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Analysis of various mathematical models of turbulence when calculating the gas dynamics in a classifier with coaxially arranged pipes

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Abstract. This scientific article deals with the problem of choosing the mathematical model for calculating the gas dynamics in a classifier with coaxially arranged pipes. Various mathematical models were analyzed in ANSYS Fluent software package. Laminar, Spalart-Allmaras, k-ω, RSM and Transition SST were considered as mathematical models. The influence of number of cells in the calculation grid on the pressure loss change in the classifier for various mathematical models was also analyzed. The results of study showed that the pressure loss in the classifier with coaxially arranged pipes is not more than 395 Pa at the inlet gas flow rate of 10 m/s. Among the considered models i.e. laminar, Spalart-Allmaras, k-ω, RSM and Transition SST, the most adequate one is Transition SST model. When changing the number of cells in the calculation grid from 1241551 to 3159388 for this model, the deviation of pressure loss in the classifier was 0.43%. The article includes an equation for the dependence of pressure loss in the classifier on the inlet rate. The distribution of gas flow rate over various sections of rectangular gaps is shown.

1. Introduction

Nowadays, most of industrial enterprises pay great attention to energy and resource saving issues. At the same time, an important problem is to increase the efficiency of production processes. As a rule, this problem is solved by updating and upgrading the devices, used in production processes. One of the important requirements for innovative devices is relatively low energy costs, which allow them to be included in a new developed concept of enterprises, including such criteria as high efficiency, resource and energy saving. Therefore, when developing new designs of devices to be used in production processes, an important task is to meet the 3 above mentioned criteria.

The authors of this scientific article were tasked with developing and creating an energy-efficient classifier for the fractionation of bulk material, based on silica gel, of up to 30 microns in size from a gas flow in the production line of the Salavat catalyst plant. This bulk material is obtained by crushing it in the mills. It should be noted that the volume fraction of collected material larger than 30 microns should be at least 98% of total fraction of collected material. Most of classic devices cannot be used to solve this problem, since they are not designed for the fractionation of finely dispersed powdery materials [1-5].

At the moment, there are various types of powder classifiers: centrifugal, dynamic, gravitational, sieve, etc. [6, 7]. The centrifugal classifier separates the finely dispersed bulk material of fractional composition within the range from 5 to 80 microns by means of centrifugal force and air flow. The range of obtained particles directly depends on the rotor rotation speed and a change in the amount of air flow. The centrifugal classifiers are divided into static ones, when the air flow is created by the movement of blades, and dynamic ones, when the movement of air flow is provided by a rotating rotor. The advantages of centrifugal classifier are the ability to control the range of material separation fineness and provide the greatest accuracy for the particle classification [8]. A significant disadvantage of this type of classifier is that large powder particles fall into the fine fraction, and small particles fall into the large separation product, therefore, there is a decrease in the efficiency of particle separation and a small efficiency of device [9]. The gravitational classifiers carry out the material separation by means of interaction of resistance and gravity forces. The separation of raw material occurs as a result of different rates of sedimentation of solid particles in a liquid medium under the influence of gravitational forces. The large particles settle down faster, and the small particles settle down slower [10-12]. The main advantage of gravity method is the simplicity of device design due to the absence of moving parts in it. The disadvantage of gravity classifier is that it is impossible to classify the finely dispersed particles. At the industrial enterprises, the most common method is the sieve method of classifying the powders, which is directly carried out by the material spilling through a set of different sieves, ensuring separation as per the required parameters by fractional composition. This type of device has simple design and is suitable for classifying the particles larger than 40 microns. Despite the positive aspects of this method, it also has certain disadvantages, such as low efficiency of sieving classifiers for the finely dispersed powders and significantly low operational life of sieves due to rapid clogging caused by sticking of particles to their surface [13].

2. Materials and Methods

In order to solve this problem, the authors developed the design of classifier with coaxially arranged pipes [14], shown in figure 1. The classifier with coaxially arranged pipes is a simple structure, consisting of cylindrical body *6*, inside of which there is an internal cylindrical pipe; in the lower part of this pipe there is an even number of rectangular holes *3* with a certain step, and the bottom part of pipe has a cone-shaped hole *4*. In the middle part of inner cylindrical pipe, there is a screen with coaxially arranged pipes *2*. There is an inlet nozzle in the upper central part of device *1*. The device also has an outlet nozzle *5*. The bunker is located in the lower part of device *7*. When assembling the device, the inner cylindrical pipe is placed in the cylindrical body through the lower hole and inserted into the central hole in its upper part, forming an inlet nozzle *1*. The strength of structure is provided by fixing the inner cylindrical pipe to the cylindrical body *6* by means of screen with coaxially arranged pipes *2* and by welding the outer part of inner cylindrical pipe, forming an inlet nozzle *1*, to the device body *6* (figure 1).

The process of bulk material fractionation in a classifier with coaxially arranged pipes can be described as follows: the gas flow with silica gel-based particles, dispersed in it, is fed into the device through the inlet nozzle *1*, then the flow moves to the rectangular holes *3*, after that some part of flow passes through them and enters the inner area of classifier, which is located between the inner wall of device body and the outer wall of inner cylindrical pipe. It should be noted that the other part of flow carries out further movement along the inner cylindrical pipe and comes through the narrowing cone-shaped hole of classifier *4*; then the flow diverges in an axisymmetric direction and moves to the upper part of device. The largest particles, due to gravitational and inertial forces, are knocked out of flow structure and settle down in the bunker *7*.

An important design feature of classifier is that when the flow moves through each rectangular hole *3*, the flow is further divided into two jets in equal parts, which move in different directions relative to each other, reaching the inner wall of cylindrical body *6*, while the gas jets turn around and move in a vortex to the upper part of device. With the rotational movement, the gas jets form vortices with high values of centrifugal forces. Each vortex has two areas of contact with neighboring vortices that in-

creases the flow movement and centrifugal forces. The gas dynamics of described process, simulated in ANSYS Fluent software package, is shown in figure 2.
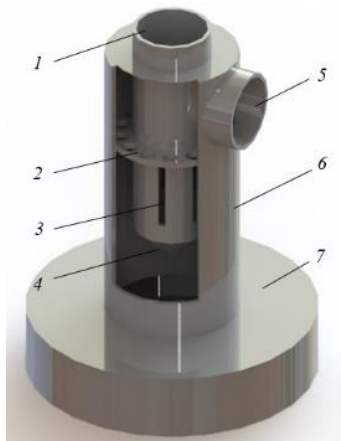

Figure 1. The classifier with co-axially arranged pipes: 1 – inlet nozzle, 2 – screen with coaxially arranged pipes, 3 – rectangular holes, 4 – additional hole, 5 – out-let nozzle, 6 – device bode (case), 7 – bunker.

During the rotational movement due to inertial and centrifugal forces, the particles of silica gel-based material are knocked out of the flow, fall into the "dead zones" between the vortices and settle down in the bunker *7*. Then, the gas flow passes through the screen with coaxially arranged pipes *2* and exits the device through the outlet nozzle *5*. It should be noted that when gas moves through a screen with coaxially arranged pipes, some part of silica gel-based particles cut into the screen wall and they are knocked out of the flow structure that contributes to additional collection. Thus, the collection of silica gel-based material particles of up to 30 microns in size in a classifier with coaxially arranged pipes is carried out mainly by means of centrifugal, inertial and gravitational forces. The most effective areas where the particles of silica gel-based material fall out of the structured flow are the following: 1) transition from the narrowing cone-shaped hole to the inner part of classifier, 2) area of vortices formation, 3) contact area of gas flow and a screen with coaxially arranged pipes.
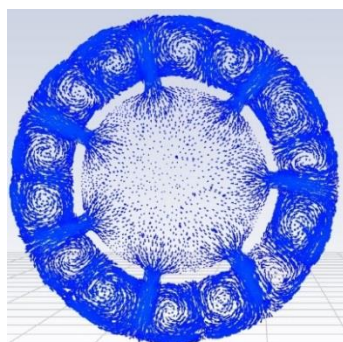

Figure 2. The gas dynamics in a classifier with coaxially arranged pipes; vortex effect (top view of cross section).

It should be noted that the construction of classifier with coaxially arranged pipes was performed with "engineering intuition". At the moment, it is necessary to create an engineering method for calculating this device. The most physically effective and cost-effective way to obtain the significant calculated dependencies between technological and design parameters is the numerical simulation of gas-dynamic processes in the proposed device. The simulation of these processes is associated with a large number of difficulties; in particular, in order to speed up the calculations and obtain reliable data, it is necessary to choose the most suitable turbulence model for this device and to determine the most optimal number of cells in the calculation grid. Therefore, the purpose of this study is to analyze various mathematical models of turbulence when calculating the gas dynamics in a classifier with coaxially arranged pipes.

ANSYS Fluent software package was chosen as a program for analyzing various mathematical models of turbulence. This software package is designed for modeling complex flows of liquids and gases with a wide range of changes in thermal properties by providing various modeling parameters and using the multigrid methods with improved convergence. The program uses the finite element method, which is a grid-based approach. Depending on the chosen turbulence model, the differential equations with partial derivatives are derived (the Navier-Stokes equation) [15-17].

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

(1)

where:
∇ – nabla;
Δ – vector Laplace operator;
t – time period, c;
v – kinematic viscosity coefficient, m^2/s;
ρ – density, kg/m^3;
p – pressure, Pa;
$\vec{v}$ – velocity vector field;
$\vec{f}$ – vector field of mass forces.

The Navier-Stokes equation is supplemented with the continuity equation:

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

(2)

These equations are also supplemented with the specified boundary conditions. During preparation for the numerical simulation, a three-dimensional geometry of classifier with coaxially arranged pipes was created in ANSYS Fluent software package, shown in figure 1. The following turbulence models were chosen for the study: Spalart-Allmaras, SST k-ω, transition SST, and RSM. The laminar model (Laminar) was also considered.

The standard SST k-w model is based on the equations of transferring the turbulence kinetic energy k and the specific dissipation rate ω. These 2 parameters can be determined by equations (3) and (4). It should be noted that the main differences between SST k-ω and k-ω models are the following: 1) sequential change of internal flow in the boundary layer to the high-Reynolds k-ε model for the outer area of boundary layer in SST k-ω model is done; 2) turbulent viscosity formula is modified in order to take into account the effects of the main turbulent shear stress transfer.

$$\frac{\partial}{\partial t}\left(\rho k\right) + \frac{\partial}{\partial x_i}\left(\rho k v_i\right) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k ,$$

(3)

$$\frac{\partial}{\partial t}\left(\rho w\right) + \frac{\partial}{\partial x_i}\left(\rho w u_i\right) = \frac{\partial}{\partial x_j}\left(\Gamma_w \frac{\partial w}{\partial x_j}\right) + G_w - Y_w + D_w + S_w ,$$

(4)

where:
G_k – generation of turbulence kinetic energy by averaged flow gradients;
G_w – generation as per w parameter;
Γ_k, Γ_w – effective diffusion k and w respectively;
Y_k, Y_w – dissipation of k and w under the influence of turbulence, respectively;
D_w – lateral diffusion; S_k, S_w – source terms to be defined depending on the task.

The advantage of k-ω model is a high accuracy in describing the wall turbulence and sensitivity to boundary conditions in the external flow.

Transition SST model, which is an improved standard SST model, was considered as well. This model provides a more accurate description of turbulence by introducing additional transfer equations,

one for intermittency, and the other one for the velocity head, calculated for the thickness of momentum loss.

Spalart-Allmares model is a relatively simple one-parameter turbulence model, with one additional turbulent viscosity transfer equation for calculating the kinematic coefficient of vortex viscosity:

$$\frac{\partial v_t}{\partial t} + u_i \frac{\partial v_t}{\partial x_i} = P_{v_t} + D_{v_t} + \varepsilon_{v_t}. \tag{5}$$

The left part of equation accounts for convection, the right part – for energy generation, diffusion, and dissipation. It should be noted that the use of this model allows to describe the entire flow area, including the wall layers. The advantages of this model are its stability and a good degree of convergence. The disadvantages include inaccuracy of calculation for shear and separated flows, and damping of turbulence.

RSM model (Reynolds Stress Model – full model of the Reynolds stress). This model is based on one of the above described models, but additionally to two differential equations of these models it is supposed to solve 6 more differential equations which describe the transfer of each of the 6 Reynolds stresses. When the model is supplemented with additional differential equations, the calculation time increases and the convergence of calculation processes as a whole becomes more complicated, which is one of its disadvantages. However, the use of the Reynolds stress model provides a deeper understanding of turbulence process.

When performing the numerical simulation, the following constant values were taken: the gas flow rate at the inlet nozzle was assumed to be 10 m/s, and pressure at the outlet of classifier was assumed to be equal to the atmospheric pressure – 101325 Pa. The geometric dimensions of classifier with co-axially arranged pipes were taken as follows: diameter of inlet and outlet nozzle – 60 mm; diameter of classifier body – 100 mm; height of classifier – 290 mm; height of inner cylindrical pipe – 192 mm; diameter of coaxially arranged pipes in the screen – 12 mm; diameter of hole in the lower conical part of inner cylindrical pipe – 16; height and width of rectangular holes – 60 mm; depth and diameter of bunker – 50 and 210 mm, respectively.

In the course of study, a three-dimensional model of classifier with coaxially arranged pipes was divided into 1241551, 2080907 and 3159388 cells (figure 3).
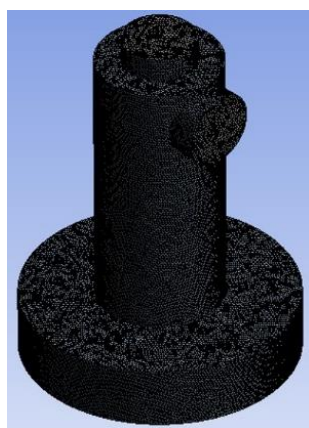

Figure 3. Grid generation. Number of cells $N = 1241551$.

When generating the dependence diagrams, the pressure loss Δp in the classifier with coaxially arranged pipes was calculated by using the following equation:

$$\Delta p = p_1 - p_5, \tag{6}$$

where p_1 – pressure at the inlet nozzle 1, Pa; p_5 – pressure at the classifier outlet nozzle 5, Pa.

3. Results and discussion

The results showed that the pressure loss in the classifier with coaxially arranged pipes is not more than 395 Pa at the inlet gas flow rate W =10 m/s. The pressure loss in the classifier was on average equal to 383, 385, 386, 390, 389 Pa when using laminar, Spalart-Allmaras, k-ω, RSM and Transition SST as the calculation models, respectively, with the number of cells from 1241551 to 3159388. The difference between the calculation models: laminar, Spalart-Allmaras, k-ω, RSM and Transition SST, when determining the pressure loss, was not more than 6%. It should be noted that with the number of cells 1241551, 2080907 and 3159388, the difference between the maximum and minimum values of pressure loss in the classifier for different calculation models was on average equal to 2.92, 4.54 and 2.48%, respectively. The use of laminar, Spalart-Allmaras, k-ω, RSM and Transition SST models, when increasing number of cells from 1241551 to 3159388, showed that the deviation values for the pressure loss in the classifier are not more than 4.44, 3.04, 1.05, 1.22, and 0.43%, respectively (figure 4).

The obtained results show that for the numerical calculations of gas dynamics in a classifier with coaxially arranged pipes, it is possible to use any of models, specified above, with the number of cells at least 1241551. However, the most suitable turbulence model for calculating the developed classifier is Transition SST, since there is the smallest change in the pressure loss in the device when the number of cells in the calculated geometry changes (figure 4).

Based on the chosen Transition SST turbulence model for a classifier with coaxially arranged pipes, a calculation was conducted to determine the pressure loss change in this device when the inlet gas flow rate changes from 5 to 10 m/s. In the course of numerical simulation, it was found that the pressure loss in the classifier is on average equal to 234 Pa at the inlet rate of 5–10 m/s (figure 5).

The following power function equation, describing an impact of inlet gas flow rate on the pressure loss in the classifier, was obtained

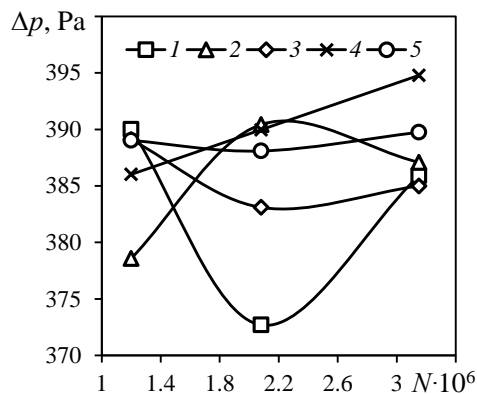$$\Delta p = 3.89 W^{1.99} . \tag{7}$$

Figure 4. The dependence of pressure loss change in a classifier with coaxially arranged pipes on the number of cells for different calculation models: *1* − Laminar; *2* − Spalart-Allmaras; *3* − k-w; *4* − RSM; *5* − Transition SST. The inlet rate of gas flow is W = 10 m/s.
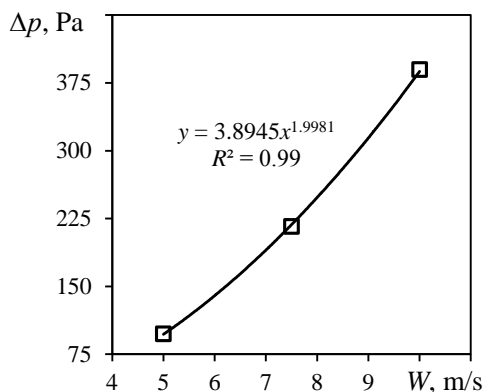

Figure 5. The dependence of pressure loss change in a classifier with coaxially arranged pipes on the inlet rate of gas flow.

Also, when using Transition SST turbulence model, the change of gas flow rate in rectangular gaps was studied, depending on the measurement point. In order to determine the gas flow rate at various points of rectangular gap, it was divided into 7 sections with a step of 10 mm. In the first and the last sections, the gas rate was equal to zero, since these were the extreme points in the upper and lower parts of gap that were directly in contact with the inner cylindrical pipe. The gas rate in the intermediate sections was on average equal to 12.4 m/s. At the same time, the maximum gas rate was reached in the upper sections, which was up to 14.8 m/s. The minimum gas flow rate of 11 m/s was determined in the central part of rectangular gaps. The gas flow rate increased again to 12.7 m/s as it moved away from the central part of gap to the lower parts under the study (figure 6).
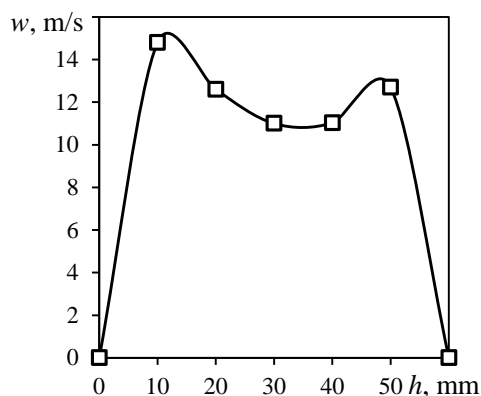

Figure 6. The dependence of gas flow rate change from a rectangular gap on the location of area where the rate was determined.

Such distribution of gas flow rates can be explained as follows: when gas moves through the inner cylindrical pipe, most part of flow is directed immediately to the narrowing areas, i.e. to the upper sections of rectangular gaps, as a result of which the maximum rate values are reached there. The rest part of gas flow is distributed to the central and lower parts of rectangular gaps and to the area, located after the hole in the cone-shaped part of inner cylindrical pipe.

When gas passes through the lower hole in the cone-shaped part of pipe, it is directed to the upper part of device, while skirting the rectangular gaps from the outside, and, as a result of this process, the flow structure changes in the lower and central parts of rectangular gaps, which leads to a change in the values of gas flow rate within them. In particular, the upward flow picks up and pushes gas, leaving the lower sections of rectangular gaps. However, as it moves towards the central part of gaps, it becomes an additional resistance for the outgoing flow from the gap, and, as a result of which the gas rate in the central parts of gaps decreases (figure 6).

Thus, the study showed that when developing the devices, the use of numerical simulation can significantly simplify this process and reduce economic costs.

4. Conclusion

In the course of study, it was found that the most correctly chosen turbulence model, combined with the optimal number of cells in the calculation geometry, contributes to the acceleration of numerical simulation of gas-dynamic processes in the developed device. Among the considered models i.e. laminar, Spalart-Allmaras, k-ω, RSM and Transition SST, the most adequate one is Transition SST model. When changing the number of cells in the calculation grid from 1241551 to 3159388 for this model, the deviation of pressure loss in the classifier was 0.43%.

It was found that with a relatively large number of cells in the calculation grid (this paper includes the study of change in the number of cells from 1241551 to 3159388), it is possible to use any model i.e. laminar, Spalart-Allmaras, k-w, RSM or Transition SST, since the deviation for the pressure loss calculation is not more than 6%, which is an acceptable value for the numerical simulation (modeling). When using Transition SST turbulence model, an equation was obtained for the dependence of pressure loss in a classifier with coaxially arranged pipes on the gas flow rate, which shows that the pres-

sure loss in the device increases with an increase of rate. The gas dynamics in rectangular gaps was also analyzed, and showed that in the central sections of gaps, the gas rate is minimal, reaching 11 m/s, and in the upper and lower sections of rectangular gaps, the rate increases up to 14.8 m/s, due to the device design features.

The advantages of developed classifier with coaxially arranged pipes are the following: design simplicity, ease of operation and high efficiency.

5. Acknowledgments

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