Experimental and numerical simulation research of sedimentation process in stationary column of aqueous suspension of solids

George Ipate[1*], *Gabriel* Musuroi[1], *Gabriel-Alexandru* Constantin[1], *Elena Madalina* Ștefan[1], *Bianca* Zabava[1] and *Marina* Pihurov[1]

[1] University POLITEHNICA of Bucharest, Biotechnical Systems Department, 313 Spl. Independentei, Romania

Abstract. Our study proposes a new mathematical model for predicting the gravitational settling velocity of sediment particles, a measure to evaluate water clarity, to provide information to environmental engineers, first responders dealing with environmental emergencies or farmers, for the most rapid and efficient management responses. New and simplified simulation program are developed to the study sedimentation process. The mathematical model proposes a first-order differential equation who is solved by a numerical method algorithm. The proposed formula has the highest degree of predictive accuracy when compared with experimental data.

1 Introduction

The static sedimentation method is very often applied in the mechanical liquid-solid separation stage to domestic and industrial effluent treatment, drinking water treatment. Also, sedimentation of small particles into a fluid is a long-standing issue and with many practical applications [1]. The study of sedimentation of solid particles in aqueous suspension is performed for both stationary and dynamic systems (streams with different flow directions) [2]. Among the parameters that influence particle behavior in suspension in the sedimentation process are density of solid particles, the size and shape of the solid particles, density and viscosity of the fluid. Likewise, the structure of the flock is a parameter that greatly influences the rate of sedimentation of the mineral particles. Sedimentation process and factors that affect it have been reviewed extensively. The influences of the particle size and shape on the particle terminal velocity have been investigated in detail for some regular geometries such as spheres, disks, cylinders, and isometric particles [3].

The behavior of solid particles in sedimentation is strong influenced by the concentration of the suspension and the more or less pronounced tendency of the particles to influence each other during sedimentation. The static sedimentation process can be addressed by considering four sedimentation regimes: a) decanting of the isolated particles; b) decanting of the coagulated particles; c) global sedimentation (decantation); d) sedimentation by sludge compression. The phenomenon that is taking place differs greatly from one regimen to another. Therefore, their separate study is a simplification of the treatment of the static settling process.

Richardson and Zaki [4] investigated the sedimentation of spherical particles in liquid-solid suspensions under the influence of gravity; they determined the reliance of the sedimentation velocity on the void proportion and have developed an expression to predicted the rate of settling of suspensions in form $v_e = v_i * \varepsilon^n$, where v_e is the sedimentation or fluidisation velocity, ε is the porosity, and n, is an exponent. Argument n, shown in Tab. 1, was described as a dependence of the flow regime, expressed by the number Reynolds Re_t, and the ratio of the particle diameter to the sedimentation cylinder d/D.

Table 1. Values of the exponent n recommended for calculating sedimentation velocity.

$Re_t < 0.2$	$n = 4.65 + 19.5 d/D$
$0.2 < Re_t < 1$	$n = (4.35 + 17.5 d/D) Re_t^{\pm 0.03}$
$1 < Re_t < 200$	$n = (4.45 + 18 d/D) Re_t^{\pm 0.1}$
$200 < Re_t < 500$	$n = 4.45 Re_t^{\pm 0.1}$
$Re_t > 500$	$n = 2.39$

---

* Corresponding author: *puiu.ipate@gmail.com*

Di Felice and Kehlenbeck in their research [5] demonstrated that the Richardson-Zaki formula is an excellent instrument in describing the profile of sedimenting undiluted suspensions. As the solid grain, and some fluid appended to them, move to the bottom, some fluid must move at the top, rising in this way the drag force and subsequently reducing the balancing settling velocity [2,4,5]. White and Verdone [6] present a numerical model used for the design of settling reservoir and calculations of limiting flow whit the equations in a dimensionless layout. They extended the example for a cylindrical separator to the case of a conical decanter geometry and demonstrated that this type can handle a increased range of solids charging.

The purpose of this paper is to achieve a solid particle sedimentation behavior simulation program using the Python language to study the influence of changes on the physical parameters involved and the effect these changes make on the corresponding graphs. Program codes are very easy to use, with direct application to solve real engineering problems, and increase students' motivation to recognize, process and apply the information they receive.

2 Material and methods

If a graduated suspension pours a concentration suspension sufficient but not too high, the following phenomena can be observed: Large particles are deposited rapidly and deposited at the bottom of the graduated cylinder (Fig. 1). Just below the surface of the liquid immediately appears a separation surface (solid-liquid interface) which separates the clear liquid or almost clear of a lower area formed by the suspension. This interface moves from top to bottom with constant speed (the straight portion of the sedimentation curve). Then the velocity decreases, the solids are collected (assembled) on the bottom of the tube and the sedimentation rate decreases, the sedimentation curve developing asymptotically parallel to the time axis.

2.1 Experimental setup

In this investigation, settling analysis were carried out in a 100 cm^3 transparent scaled glass cylindrical tank. Size and height of the cylinder were 3.0 and 21.5 cm, respectively. It was loaded with a specific mass of the particle and water. For tests has been used an aqueous suspension of the dish cleaning powder as follows: in 100 mL of tap water was added an amount of 5 g of powder.
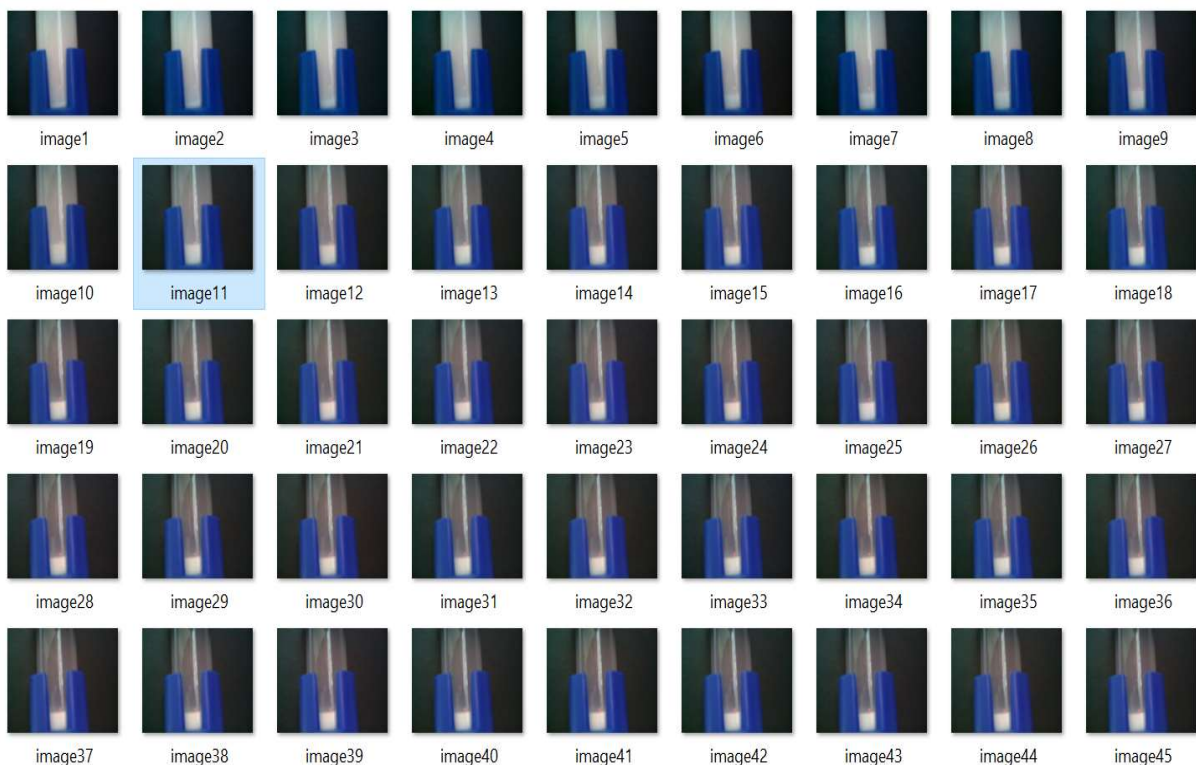

Fig. 1. Image capture of sedimentation process in stationary column.

By measuring the time evolution of the interface height, the sedimentation curve can be drawn. At first it is possible to observe the sedimentation of coarse particles at speed big fall, superior to other smaller particles. After one sometime begins to notice in the upper part of the cylinder an area of clear liquid, and at the bottom of the suspension area and area compression of the sediment at the bottom of the cylinder. It is noted over time the downward trend of the interface line position between the volume of clarified liquid and the volume of suspension still unsettleable. Progressively,

clarified interface clear water-suspension descends, while suspension-concentrated sediment fixed interface is lifted and at a particular time these interfaces attain the similar height and overlap. In the present instance, in column maintain only two regions, namely, clarified water and concentrated sludge settled zone [2]. The entire sedimentation process can be easily observed from recorded capture shown in Figure 1.

2.2 Programming language

The study of the dynamic behavior of physical systems is done with mathematical models in the form of ordinary differential equations. The program for study solid-liquid separation by gravitational sedimentation was developed using the Pyhton programming language (vers 3.4). This program has a very user-friendly interface, as users only need to enter only relevant information to calculate complete system solution differential equations. The model describing the settling velocity and interface height is a first-order linear system that are solved in Python with the Scipy.integrate package using function ODEINT. This program can be an extremely effective tool academic community of professors and students, and others.
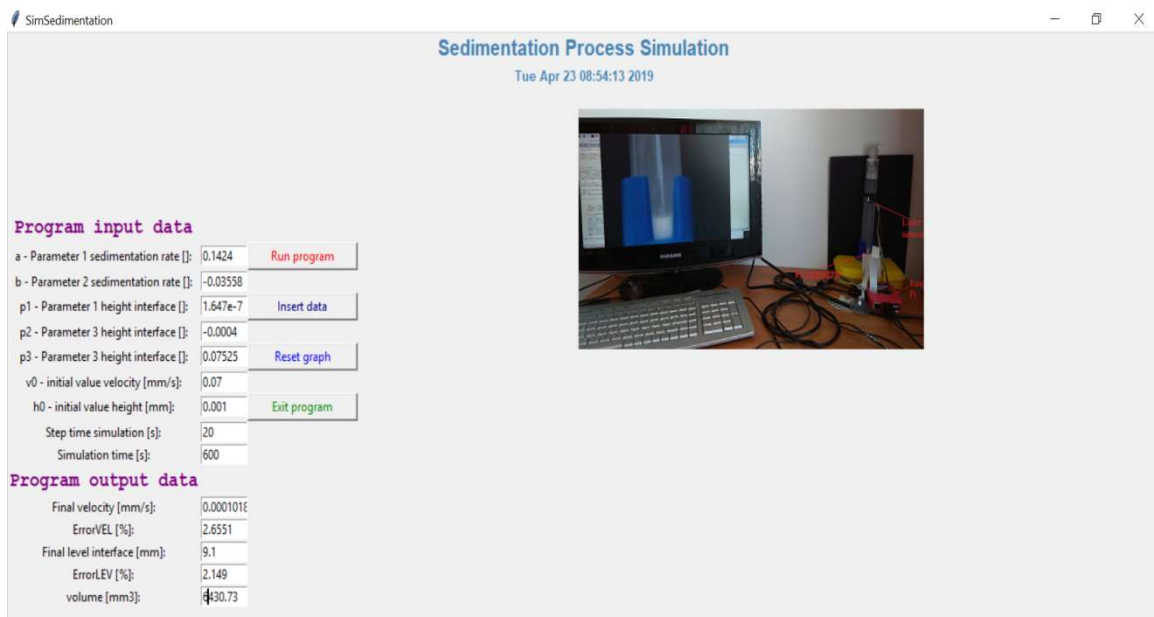

Fig. 2. GUI Python program.

Figure 2 illustrates the friendly user interface program of the settling velocity and height interface simulation model. The Tkinter package that is available to Python programmers provides a robust and independent windowing toolkit to create Graphical User Interface. By modifying the input data in mathematical models, (for initial time $t_0=0$ to final time t_{sim}) settling rate values and solid-liquid interface height can be predicted. Firstly, users can select initial condition (v_0 and h_0) to solve ODE's by press "Input data" button. The initial values v_0 and h_0 of the dependent variables $v(t)$ and $h(t)$ are specified in the columns B, rows 6 and 7 for the differential equation. Once the "Run program" button is clicked, the simulation run, and the numerical values will be calculated automatically based on the integration time step. Solve button is associated with Python code that is written to compute the solution of the ODE's using Adams/BDF method with an automatic stiffness detection and switching and after that, to graphically plot these values. Also, the average error between numerical and experimental value is calculated and printed in rows 11 and 13 of column B. By pressing the "Reset graph" button, the results obtained by running the simulation program are deleted.
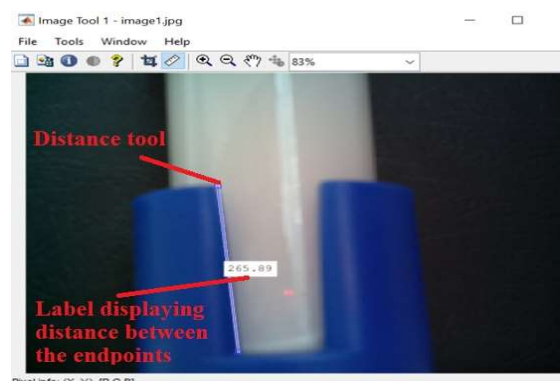

Fig. 3. Distance measurement by image processing method.

The method of digital image processing using the Image Processing Toolbox in MATLAB was used for the experimental data (measurement) of the liquid-solid interface. The distance between two pixels in a digital image is a quantitative amount. The advantage of defining Euclidean Distance between two coordinate points is that it is intuitive, and the main disadvantage is the presence of a cost great computing due to the use of radical but also from the cause of the resulting incomplete value and the necessary interpolation. For the solid-liquid interface level measurement, the "Distance Tool" was used, representing a traceable, resizable, overlapping axle that measures the distance between the two endpoints of the line. The Distance tool displays the measured distance in a superimposed over-line text tag. The tools specify the distance in the data units determined by the XData and YData properties, which are default pixels. Figure 3 shows an example of Measurement of Distance on an Axis. Capturing the images at a time interval of 20 seconds was done with a Raspberry Pi camcorder equipped with an 1/4-inch OmniVision OV5647 5-megapixel sensor. This camera can capture high-quality images as well as unbelievable 720p HD frames at 60 frames per second (fps) or Incorporating a range of advanced technologies and useful features in a rugged and compact body at 1080p HD at 30fps.

2.3 Numerical model

Supposing uniform particle density and size, the solids fall down at the same rate, traveling a distance *dh* during the settling time period *dt*. The grain settling velocity is given by [4]:

$$v\,(t) = dh(t)/dt \tag{1}$$

The cylindrical column tank is occupied by the solid particle volume given by:

$$V(t) = h(t) \cdot A \tag{2}$$

where A is the cross segment zone of the settling column.

The settling velocity of solid particles in the sedimentation process described in the scheme in Figure 1 can be also modelled, according to the law of motion, by the following first-order differential equations:

$$dv/dt = a \cdot b \cdot \exp(b \cdot t) \tag{3}$$

where a, b are parameters that depend on the particle size and shape, suspension concentration and flow regime. Relationship (3) is a derived form of the equation proposed by Richardson-Zaki. The model predicts that the distribution of particle settling velocities evolves toward a steady state.

The solid-liquid height interface can be modelled, by the following first-order differential equations:

$$dh/dt = 3 \cdot p_1 \cdot pow(t,2) + p_2 \cdot t + p_3 \tag{4}$$

where p_1, p_2 and p_3 are parameters determined by regression of experimental data.

3 Result and discussion

The terminal settling velocity of the dish cleaning powder, quantified by the settling column, is 1.14 cm/h (Figure 4). This amount is much littler than the numerical simulation value. According to Zhaowei and Belovich, this little variance is most likely induced by particle inertial effects, and this are hard to estimate. It is excluded to prevent the convective movement of the particles in the water-solid mixture. Particle inertia affect the deposition velocity of both small and macro level. Convection can also be reduced by slowly pouring the suspension into the cylinder [7].
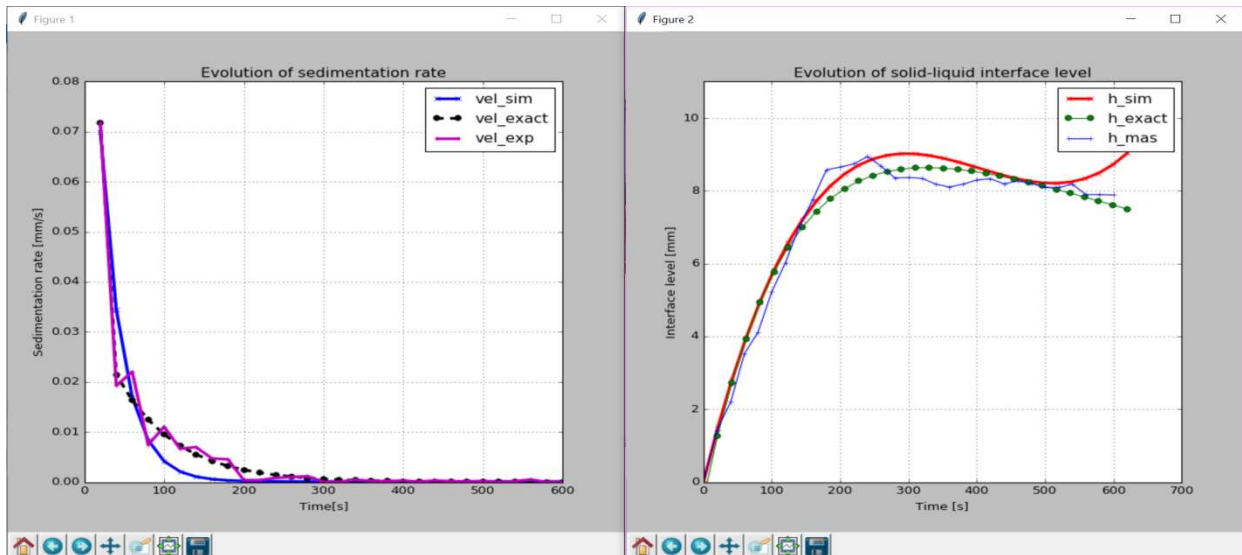
Fig. 4. Batch sedimentation curves for polydisperse suspensions.

The full solution is shown in Figure 4 (left). The magenta continuous line represents the experimentally determined settling curve, while the continuous blue line represents the settling curve curve obtained by numerical simulation. A second chart of the similar data, this time applying the analytical calculated data of settling velocity, is shown in Fig. 4 (left) whit discontinues black pointed line.

The sedimentation curve has two distinct parts, respectively two lines straight lines connected to each other. Extending the two straight segments of the curve, representing the tangents traced to the curve at the appropriate points the time t = 0 and the final time form an angle. The intersection of the bisector the angle of the tangents with the sedimentation curve represents the point defines the critical height and critical time values to be computed sedimentation rate [2]. In short, from the upper side of the cylinder to the floor, solids concentration, gently grows and at the floor it reaches a maximum [8]. Figure 4 (right) shows the curves of the liquid-solid interface according to time; the continuous red line shows the values obtained by the numerical solution, the continuous line with green dots represents the analytical solution of the model, while the blue line is the curve determined experimentally by the image processing method. The fair accordance between the data and the predicted values evidently suggest that Eq. (4) and (5) provides a faithful method to establish suitable values for both settling velocity and height solid-liquid interface.
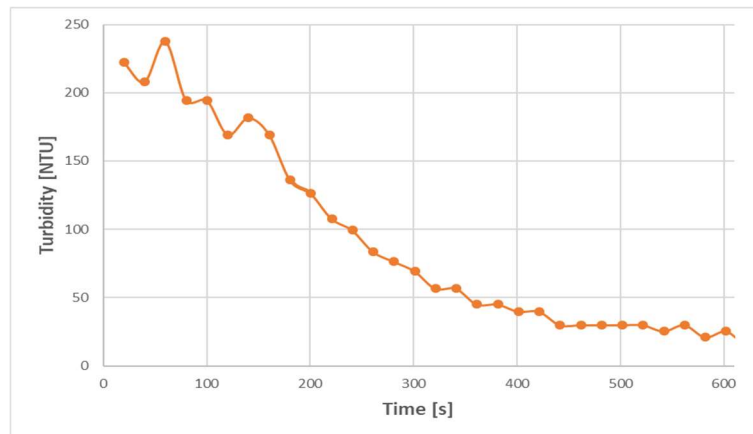

Fig. 5. Time evolution of water turbulence at a distance of 55 cm from the bottom of the cylinder.

The water clarification curve corresponding to the height of 55 cm from the bottom of the cylinder in which the turbidity of water was measured was plotted in Figure 5. Also, the diminished settling velocities allow significant effect for sediment conveyance modelling near to, and among, sheet flow covering and in the swash region [11]. Future research will extend the application of the model to estimate the sedimentation rate of suspensions consisting of small and light particles, or heavier and larger particles. It is also necessary to carry out experiments with various suspensions, more complex, for further testing of different models.

Conclusions

To study the sedimentation process of solid particles in a suspension for this work, a simulation program was developed in the Python environment. This gave the opportunity to obtain indirect information about the points in the decanting curves obtained for different concentrations of solid matter. The settling tank mentioned here supply an affordable, rapid, and truthful method for calculating particles settling velocities and such can differentiate the settling velocities. The numerical solution have been certify using dust particles with recognized physical characteristics and triggered in less than 5% error matched with the experimental values obtained for settling velocity of particles determined when wise settling test with various feed solids concentration in suspensions unless flocculant. Therefore, it can be concluded that the dynamic simulation model can be used to estimate the suspension behavior in a decanter and the simulation results are reliable.

Acknoledgement

References

1. E.M. Tory, R.A. Ford, Advances in Fluid Mechanics III, WIT Press Ed., Stochastic simulation of sedimentation, 663-672, (2000).
2. V. V. Safta, M. Dilea, G. A. Constantin, J. Mech. Eng. Aut., Plotting the clarifying curves and determination of the specific amount of settled material during the initial period to sedimentation in stationary column of aqueous suspensions of solids, **3**, 203-208, (2013).
3. M. H. Nasab, JME, A new approach for obtaining settling velocity in a thickener using statistical regression: A case study, **7(1)**, 47-56, (2016).
4. J.F. Richardson, W.N. Zaki, Trans. Inst. Chem. Eng., Sedimentation and fluidisation - Part I, **32**, 35-53, (1954).
5. R. Di Felice, R. Kehlenbeck, Chem. Eng. Technol, Sedimentation Velocity of Solids in Finite Size Vessels, **23 (12)**, 1123-1126, (2000).
6. D.A. White, N. Verdone, Chem. Eng. Sci., Numerical modeling of sedimentation process, **55(12)**, 2213-2222, (2000).
7. M. Zhaowei, J. M. Belovich, Biotechnol. Progr., A simple apparatus for measuring cell settling velocity. **26(5)**, 1361-1366, (2010).
8. G.A. Parsapour, M. Hosseini-Nasab, M. Yahyaei, S. Banisi, Sep. Purif. Technol., Effect of settling test procedure on sizing thickeners, **122,** 87-95, (2014)
9. H. Z Ha, S. Liu, Can. J. Chem. Eng., Settling Velocities of Polydisperse Concentrated Suspensions, **80(5)**, 783 – 790, (2008).
10. J. Martin, N. Rakotomalala, D. Salin, Phys. Fluids, **7 (10)**, Accurate determinaion of the sedimentation flux of concentrated suspensions, 2510-2512, (1995).
11. T.E. Baldock, M.R. Tomkins, P. Nielsen, M.G. Hughes, Coastal Engineering, Settling velocity of sediments at high concentrations, **51**, 91 – 100, (2004).