.21 m/s more than 120, 250, 410, 660, 870, 1130, 1180, 1210, 1320 and 1350 iterations are required, respectively (Fig. 5).

An averaging procedure was applied to compare the results of numerical modeling with laboratory experiments. The average value of the pressure loss was determined in a certain range of iterations, where the process becomes stationary or quasi-stationary. Similar studies were also carried out for the different elements in the mesh: 1131031 and 2813963 cells, see Fig. 6.

Thus, studies have shown that the model of gas dynamics in the developed classifier with coaxial pipes has a relatively small error of up to 10–16%. As a result, it is possible to estimate the cross-effect of many process parameters such as particle size and density. Besides, by refining the mesh, the reliability of the results increases, but the computation time also increases. In addition, full convergence with an error of less than 1% is practically impossible due to the complicated vortex structure in the inter-pipe space.

Conclusion

According to the results of the work, the following conclusions can be made:

• The application of k-w SST model of turbulence allows simulation of gas dynamics in the developed classifier with coaxial pipes with an acceptable error for engineering calculations.

• Entering the quasi-stationary regime with pulsations of pressure loss values from the number of iterations with a certain pitch is caused by the complex structure of vortex formation in the inter-pipe space of the classifier and the occurrence of reverse currents in the area of circular holes in the inner cylindrical pipe.

• The permissible number of iterations to reach a quasi-stationary mode starts from 120, depending on the gas velocity at the inlet.

• An increase in the gas velocity at the inlet results in increasing the required number of iterations to reach the quasi-stationary regime due to the high frequency of oscillations of the vortex centers.

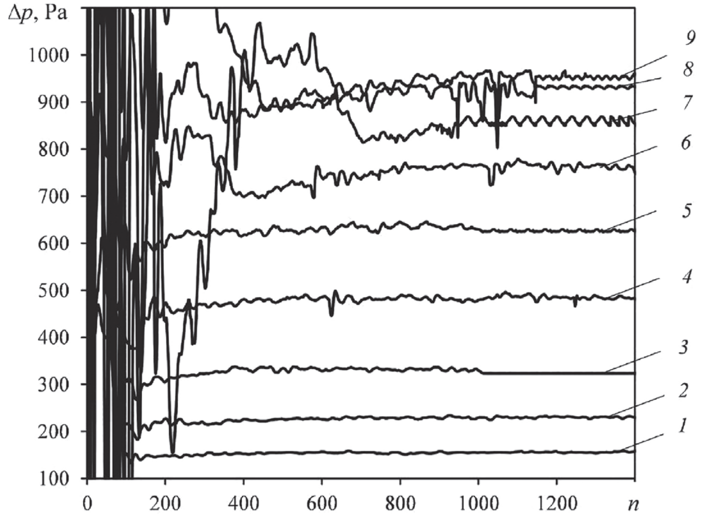

Fig. 5. Dependence of the change in the pressure loss in the classifier on the number of iterations at different initial average velocities, m/s: 1 – 8.94; 2 – 10.86; 3 – 13.09; 4 – 15.81; 5 – 18.09; 6 – 19.88; 7 – 21.26; 8 – 21.92; 9 – 22.21

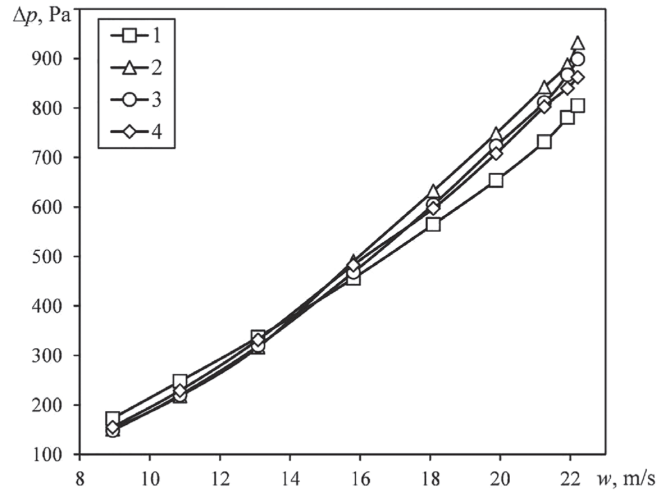

Fig. 6. Pressure loss of the classifier as a function of gas velocity at the inlet when changing the number of elements n: 1 – experimental data; 2 – 1131031; 3 – 2813963; 4 – 6749250

• The error between the laboratory experiment and the numerical simulation is not more than 16, 15, and 10% at the number of the elements in the mesh 1131031, 2813963, and 6749250 pcs, respectively.

The study has shown that numerical simulation significantly reduces the time and financial costs when developing a classifier with coaxial pipes, allowing a wide range of different parameters to be taken into account. Therefore, the study of the vortex center oscillations in the inter-pipe space of the classifier by experimental and numerical methods is planned in this work.

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