На рис. 7. зображена вихідна амплітудно-частотна характеристика мікрорезонатора послідовного типу, яка показує випадок використання мікрорезонатора із неідентичними масами та вплив кожної складової на характер кривої.

Висновки. Отже, запропонована модель мікрорезонатора послідовного типу дає змогу розширити смугу пропускання, запропоновані рівняння дозволяють розрахувати оптимальну конструкцію, щоби максимально наблизити вихідні характеристики мікрорезонатора до тих, що вимагаються радіочастотною системою.

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MODELLING THE PROCESS OF SEDIMENTATION WITH THE USE OF NUMERICAL METHODS

The aim of works, which are contained in the article, is checking the correctness and the quality of simulation of sedimentation process reached results with the use of numerical methods. The author wanted to determine on the level of differences between calculation results with the use of CFD methods and results reached in the real system. These simulations were to give the answer if it is possible to apply the software FLUENT for simulation of the sedimentation process and how big error will appear.

Introduction. Nowadays the computer usage in many fields of life does not surprise anybody. Its general accessibility is natural. The aggressive development of computer technology, and the increase of computing power also made possible the aggressive progress of information technologies, using well-known methods for ten years. One of such technologies are numeric calculations using the finite element method or the finite volume method. Executable simulations, with the use of these methods, allow us to save a lot of time, work and money. With use of these methods we are able to simulate real systems or objects in large approximation.

We should remember that we are not able to simulate every real system or object. There are such complicated systems, that we will not be able to create the virtual of the real system still for long time. The process of sedimentation belongs to this category. From available software's only the software module FLUENT offers models, which are able to accomplish the simulation of the sedimentation process.

The aim of works, which are contained in the article, is checking the correctness and the quality of simulation of sedimentation process reached results with the use of numerical methods of the package FLUENT. The author wanted to determine on the level of differences between calculation results with the use of CFD methods and results reached in the real system. These simulations were to give the answer if it is possible to apply the software FLUENT for simulation of the sedimentation process and how big error will appear.

In order to check the ability of packet FLUENT to simulation sedimentation process the series of simulation were done. The simulations were done for a static sedimentation and a flow sedimentation on the laboratory stands.

The static sedimentation was realized in vertical and inclines cylinder with 1 m height. The sedimentation curve, that is the line illustrating the settling velocity of the interface between clear water and thickening suspension, was used as a comparative criterion of the real system and the computer simulation.

The flow sedimentation was realized in a laboratory stand which imitate the single duct of lamella. The stand consisted of an overflow and underflow zone with lead-on and lead-off suspension system enabling the realization of continuous suspension separating into clear water and thickening suspension. For this case the suspension concentration in the overflow and underflow zone, the sedimentation effectiveness and the thickness level were taken as a comparative criterion.

1. Packet FLUENT. The FLUENT program belongs to the family of CFD (Computational Fluid Dynamic), which are used to detailed analyses of problems connected with the fluid flow, the energy and the mass exchange. This software usage allows us to eliminate the expensive experimental researches during design and modernization of devices. This program has a huge possibilities. Proof to that is the applicability in many differential domains.

Currently there are two approaches for the numerical calculation of multiphase flows: the Euler-Lagrange approach and the Euler – Euler approach.

1. Euler -Lagrange approach – the fluid phase is treated as a continuum by solving the time-averaged Navier – Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets through the calculated flow field. The dispersed phase can exchange momentum, mass, and energy with the fluid phase. A fundamental assumption made in this model is that the dispersed second phase occupies a low volume fraction, even though high mass loading is acceptable. The particle or droplet trajectories are computed individually at specified intervals during the fluid phase calculation.

2. Euler – Euler approach – the different phases are treated mathematically as interpenetrating continua. The volume of a phase cannot be occupied by the other phases. These volume fractions are assumed to be continuous functions of space and time and their sum is equal to one. They are three different models in FLUENT:

- The VOF model is a surface-tracking technique applied to a fixed Eulerian mesh. It is designed for two or more immiscible fluids where the position of the interface between the fluids is in the centre of interest. In VOF model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain.
- The mixture model is designed for two or more phases (fluid or particulate). As in the Eulerian model, the phases are treated as interpenetrating continua. The mixture model solves for the mixture momentum equation and prescribes relative velocities to describe the dispersed phases. Applications of the mixture model include particle-laden flows with low loading, bubbly flows, sedimentation, and cyclone separators. The mixture model can also be used without relative velocities for the dispersed phases to model homogeneous multiphase flow.
- The Eulerian model is the most complex of the multiphase models in FLUENT. It solves a set of ”n” momentum and continuity equations for each phase. Coupling is achieved through the pressure and interphase exchange coefficients. The manner in which this coupling is handled depends upon the type of phases involved; granular (fluid-solid) flows are handled differently than non-granular (fluid-fluid) flows. For granular flows, the properties are obtained from application of kinetic theory. Momentum exchange between the phases is also dependent upon the type of mixture being modelled. FLUENT's user-defined

functions allow you to customize the calculation of the momentum exchange. Applications of the Eulerian multiphase model include bubble columns, risers, particle suspension, and fluidised beds [2].

For simulations of the sedimentation process the mixture and Eulerian model were use. They were apply because of two reasons. Firstly, in ours researches the suspension concentrations are very high, because of that we cannot use the Euler-Lagrange approach. Secondly, the VOF model is designed for two or more fluids, in our case we have fluid and solid as the dispersed phase, and we also cannot apply the VOF model.

2. The simulation of static sedimentation process . In order to compare the results taken from the computer simulation with the results taken from real system, author decided to use the static sedimentation curve. The periodical sedimentation of solid phase particles in the liquid proceeds when the flow rate supplied to the vessel and the flow rate of the underflow sludge and the flow rate of clarifying water equal zero. This process can be observed during the research called "sedimentation test". On the basis of the test the graph called sedimentation curve is prepared (fig. 1). This curve characterizes behaviour of the suspension [2, 4, 5].

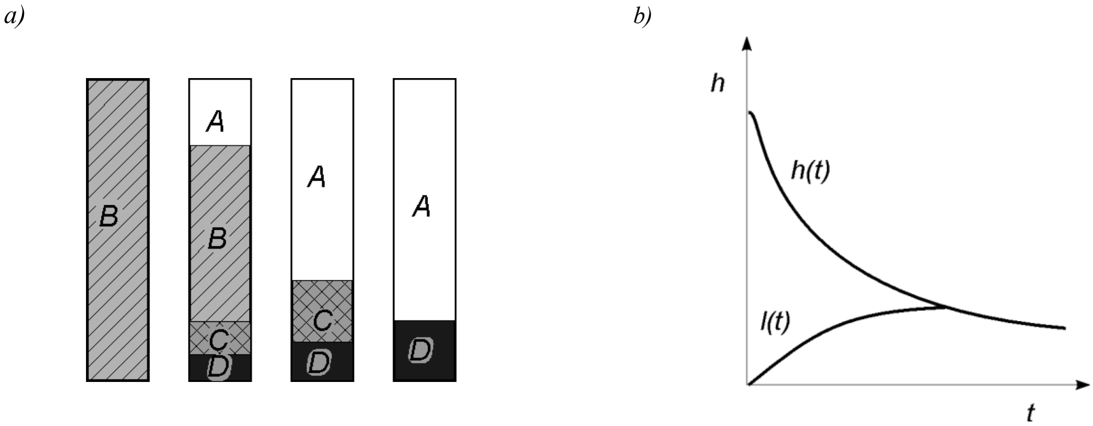


Fig. 1. Course of the periodical sedimentation, a) physical picture,
b) the graph of the high of the level separation h and l in function of time t

During the suspension sedimentation in vertical cylinder we can have even four zones with different concentrations, but not always. The picture (fig. 1 a) shows as the suspension distribution in vertical vessel in a following while of time for the example of sedimentation test. We can notice four zones: A – zone with clear water, B – zone with the constant concentration which is equal the started concentration, C – zone with the variable concentration, and D – zone with thickening sludge.

The sedimentation test is realized in vertical cylinder. The transparent cylinder is filled with homogeneous suspension and than we register the height of position of separation surface between following zones during the sedimentation. Points, which describe the position of separation surface between zones A and B, in following while of time compose sedimentation curve of suspension *h(t)*. Whereas the position of separation surface between zones B and C compose the sludge accretion curve *l(t)*.

First step to comparison simulation results of sedimentation process, realized in Fluent, with sedimentation results in real system were realized the sedimentation tests (research) on laboratory stand. Than for the realized tests there were done the simulations in packet Fluent.

For the research was used the industrial suspension from the process of copper ore enrichment (sludge after flotation), with concentration of about $S=130\ kg/m^3$ and with a solid particle density equal $\rho=2700\ kg/m^3$.

The laboratory research was realised on the stand presented at the picture (fig. 2).

The author conducted a static research of sedimentation process according to the PN-G-04570 norm. The suspension to the tests was prepared in the tank. It means that the suspension was mixed (homogenizing) for 30 minutes and after using the beaker the cylinders were filled. The maximum level of suspension column was equal 0.93 m. The filled cylinders were placed at the measurement bed.

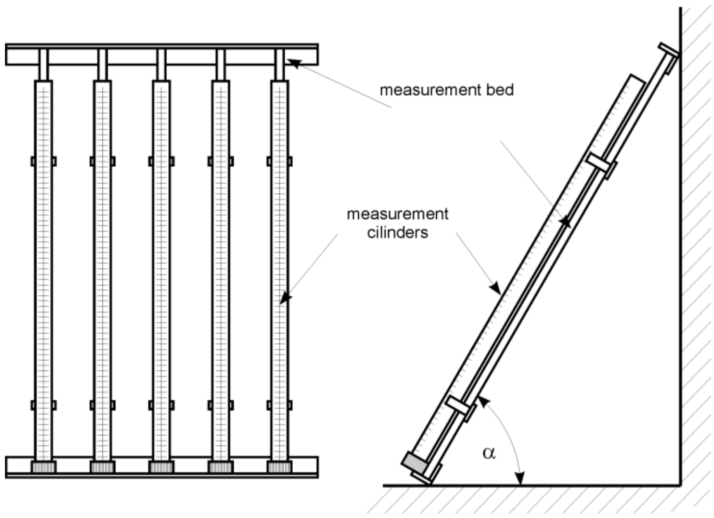


Fig. 2. Stand to the static research of the multiflux concentration process of suspension

Suspension in the cylinders was mixed directly before the sedimentation test. It means that closed cylinder was inverted for about 5 minutes until reaching the homogeneous concentration in a whole volume. After that the measurement started. The single measurement took about from two to four hours. Only the sedimentation curve was determined. After measurement the concentration in the cylinder was assigned to the filter method.

Determination of the sedimentation curve consisted in reading the position of the phase-border between clear liquid and suspension.

There were done two sedimentation tests: one for the vertical cylinder and one for inclination angle of the cylinder 45°.

For the carried laboratory tests of static sedimentation the simulation in Fluent was done. On the picture (fig. 3, fig. 4) is presented the geometry, for which the simulation of static sedimentation was done. In carried simulations two models were used: the mixture and Eulerian models.

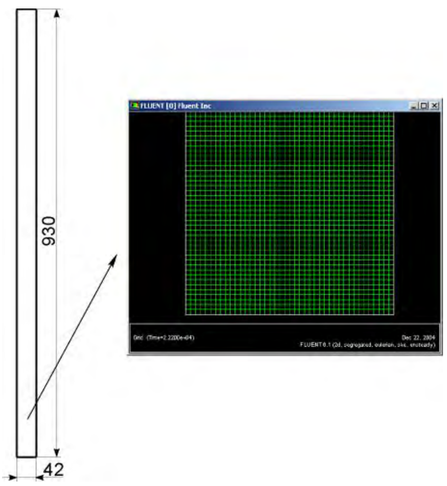


Fig. 3. The system geometry for simulation the static sedimentation and the mesh – vertical cylinder

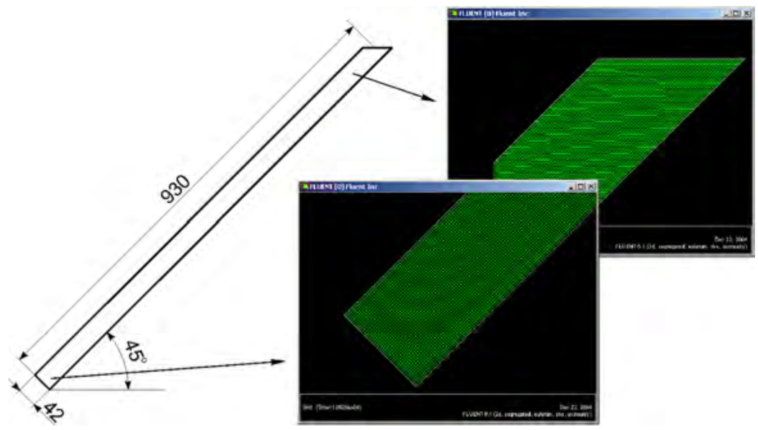


Fig. 4. The system geometry for simulation the static sedimentation and the mesh – inclined cylinder

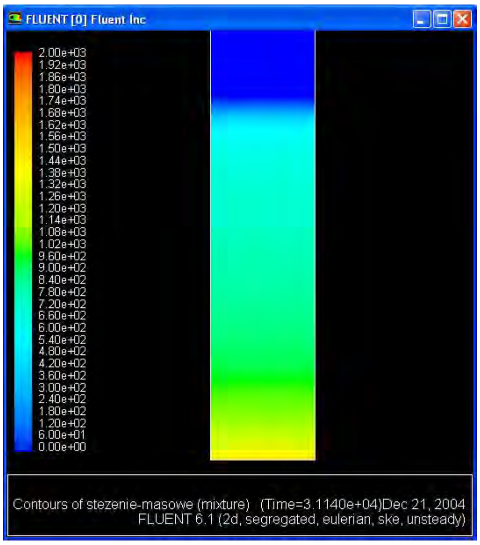
3. The simulation of monodispersed suspension. In simulations with use of these models we have two phases. One is treated as a continuous (liquid), but the second as the dispersed (solid particles) distributed in a continuous liquid. In simulations we defined the dispersed phase by setting the diameter of the particles and by setting the volume fraction. In fact the suspension has the particles with different shape and different size. For the suspension used in research the volume fraction of the solid phase was calculated from the equation ((1) and amount 0.04815 m^3/m^3.

$$\varphi = \frac{S}{\rho} \qquad (1)$$

For the sedimentation process the grain composition is very important. But in simulation presented in these part of article the monodispersed suspension was used. The suspension used in research for log-normal density distribution function of particles size had the parameters of the distribution function equal m=3.091 and σ=0.367. For that parameters of distribution the grain of diameter about 25 μm divides the cumulating distribution on equal two part. Therefore in simulations was used the monodispersed suspension with grain of diameter equal 25 μm.

The graphics results of simulations (schedule concentration) for Eulerian model for vertical and inclined cylinder are presented on picture (fig. 5).

a)



b)

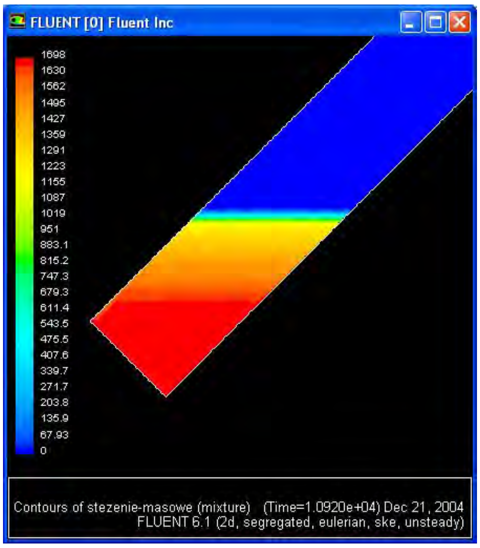


Fig. 5. Schedule concentration of suspension at the end of simulationi – Eulerian model
a) verticle cylinder, b) inclined cylinder – angle 45°

Schedule of concentration in axis of the cylinder for his vertical setting and the mixture model after 2 and 80 minutes of sedimentation process is presented at the pictures (fig. 6, fig. 7).

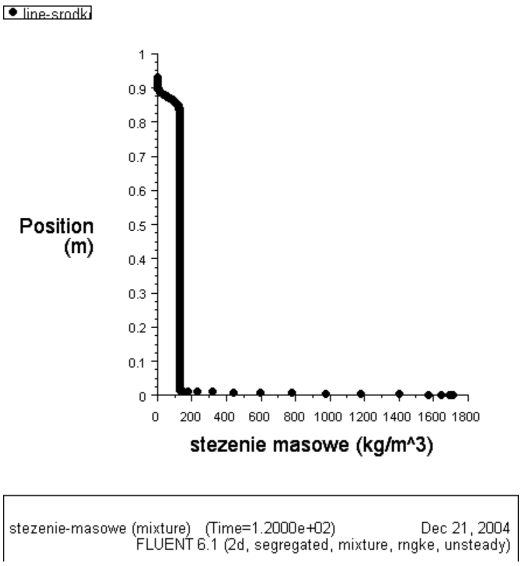


Fig. 6. Schedule of suspension concentration in axis of the cylinder for his vertical setting – mixture model – 2 min

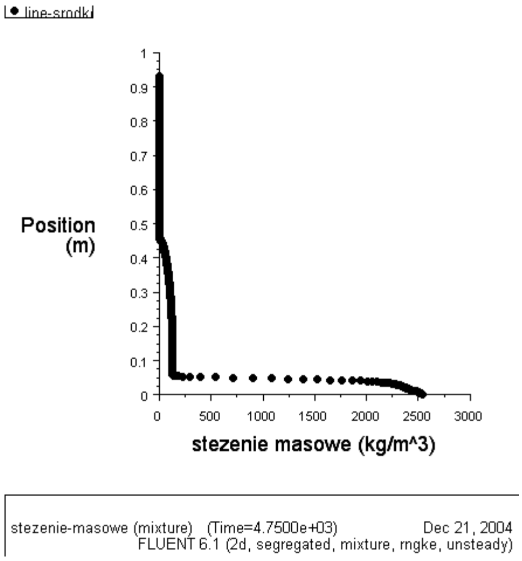


Fig. 7. Schedule of suspension concentration in axis of the cylinder for his vertical setting – mixture model – 80 min

Schedule of concentration in axis of the cylinder for his vertical setting and the Eulerian model after 10 and 100 minutes of sedimentation process is presented at the pictures (fig. 8, fig. 9).

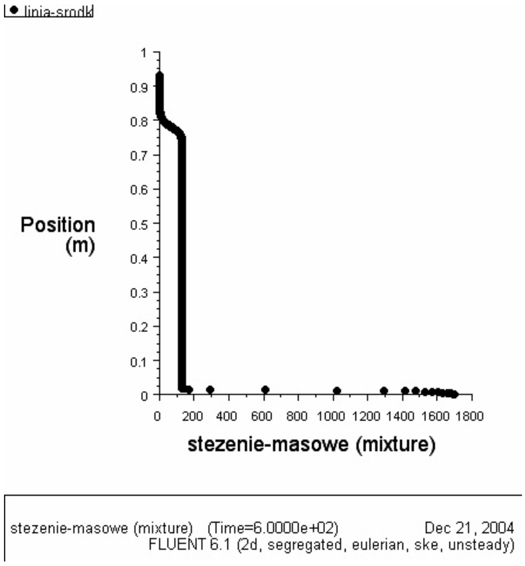


Fig. 8. Schedule of suspension concentration in axis of the cylinder for his vertical setting – Eulerian model – 10 min,

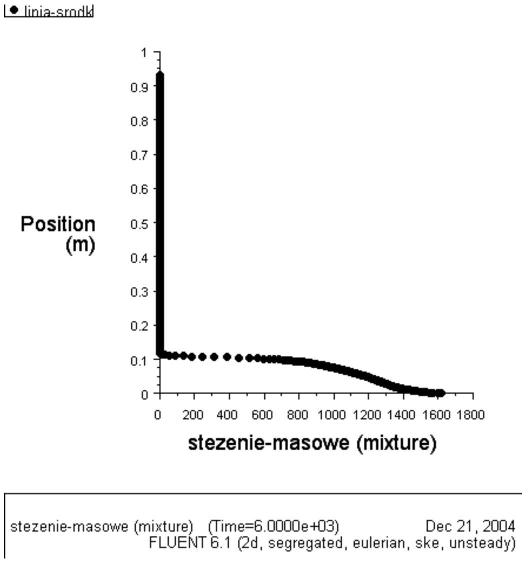


Fig. 9. Schedule of suspension concentration in axis of the cylinder for his vertical setting – Eulerian model – 100 min

From presented graphs of schedules of suspension concentration for different time moments it is seen that the gained results are rather correct. On the graphs we can notice the characteristics zones of sedimentation process. But gained results have essential difference in comparison with the real system, the gained concentration of suspension in compression zone is much higher from concentration gained during the laboratory research.

For tested suspension the average concentration in compression zone should be equal about 600 kg/m^3, but during the simulations it is much higher (fig. 6, fig. 8) and for Eulerian model reach value 1800 kg/m^3, and for mixture model reaches 2500 kg/m^3.

The comparison of the laboratory research to the simulation for vertical cylinder is presented at the graph (fig. 10). The graph presents a juxtaposition of sedimentation curves for laboratory research and simulations for mixture and Eulerian models. Whereas the comparison of the laboratory research to the simulation for inclination cylinder is presented at the graph (fig. 11). The graph presents a juxtaposition of sedimentation curves for laboratory research and simulations for mixture and Eulerian models.

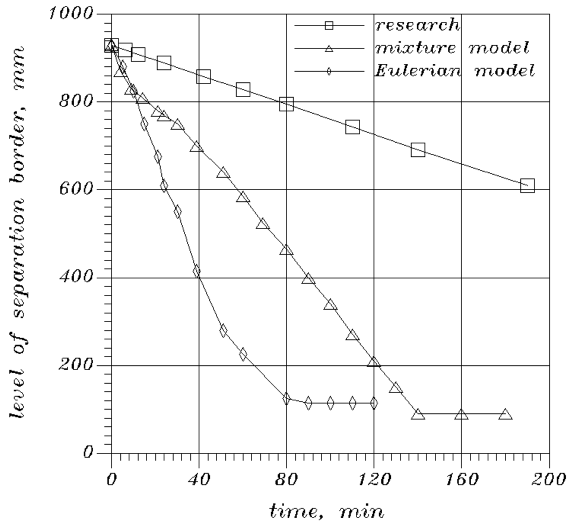


Fig. 10. The sedimentation curve for research and simulations – vertical cylinder

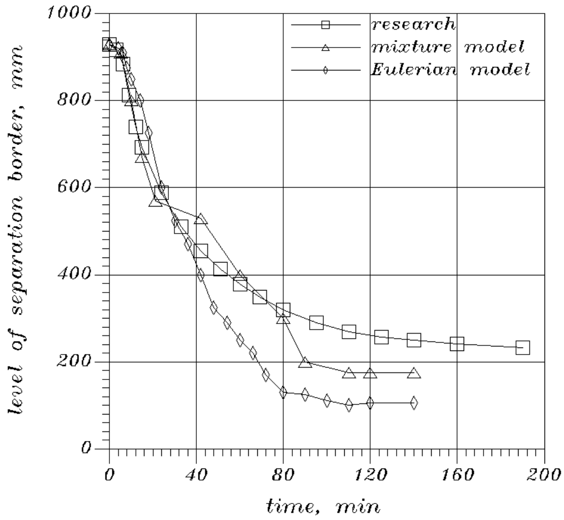


Fig. 11. The sedimentation curve for research and simulations – inclined cylinder

As we see on the comparative graphs, the differences simulation results and research results are very high. Especially we can see that for the sedimentation realized in vertical cylinder. So high difference in simulation results and research results are probably because of the usage the monodispersed suspension in computer simulations. Application for simulation the suspension, which granular constitution would be described e.g. density function of log-normal distribution, probably would decrease differences in results.

4. The simulation of monodispersed suspension. Simulation of sedimentation process of polidispersed suspension was the next step of led tests. Polidispersed suspension was defined by insert seven phases. First phase was defined as a continuous and she had the parameters of water. The following phases were defined as discrete with parameters such as the parameters of solid part of suspension. The following phases had the different diameters of grains and different volumetric part in all system. The parts of each phase, and the diameters of grains in these phases were calculating for log-normal density distribution function of particles size. The suspension used in research had the parameters of the distribution function equal m=3.091 and σ=0.367. The distribution function of particles size was partite on intervals. The average value of grain diameter and percentage portion of every interval in whole distribution was calculating for each interval. For the suspension, with concentration 130 kg/m^3 and her density 2700 kg/m^3, volume fraction of the solid phase amount 0.04815 m^3/m^3. After we regard the volume fraction of the solid phase in suspension and percentage portion of every interval in distribution function of particles size we receive volume fraction of each phase what is presented in the table 1.

Table 1

The parameters of phases describer the solid part of suspension in simulations

Interval of particles size	The average particle diameter	Percentage portion in distribution function	Volume fraction each phase in suspension
μm	μm	%	m^3/m^3
0÷10	5	1.6	0.00076
10÷20	15	38.2	0.01838
20÷30	25	40.3	0.01942
30÷40	35	14.7	0.00709
40÷50	45	3.9	0.00188
>50	55	1.3	0.00057

For suspension defined above the simulations of sedimentation process were done for vertical and inclined cylinder. The simulations were done with use Eulerian model.

Schedule of concentration in axis of the cylinder for his vertical setting after 10 and 100 minutes of sedimentation process is presented at the graphs (fig. 12, fig. 13).

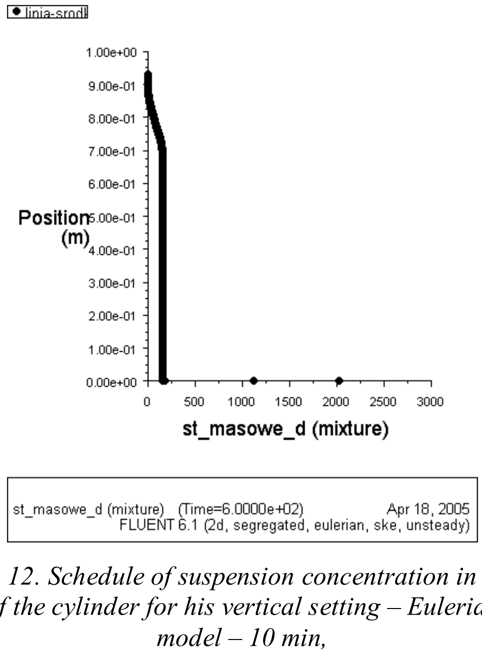


Fig. 12. Schedule of suspension concentration in axis of the cylinder for his vertical setting – Eulerian model – 10 min,

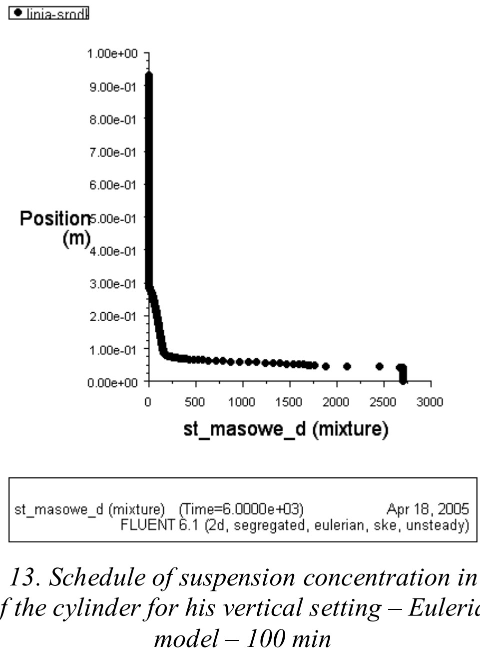


Fig. 13. Schedule of suspension concentration in axis of the cylinder for his vertical setting – Eulerian model – 100 min

From presented graphs of schedules of suspension concentration for different time moments it is seen that the gained results are like previously rather correct. On the graphs we can notice the characteristics zones of sedimentation process. But as we see the gained concentration of suspension in compression zone is much higher from concentration gained during the laboratory research. For tested suspension the average concentration in compression zone should be equal about 600 kg/m^3. In simulations for polidispersed suspension this concentration reach to 2700 kg/m^3.

The comparison of the laboratory research and the simulations for monodispersed suspension to the simulations for polidispersed suspension are presented at the graph (fig. 14) – vertical cylinder and (fig. 15) – inclined cylinder. The graphs present a juxtaposition of sedimentation curves for laboratory research and simulations for Eulerian model and the monodispersed and polidispersed suspension.

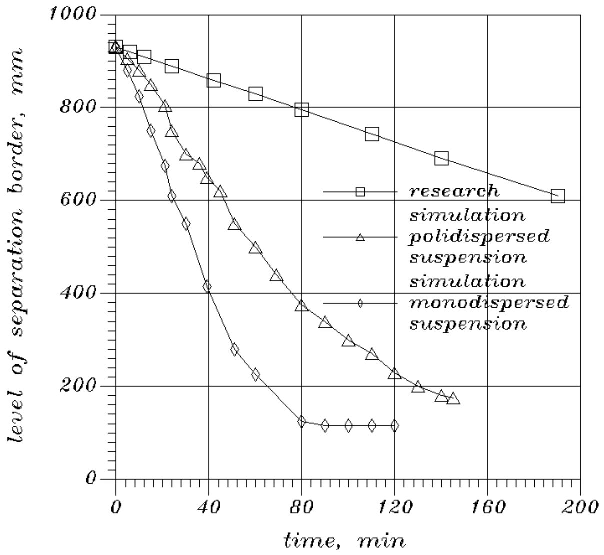


Fig. 14. The sedimentation curve for research and simulations for monodispersed and polidispersed suspension – vertical cylinder

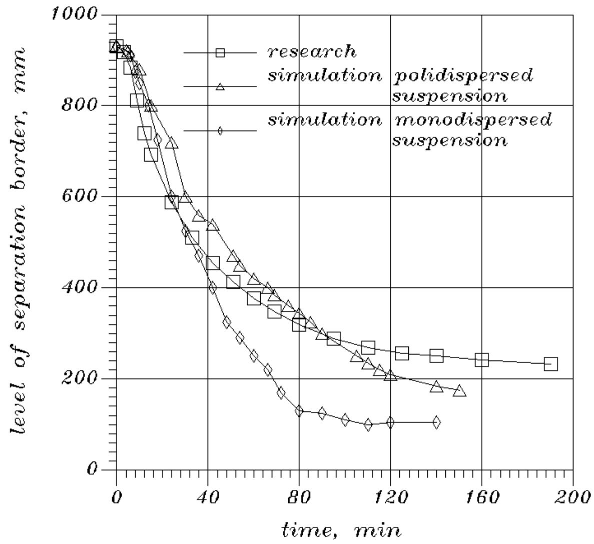


Fig. 15. The sedimentation curve for research and simulations for monodispersed and polidispersed suspension – inclined cylinder

As we see on the graphs (fig. 14, fig. 15), the differences research results and simulation results for polidispersed suspension are smaller than for monodispersed suspension. The dirrerences are smaller but still very high especially for perpendicular cylinder.

5. The simulations of flow sedimentation process. The comparison was done also for the results gained from the sedimentation process realized in flow settling system.

On the laboratory stand presented at the picture (fig. 16) was done the research of flow sedimentation for suspension described in the previous chapter. The research was done for sedimentation duct inclined at an angle 45° and for his vertical position. The research was realized for the flow rate stream of feed equal Q=100 cm^3/min, concentration of the suspension equal S=130 kg/m^3 and the portion of the underflow stream referred to the feed stream equal u=0.5.

The simulation of sedimentation process was done in planar system. The geometry which was used to realized simulation of flow sedimentation is presented at the picture (fig. 17).

Two simulation were done: first for the vertical geometry setting and the second for the geometry sets at the angle 45°. The simulations were done with using the Eulerian model. The juxtaposition of results gained from research and simulations is presented at the graph (fig. 18, fig. 19). The graph (fig. 18) presents the feed, underflow and overflow concentration for sedimentation with vertical settings of the duct, but at the graph (fig. 19) for the inclined duct.

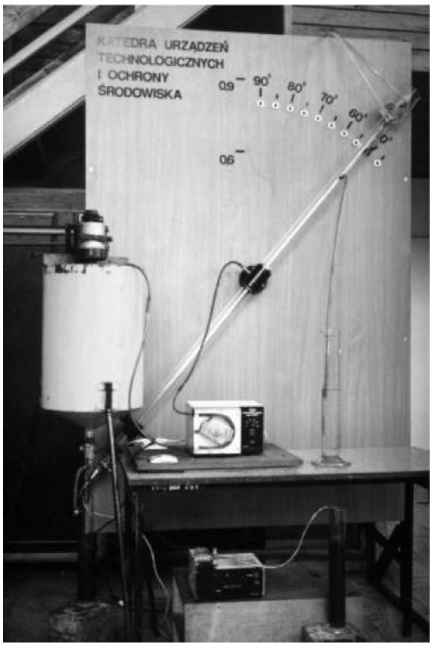


Fig. 16. The laboratory stand to research of flow sedimentation

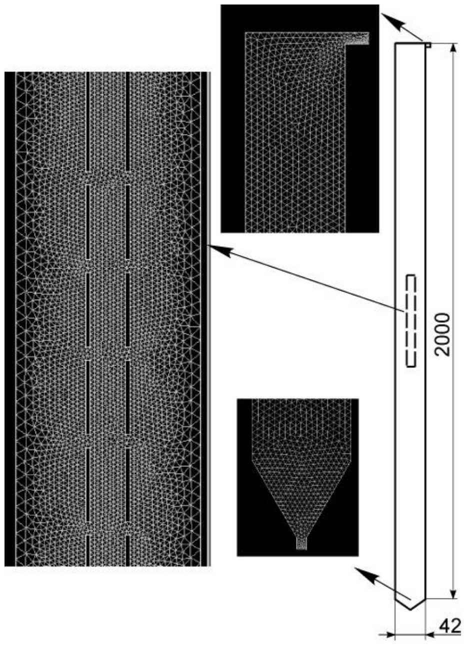


Fig. 17. The geometry to simulation of flow sedimentation in a planar system with mesh

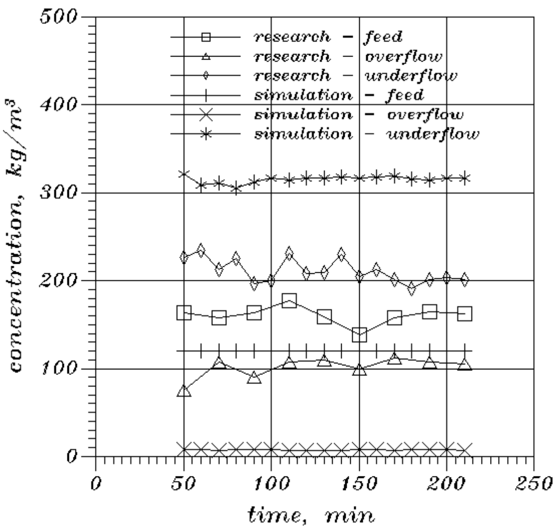


Fig. 18. The feed, overflow and underflow concentration – vertical duct

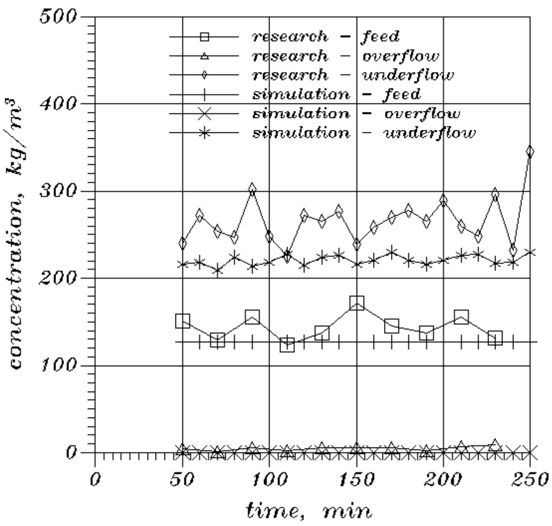


Fig. 19. The feed, overflow and underflow concentration – inclined duct

The presented results show, that also for sedimentation realized in flow system the results gained from the research are in considerable degree differ from the results gained from simulation. Especially we can see that in vertical duct.

For the flow sedimentation the use of sedimentation efficiency and thickening rate is more useful for comparison than something else (e.g. sedimentation concentration). We can only with two parameters describe the quantity of devices working, and we can use that to compare with another devices. The sedimentation efficiency we can calculate from the equation (2), and the thickening rate from the equation (3).

$$\eta = 1 - \frac{S_p}{S_n} \tag{2}$$

$$z = \frac{S_w}{S_n} \tag{3}$$

Where: S_p, S_n, S_w – suspension concentration in the overflow, feed and underflow.

In these cases the most easily is to use the average value of suspension concentration of the given research or of the simulation.

The sedimentation efficiency and the thickening rate is calculated from the equations (2) and (3). For the flow sedimentation research realized in vertical duct we receive the efficiency $\eta=0.367$ and the thickening rate $z=1.3$, but for the simulation of sedimentation we receive adequately $\eta=0.938$ and $z=2.6$. We see that for these case the difference are very high. The results from simulation and research are completely different, and we cannot use them for describing the sedimentation in real system.

Whereas, for the flow sedimentation research realized in inclined duct we receive the efficiency $\eta=0.961$ and the thickening rate $z=1.9$, but for the simulation of flow sedimentation we receive adequately $\eta=0.999$ and $z=1.74$. In these case the difference are considerably smaller than in the vertical duct.

Conclusion. On the basis of the above simulations we can say that there is a possibility to use the package Fluent to model and analyse the sedimentation process. The course of sedimentation process and the schedule of concentration during the simulation are consistent with the sedimentation theory. However when we compare the simulations results with the results from research, we receive very high differences. The differences are probably the effect of applied simplification in simulations.

The research shows that it is very complicated problem, which needs an apply of exact parameters of modelled suspension. Using the monodispersed suspension in the simulations was too big simplification and did not allow to receive comparable results with results got in reality. The use in simulations of sedimentation the polidispersed suspension reduced the differences in results between research and simulations. However it did not it allow to get full compatibility with realized in real system research.

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