Development of a Model to Evaluate the Settling Time of Mineral Particles

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Abstract: Settling time is one of the most important parameters in mineral processing industry, to design flow of processing and to define input data rate. It can be defined as a function of average particle settling velocity through a fluid medium and the target of this research is to develop a model to evaluate the settling time of mineral particulates. During this study, parameters which affect the settling time were identified, existing models were evaluated and error functions were introduced to coincide theoretical results and experimental results, a new function was formulated and verified to measure the settling time. Characteristics of particles such as shape, size and density as well as the characteristics of medium such as viscosity, density and the temperature were identified as the parameters that affected. Steel and glass particles in spherical shape were selected with known density for the experiment. Newton's law and Stokes law that developed theoretically were referenced with their defined limitations to take experimental results on measuring the settling time of mineral particles. To reduce the gap between theoretical results and experimental results, new error functions were introduced to Newton's law and also another relationship was derived theoretically to calculate the time taken to reach particles' terminal velocity.

Keywords: Settling Time, Settling Velocity, Mineral Processing

1. Introduction

Mineral processing begins when an ore has been delivered from mine to the processing plant. It targets to differenciate valuable mineral from gangue and the technique that selected for processing, directly effects to an efficient outcome. Within the ore body, valuable minerals are mixed with waste rock. Liberation and concentration are the major stages of mineral processing. Size reduction of bulk material is the first stage and it is followed by processing to remove waste. After producing the enriched portion, it is provided to different industries as their requirements.

Techniques that are used to mineral processing are mainly based on physical and chemical properties of mineral. Characteristics of fluid medium using, is another factor that affects. Sedimentation is one method that can be followed in dewatering process and as the core of sedimentation; it gains a deposition of minerals. Therefore, the settling velocity of mineral particles becomes an important parameter that is useful to enhance the efficiency of the process. It is the primary factor that defines the data rate given and it is important to design the flow of processing. Therefore measurement of settling time is an essential test that should be followed.

Definition of settling time is the time required for a mineral particle to travel from the surface of the liquid to the bottom at an inherent settling velocity [1].

$$\text{Settling time} = \frac{\text{Liquid Depth (m)}}{\text{Settling Velocity }(\frac{\text{m}}{\text{s}})} \text{ ....(1)}$$

As settling time is an important factor in mineral processing, this research will be valuable enough to develop a model to evaluate the settling time as an important parameter in mining and mineral processing industry.

2. Material and Methods

In development of a model to evaluate the settling time of mineral particulates, below material and methodologies were instrumented.

2.1 Material selection

Glass and steel samples with the shape of sphere were used as major particles. A glass tube and a polythene tube were used to make a water column with enough depth to settle particles without any surface disturbance. A vernier caliper, an electronic balance and a measuring cylinder were used to calculate the density and an accurate stopwatch with a digital camera was utilized to measure the settling time in a precise way.

Specifications of selected steel and glass samples for the experiment are given in Table 1.

Table 1: Specifications of selected samples

Shape of particle	Non spherical	Spherical	
Material	Quartz	Glass	Steel
Size of material Φ(mm)	0.075 - 0.300 0.300 - 0.425 0.725 - 1.000	3.07 5.03	3.20 4.08 4.90 6.33

2.2 Methodology

As the preliminary step, all parameters that affect settling time were identified based on literature. They are, size, shape and density of particle, fluid density, viscosity and temperature [2 and 3].

Then, an experimental setup was followed to evaluate the settling time of selected particles. Steel particles and glass particles with different diameters (Table 1) were used and 30 balls from each category were used to make the results more accurate. Notation of one ball of glass as "Glass S'1-B1" to "Glass S'2-B30" and steel ball as "Steel S1-B1" to "Steel S4-B30" has been used through out this paper.

A theoretical relationship for settling velocity and affected parameters were developed. It was based on the forces applying to a settling particle through a liquid medium (Figure 1) developed under two cases.

Case (i) – After the particle reaches its' terminal velocity

Case (ii) – Until the particle reaches terminal velocity

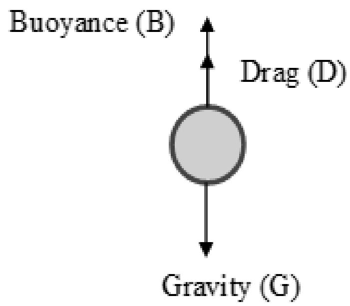

Figure 1: Forces applying to a settling particle through a liquid medium

$$F = m\,(dv/dt) \quad (2)$$

$$B + D - G = m\,(dv/dt) \quad (3)$$

$$B = \frac{4}{3}\pi r^3 \rho_s g \quad (4)$$

$$D = 6\pi \eta r v \quad (5)$$

$$G = \frac{4}{3}\pi r^3 \rho_f g \quad (6)$$

$$2\left[\frac{2}{3} r^2 g\,(\rho_s - \rho_f) + 3\eta v\right] = \frac{4}{3} r^2 \rho_s (dv/dt) \quad (7)$$

Case (i);

$$(dv/dt) = 0$$

$$V = \frac{2}{9\eta} r^2 g\,(\rho_s - \rho_f) \quad \text{..........(8)}$$

Where,

r – Radius of particle (m)
g - Gravitational acceleration (m/s^2)
ρ_s- Density of particle (kg/m^3)
ρ_f- Density of fluid (kg/m^3)
η - Viscosity of fluid (kg/s.m)

If the acceleration of particle is not equals to zero, (before the particle get its' terminal velocity), then case (ii) is applicable.

Case (ii);

$$(dv/dt) \neq 0$$
$$A + Bv = (dv/dt)$$

Where,

$$A = g\,(\rho_s - \rho_f)/\ \rho_s$$
$$B = 9\eta/\ 2r^2\rho_s$$

$$t = \ln \sqrt[B]{\frac{Bv+A}{A}} \quad \text{............(9)}$$

According to the results from experiment, error functions were introduced to minimize the gap between experimental and theoretical values.

$f\,(V_{Experiment}) = f\,(V_{Theoretical}) + f\,(V_{Error})$

$f\,(V_{Error})\ \alpha$ (particle size)^n
$f\,(V_{Error}) = K_1$ (particle size)^n..........(10)

$f\,(V_{Error})\ \alpha$ (particle density)^m
$f\,(V_{Error}) = K_2$ (particle density)^m.....(11)

K_1, K_2, n, m are constants that defined and each value was calculated from the results on experiments.

3. Results

Finalized results can be detailed as follows:
Density of glass balls = 2.39 g/cm^3 and that of steel balls= 7.86g/cm^3. Diameters of selected samples have shown in Table 1.

Table 2: Calculated error percentages for glass and steel

Density (g/cm^3)	Particle size Φ (mm)	Error percentage (%)
2.39	3.07	41.70
	5.03	35.54
7.86	3.2	57.03
	4.08	32.68
	4.9	17.96
	6.33	12.70

A graph of Particle size vs Error percentage was plotted as presented in Figure 2.

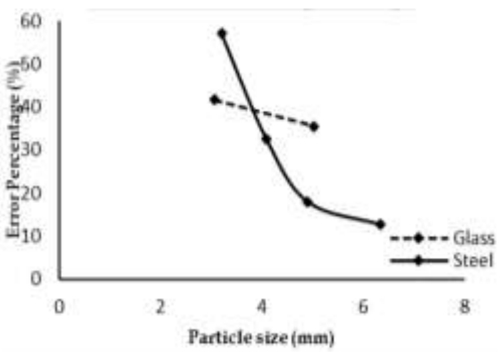

Figure 2: Particle size vs. Error percentage

$f\,(V_{Experiment}) = f\,(V_{Theoretical}) + f\,(V_{Error})$ ....(12)
$f\,(V_{Error}) = K_1$ (particle size)^n..........(13)
$f\,(V_{Error}) = K_2$ (particle density)^m.....(14)

Graphs of calculated error percentage in settling time vs size of particle for steel and glass were plotted by using MATLAB software. A graph of error percentage vs particle density was also plotted.

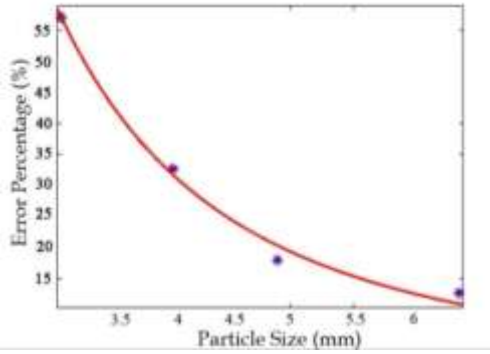

Figure 3: Paricle size vs. Error percentage for steel

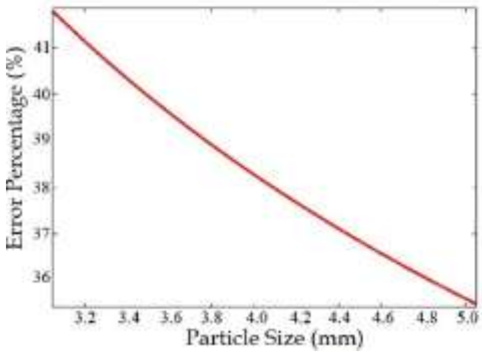

Figure 4: Paricle size vs. Error percentage for glass

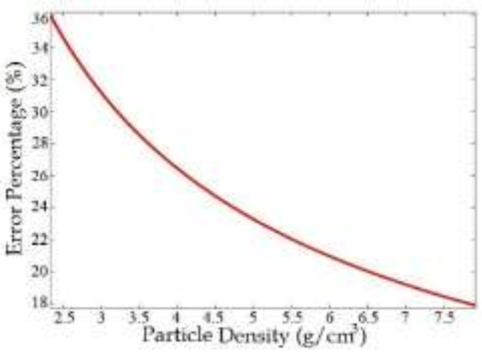

Figure 5: Paricle Density vs. Error percentage

The values of K_1, K_2, n and m were achieved from above plotted graphs and they are detailed below.

(With 95% confidence bounds)

Table 3: Caculated values for defined constats

	Particle size (mm)	
	K_1	***n***
Glass	59.96	-0.3237
Steel	970.4	-2.432
	Particle Density (g/cm³)	
	K_2	***m***
	52.98	-0.5246

4. Discussion

The factors noted in the evaluation of settling time of mineral particulates, the characteristics of mineral particles and the characteristics of fluid that makes the medium are highly affected. Size of particle, shape of particle and density of particle were the parameters that could change and it is according to the designing of settling tanks in many industries, because it is based on detailed parameters earlier[4].

Most existing models to evaluate the settling time are restricted with the shape of spherical particles. That's because the availability of exact spherical particles are very rare in mining industry. However, the experiment can also be conducted considering the equivalent diameter of non spherical particles as well. For easy comparison on existing models and also with the availability, materials were selected as spherical particles.

Theoretically developed model was introduced to calculate the settling time of mineral particulates which are greater than Φ 500 μm [5]. While making the other parameters constant, than the method of considering those parameters, the deviation from theoretical values through an experiment was observed.

Experimented ten balls from each selected particle size, from spherical ones which are greater than 500 μm diameter and an average value of error percentage was taken for more accurate results. Using these results, a graph of time taken to pass a distinct depth vs. velocity that passed in that specific depth were plotted for each sample. It could be observed that the theoretical value was greater than experimental value and there is a possibility for a small error due to practical and human behaviour. To reduce human errors, video capturing was used and the time was observed from that. Here, suggesting an electronic device, which has the capability to detect the particle while it is settling at some considering points with spreading a radar or laser wave or the change of capacity of the corresponding point, so that the time can be measured in a more accurate way.

Measuring of time was started from leaving some depth to allow it to reach its terminal velocity. After it reaches its terminal velocity, the time taken to pass in equal depths should be similar. However, using the derived equation to find the velocity before it reaches its terminal velocity, the time taken to get that terminal velocity can be found. Hence, the time that cannot be measured practically, can be calculated through this model.

When considering the settling behavior of particles, perfect spherical particles made a straight path from top to bottom through a newtonian liquid medium to settle if there was no any surface effect. Non-spherical particles made an arbitrary way to settle, because the forces applying on a spherical particle are equal on each opposite directions and it can be cancelled out, however on non-spherical particle, the forces can be equal but it makes different directions due to the magnitude of forcing [6].

For the model that derived for particle reaches its terminal velocity, the developed error function was added in order to reduce error in practice. It is obvious that, to get accurate results in the practice of mineral processing industry, it is targeted to reduce the gap between results from theoretical models and practical purposes which are greater than the diameter of 500 μm spherical particles. It will help to make more efficient processes and better designs in the flow of mineral processing industry.

5. Conclusions

The following conclusions can be made according to the results of this research:

- A gap between the theoretical models and experimental results has been found, and to reduce this difference an error term was introduced.
- For the defined new model 1 (Figure 6), an equation of error function was introduced to reduce the gap of results between theoretical and practice.

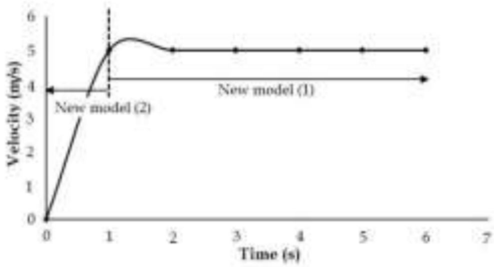

Figure 6: Velocity-Time graph for a settling particle

with 95% confidence level,
For steel;

$$f\,(V_{Error}) = 970.4\,(\text{particle size})^{-2.432} \quad (15)$$

For Glass;

$$f\,(V_{Error}) = 59.96\,(\text{particle size})^{-0.3237} \quad (16)$$

With the restrictions of particle size = 5 mm and shape of spherical, an error function in differentiate of particle density,

$$f\,(V_{Error}) = 52.98\,(\text{particle density})^{-0.5246} \quad (17)$$

For the defined new model 2 (Figure 6), the range of before the particle reaches its terminal velocity, an equation was derived to calculate the time that is needed to reach the terminal velocity that cannot be measured practically.

$$t = \ln \sqrt[B]{\frac{Bv+A}{A}} \quad \text{....(18)}$$

where,

$$A = g\,(\rho_s - \rho_f)/\,\rho_s \quad \text{....(19)}$$

$$B = 9\eta/\,2r^2\rho_s \quad \text{....(20)}$$

t –Time for settling (s)

ρ_s-Particle density (kg/m^3)

g–Gravitational acceleration (m/s^2)

ρ_f-Fluid density (kg/m^3)

r -Radius of particle (m)

η-Viscosity of fluid (kg/s.m)

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