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NUMERICAL SIMULATION OF COAL SUSPENSION SEDIMENTATION

SYMULACJA NUMERYCZNA PROCESU SEDYMENTACJI ZAWIESINY WĘGLOWEJ

The article describes the feasibility of numerical simulation of sedimentation process of coal suspension, with high concentration, using the Ansys Fluent package, with the assumption monodisperse grain composition of the disperse phase of the suspension. The analysis contains selection of computational model, determine the parameters for analysis and comparison of the results with laboratory tests. To comparison laboratory measurement and numerical simulation sedimentation test was used. In the analysis was used suspension from the coal purification process.

Keywords: coal suspension, sedimentation, numerical simulation of sedimentation, sedimentation test

W artykule zamieszczono analizę możliwości prowadzenia symulacji numerycznych procesu sedymentacji zawiesiny węglowej o wysokim stężeniu, z wykorzystaniem pakietu Ansys Fluent przy założeniu monodyspersyjnego składu ziarnowego fazy dyspersyjnej zawiesiny.

Analiza zawiera dobór modelu obliczeniowego, określenie parametrów analizy oraz porównanie uzyskanych wyników z badaniami laboratoryjnymi. Do porównania pomiaru laboratoryjnego oraz symulacja numeryczna wykorzystano test sedymentacyjny. W analizie wykorzystano zawiesinę z procesu oczyszczania węgla.

Słowa kluczowe: zawiesina węglowa, sedymentacja, symulacja numeryczna sedymentacji, test sedymentacyjny

1. Introduction

One of the essential elements in coal mining systems is the process of its enrichment. This involves leaching of pollutants from the coal extracted. During this process, considerable amounts of water up to 1÷1.5 m^3/T of processed raw material are used (Blaschke, 2009). The enrichment results in formation of a fine suspension comprising a solid fraction in the form of coal sludge with

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a particle size of a few to tens of micrometers. The solid fraction of the suspension is composed mainly of waste rock and coal. The resulting slurry usually have concentrations up to several tens of kilograms per cubic meter and the density of solids in the range of 2300÷2400 kg/m^3. What causes it constitutes a system with poor sedimentation properties.

In view of the fact that in industrial plants, in most cases use closed water circuits, this is related to the necessity of carrying out a cleaning process at a high level, such that there is no accumulation of contaminants is still circulating in a closed circuit (Blaschke, 2009). Process release a portion of the solid from the suspension normally is carried out in settling tanks (Kowalski, 2004; Burger & Wendland, 2001; Bandrowski et al., 2001; Banaś, 2004a), that is devices using sedimentation process. The intensification of the process of sedimentation, the optimization of the process as well as the construction settlers still an important research topic (Bajcar et al., 2010, 2011; Branny & Swolkien, 2010; Rostami et al., 2011; Goula, 2008; Samaras, 2010; Xanthos, 2011; Malcher & Gzyl-Malcher, 2012; Surowiak & Brozek, 2014; Tryggavason & Zaleski, 2011).

Sedimentation is one of the most common processes used in water purification systems. The popularity use of the sedimentation process in practical applications due to a number of factors, may include basic low operating costs of carrying out this process and their relatively simple structure. Extensive use of the sedimentation process in practice has resulted in a number of mathematical and empirical models (Bustos et al., 1999; Tory, 1996; Prosperetti & Tryggvason, 2007; Bandrowski, 2004) describing its course, or the effects of sedimentation devices (Gidaspow, 1994; Lundberg & Halvorsen, 2008). However, in most cases, models describing the sedimentation impossible to measure the concentration distribution in the device by a sedimentation analysis.

A very important change in the possibilities to analyze the operation of sedimentation tanks and the process of sedimentation itself has been achieved thanks to numerical methods, the use of which allows one not only to obtain information on the sedimentation rate in the device, but also to model multiphase systems (Goula et al., 2008; Bargiel & Tory, 2004; Kolodziejczyk, 2013). Furthermore, the use of numerical methods to calculate sedimentation allows, besides calculating slurry concentrations in the sedimentation device, to know its changes over time. Modeling of multiphase systems, which includes suspensions, is an issue that is continuously developed (Gicala, 2011; Kolodziejczyk, 2014). Unfortunately, due to a very broad spectrum of factors affecting the sedimentation properties of suspensions, to obtain reliable results of numerical simulations of sedimentation, it is an extremely difficult task. The reasons for this state of affairs should be sought in the level of complexity of the interactions that occur during the process of sedimentation. Depending on the physio-chemical properties of the slurry (eg. concentration, composition, grain size, structure of the dispersion fraction, etc.) (Banaś, 2004b) we can acquire different processes for suspensions of similar characteristics.

The aim of the work presented in this article is to analyze the feasibility of a numerical simulation of coal slurry sedimentation process using the Ansys Fluent package, assuming a mono-disperse grain composition of the dispersal phase of the suspension. The analysis contains a selection of the computational model, determining the parameters for analysis and a comparison of the results of laboratory tests. The analysis is carried out using a suspension derived directly from the coal purification in the installation of a coal enrichment plant.

2. The parameters used in the analysis of the suspension

The material to be analyzed is the suspension sampled from the coal enrichment process at a coal processing plant, which was taken from the feed stream of sediments into sedimentation tanks after the enrichment process. The marked concentration of the suspension sampled from the plant was 45 kg/m^3. In contrast, the material density of the disperse phase is determined by means of helium using an analyzer AccuPyc 1340 Pycnometer was 2299.7 kg/m^3. Particle size distribution of the disperse phase was also measured for the sampled slurry, which was carried out using a laser diffractometer Mastersizer 2000. The measured parameters of the grain size distribution of the suspension d_{10} = 1.071 microns, d_{50} = 5.001 microns, d_{90} = 40.991 Pm indicate that it is a fine-grained suspension, with 90% of the particles having a diameter of less than 40 microns. Since the measured particle size distribution of the disperse phase had a shape similar to the log-normal distribution, it was assumed that this distribution should be suitable to describe the grain composition. On the basis of the measurement data, parameters of the log-normal distribution were set, which respectively are:

m = 2.066 – the average value of the natural grain size logarithm,

σ = 1.4945 – standard deviation of the natural logarithm of the particle size.

On the basis of the average of m = 2.066 log-normal distribution, the grain size was calculated at d_m = 7.89 microns and is slightly higher than the d_{50} obtained from the measurement.

3. Selection of the tool and computational model

In order to carry out numerical simulations of coal slurry sedimentation, one needs a selection of tools and a numerical model that one can use for modeling. In the current analysis, it was decided to use the software package ANSYS Fluent as a strong leader in the field of computational capabilities for modeling of multiphase systems.

By setting out to model a multiphase system, one must assume a fundamental element to determine which class numerical model will be the most suitable one to carry out simulations of interest. Currently, we can distinguish models belonging to two classes for multiphase systems Euler-Lagrange (DPM) or Euler-Euler modeling. The Discrete Phase Model (DPM) which helps model mulch-phase systems with a granular disperse phase assuming a low concentration of the dispersed phase. DPM models are characterized by the fact that in the continuous phase of the fluid, the movement of each grain of the disperse phase is calculated. In connection with this method of calculating the disperse phase is not possible to model multiphase systems with a high proportion of the disperse phase.

The models belonging to the second group (Euler-Euler) are VOF, Mixture and Eulerian. These models analyze the movement of each phase (dispersed and continuous) as a continuous medium. In the calculation area, each of the phases is represented by its volume fraction. Depending on the model, the interactions between the phases are considered differently. Therefore, each model is dedicated to a different group of multi-phase systems or allows to analyze the system in other respects.

The main criterion for choosing a model class is the volume fraction of the disperse phase. In the case of the suspension analyzed, the volume fraction of the dispersed phase will be, for the initial concentration, s_{0z} = 45 kg/m^3 and the density of the solid part ρ_d = 2299.7 kg/m^3 was,

in accordance with equation (1) $\alpha_d = 0.0195$. As the volume of the dispersion fraction is almost 2%, one can classify the sedimentation process which will occur in the suspension as a process of hindered sedimentation (Bandrowski, 2001).

$$\alpha_d = \frac{s_0}{\rho_d} \tag{1}$$

An additional criterion that can be used here to calculate the average distance between particles of the disperse phase, which one can determine from the load of suspension particles and density ratio in the phases. The load of suspension with particles is determined according to (2) and is $\beta = 0.0459$.

$$\beta = \frac{\alpha_d \cdot \rho_d}{\alpha_c \cdot \rho_c} \tag{2}$$

where

d — index of the disperse phase,
c — index of the continuous phase.

The ratio of the density of the disperse phase and the continuous phase shall be $\gamma = 2.2997$ (3).

$$\gamma = \frac{\rho_d}{\rho_c} \tag{3}$$

With regard to the above relations (2) and (3) one can determine the average distance between the particles in suspension from equation (4), which is $L/d_d = 2.99$ (Crow i in., 1998).

$$\frac{L}{d_d} = \left(\frac{\pi}{6} \frac{1 + \frac{\beta}{\gamma}}{\frac{\beta}{\gamma}} \right)^{\frac{1}{3}} \tag{4}$$

If the average distance between the particles is greater than 8 then there is confidence that each grain falls freely, independently of the other grains, and the model DPM can be deemed appropriate to describe the motion of the grains. However, in the system where the average distance between particles is less than 8, one should consider one of the VOF models, Mixture or Eulerian (ANSYS® Inc., 2010). Since the VOF model allows modeling multiphase systems where both the continuous phase and the dispersion phases are liquid, it cannot be used for modeling the sedimentation of coal slurry.

The criterion for using the Mixture model or Eulerian is the Stokes number defined as the product of the reaction time of the grain and the system, where the particles' response time is calculated from the equation (5) and for grain $d_m = 7.89$ microns is $\tau_d = 8 * 10^{-6}$ s

$$\tau_d = \frac{\rho_d \cdot d_d^2}{18 \cdot \mu_c} \tag{5}$$

while the response time of the system t_s It is calculated based on the dominant flow rate v_s as well as the dimension of the characteristic system L_s (usually the way from input to output) according to equation (6).

$$t_s = \frac{L_s}{v_s} \tag{6}$$

Finally, the Stokes numbers will be calculated according to (7).

$$S_t = \frac{\tau_d}{t_s} \tag{7}$$

The limit value of the Stokes number is 1. For $S_t << 1$ we can use any model of the multiphase system, and for the number of S_t above 1 use the DPM or Eulerian model.

In the case of modeling static sedimentation, a system without flow is analyzed, therefore, the dominant component will be movement of particles of the disperse phase, thus making the Eulerian a more appropriate model to describe the process of static sedimentation. Due to the volume fraction of the disperse phase, the DPM model cannot be used.

4. Eulerian model

The Eulerian model, used to model multi-phase systems, allow the implementation of the simulation in which there is one main phase (solid) and at least one disperse phase. In this model, there is no limit to the number of dispersion phases beyond the limits of hardware consisting in the availability of memory and computing power. Additional restrictions may be connected with the inability to achieve convergence. The Eulerian model, among all models of multiphase systems, is the one with the greatest demand for computing power and RAM. However, it is a model that offers the widest possibilities when calculating the interaction between the phases.

A characteristic feature of this model is that for each phase, a continuity equation and a momentum equation are solved. In this model, it is assumed that the pressure at any point is the same for all phases. Other sizes are calculated individually for each phase. In this model, it is possible to take account of various types of inter-phase interactions as well as calculation of flow by one of the turbulence models for the various phases.

Each phase of the Eulerian model is treated as interpenetrating continua, representing a multiphase system, in which each phase has its share of volume described as α_q.(Anderson and Jackson,1967), where the total volume of shares of the various phases in the whole system is *1* (8)

$$\sum_{q=1}^{n} \alpha_q = 1 \tag{8}$$

continuity equation for phase q will have the form (9):

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v_q}\right) = \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right) + S_q \tag{9}$$

where:

$\vec{v_q}$ — the speed of phase q,

$\dot{m}_{pq}$, $\dot{m}_{qp}$ — flow of mass between two phases,

S_q — the external source of mass.

while the momentum equation for q phase will be described in the equation (10):

$$\frac{\partial}{\partial t}\left(\alpha_q \ {}_q\vec{v}_q\right)+\nabla\cdot\left(\alpha_q \ {}_q\vec{v}_q\vec{v}_q\right)=-\alpha_q\nabla \mathrm{p}+\nabla\cdot\bar{\bar{\tau}}_{\mathrm{q}}+\alpha_q \ {}_q\vec{g}+ \\ +\sum_{p=1}^{n}\left(\vec{R}_{pq}+\dot{m}_{pq}\vec{v}_{pq}-\dot{m}_{qp}\vec{v}_{qp}\right)+\left(\vec{F}_q+\vec{F}_{lift,q}+\vec{F}_{vm,q}\right) \tag{10}$$

where:

$\bar{\bar{\tau}}_q$ — phase q stress tensor,
$\vec{F}_q$ — the force of external impacts,
$\vec{F}_{lift,q}$ — lifting force.
$\vec{F}_{vm,q}$ — mass force (inertia)
$\vec{R}_{vm,q}$ — the force of inter-facial interactions – dependent on friction, pressure, or cohesive interactions.

5. Laboratory tests of the static sedimentation process

One of the methods for assessing the sediment properties of the suspension and the run of the sedimentation process is the study of static sedimentation. Such measurements can be carried out only for the suspension of parts of constant volume fractions above 0.1%. The suspension intended for tests contains about 45 kg of solid mass in one cubic meter (the volume fraction of the solid part at 2% (1)), thus in the course of the sedimentation process will be within the sedimentation held back, allowing the use of a sedimentation test (Kynch, 1952) to the assessment of the results of numerical simulation. In the course of the hindered sedimentation, due to the occurrence of zone sedimentation, zones form in the slurry with different concentrations, in particular, a clear liquid zone is formed and separated by a clear boundary layer of slurry. Test execution of sedimentation of the slurry involves logging the level of the boundary between clean liquid and a first zone of the thickened sludge versus time. On the basis of the sedimentation curve one can determine, for example, sedimentation rate for slurry of a given concentration, the maximum attainable level of compression, as well as the size of the sedimentation tank required to produce clean current and an outflow with a predetermined concentration (Bandrowski, 2001).

The laboratory measurement for static sedimentation was realized in a measuring cylinder having an inner diameter of 42 mm and a height of slurry column of 0.93 m. The measuring cylinder was set vertically during the measurement. The measurement was carried out on a crude suspension without additives, and the sedimentation curve obtained during the measurement is shown in the graph (Fig. 1).

The sedimentation curve confirmed that this is a suspension with poor sedimentation properties. The inflection point of the sedimentation curve occurs only after about 10 hours of sedimentation. On the basis of the sedimentation curve one can determine the maximum density of the precipitate obtained by means of static sedimentation, which for the test suspension shall be $s_2 = 276$ kg/m^3.

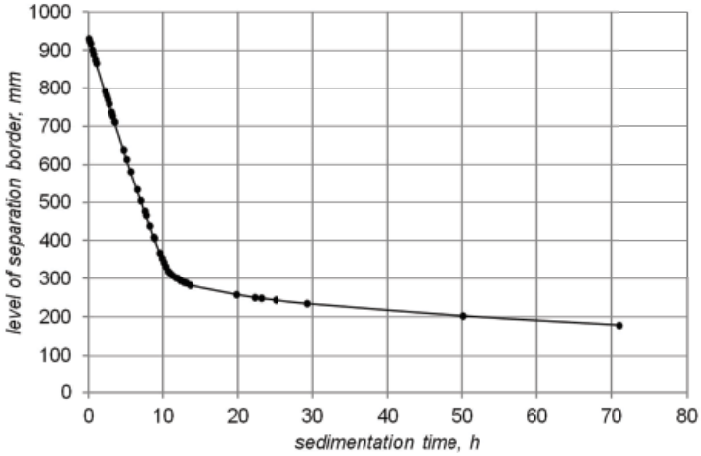

Fig. 1. Static sedimentation curve – laboratory measurement

6. Numerical simulations of static sedimentation

Based on the analysis performed, numerical simulations of static sedimentation were made. The simulations were performed by using the Eulerian calculation model on the assumption of a granular disperse phase. In its analysis, the simplification of replacing the poly-disperse grain composition with a mono-disperse suspension system with the accepted grain size equal to the diameter of a boundary grain at $d_m = 7.89$ microns for the test suspension. Numerical simulations were carried out for a cylinder with identical geometrical parameters as in laboratory testing. The cylinder was divided into a grid comprising 27,561 hexahedral elements (Fig. 2). The simulations were conducted as variable over time. The time-dependent analyzes include a very important element which is the selection of an appropriate time step. The research conducted so far shows that in sedimentation systems, the time step should be at the level of 1 s (Kołodziejczyk, 2011, 2012), but for different suspensions this value can vary. In the analysis, several numerical simulations assumed a different time step. The analyzes assumed, respectively, the following time step: 0.5 s, 1.0 s 2 s, 5 s. Since the implemented system used static sedimentation, no flow to all the walls of the geometry were assigned the boundary condition "wall". In the numerical simulation, as an initial condition, a uniform slurry concentration in the entire volume was adopted, established by the volume fraction of the disperse phase. In the run simulations, also a maximum density of the disperse phase amounting to 0.12 was assumed (adopted on the basis of the maximum concentration of sludge $s_2 = 276$ kg/m^3).

The result of numerical simulations of sedimentation in the form of curves is shown in Figure (3). The cited results show that despite the inclusion of suspension of all interactions in the model, no full compliance in the course of the curve and laboratory simulation was achieved. From the graph we can see that the sedimentation curves for time step 2s and 5s differed significantly from ones from the laboratory measurement. The most consistent sedimentation curve with the laboratory curve is seen at time step of 1s. The sedimentation curve for time step of 0.5 s, despite the initial compliance with the curves from the laboratory tests, finally acquired a too pronounced slant.

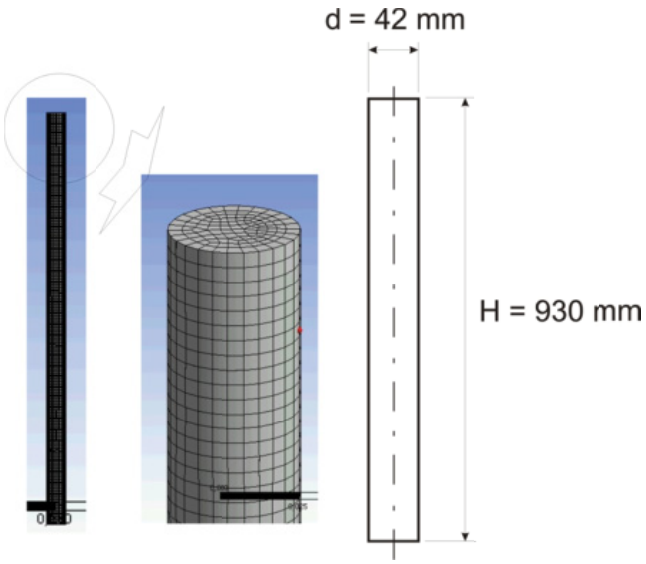

Fig. 2. The geometry used in the simulations divided into a grid of elements

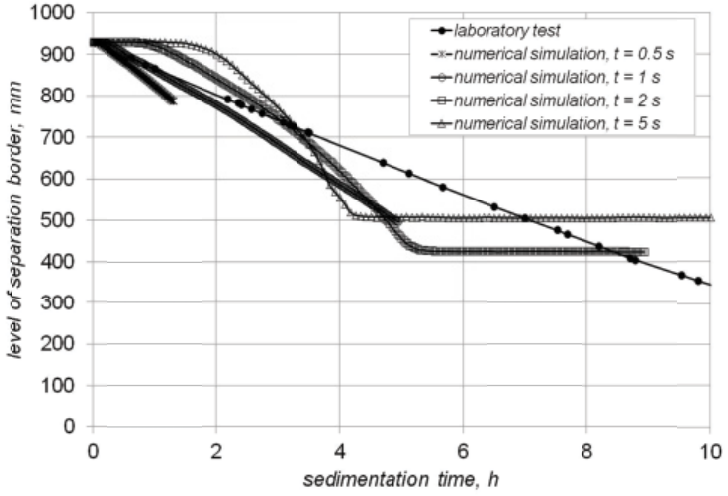

Fig. 3. Juxtaposition of sedimentary curves with laboratory measurements and numerical simulation

An important element of the numerical simulation calculations is the time required to calculate the given task. Despite the fact that the model to be analyzed – its numerical grid – may include small models is the time required to calculate one hour of sedimentation, assuming the time step 1s requires about 60 hours of CPU time, and the time step at 2s, the processor time is approx. 35 hours.

7. Conclusions

The analysis was carried out as a simulation of the mono-disperse system. The replacement of the suspension of a poly-disperse particle size distribution by a mono-disperse suspension in the case of hindered sedimentation back may be appropriate to the nature of sedimentation occurring in such a system – i.e. zone sedimentation irrespective of the grain size. However, as we see from the result, full compliance of laboratory and simulation measurements was not achieved, therefore one should attempt to perform a simulation for such a system assuming a poly-disperse grain composition of the disperse phase.

A major problem in the implementation the numerical calculations using the Eulerian model is the required computation time. For the small model containing less than 30,000 numerical grid elements, the processor's computing time was about 60 times longer than the physical process execution time. The volume of suspension for which the calculation was carried out was about 1.2 dm^3. Sedimentation tanks found in real systems have a size of several tens of thousands of times greater than the analyzed system, which in turn can result in considerable difficulties in technical implementation of the numerical simulations of the real-life systems.

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