

Studying the Factors Affecting the Settling Velocity of Solid Particles in Non-Newtonian Fluids

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Abstract

The aim of this research is to study the factors affecting the settling velocity (V_s) in Non-Newtonian fluids which are the rheological properties, concentrations of non-Newtonian fluids, particle shape and size.

An experimental apparatus was designed and built, which consists of Perspex pipe of length of 160 cm. and inside diameter of 7.8 cm. to calculate the settling velocity, also electronic circuit was designed to calculate the falling time of particles through fluid.

Two types of solid particles were used; glass spheres and crushed rocks as irregularly shaped particles with different diameters and compared with each other. The concept of equivalent spherical diameter (D_s) was used to calculate the diameters of irregularly shaped particles.

The settling velocity was calculated for Non-Newtonian fluids which represented by Power-Law fluid. Two types of polymers were used, Carboxy Methyl Cellulose with concentrations of (3.71, 5, 15 and 17.5) g/l and polyacrylamide with concentrations of (2, 4 and 6) g/l.

The results showed that the settling velocity decreased when fluid becomes far from Newtonian behavior (flow index n decreased) and also when concentrations of polymer solutions increased, also, the settling velocity increased with particle diameter or volume.

Three sets of equations were concluded; the first relates settling velocity with flow index (n), the second relates settling velocity with concentrations, and the third relates settling velocity with particle diameter.

Key words; Fluid flow, particle dynamic,

Introduction

Knowledge of the terminal velocity of solid in liquid is required in many industrial applications. Typical

examples include hydraulic transport slurry system for coal transportation, thickeners, mineral processing, solid-liquid mixing, water waste processing, cement industries, fluidized bed equipment, drilling for oil and gas, geothermal drilling [1].

The theory of settling finds an extensive application in a number of industrially important processes, the shape of the particle is an important factor in these processes. The extremes of interest are given by the examples of the paint industry, which is concerned with colloidal sized particle settling in highly viscous polymer fluids, also oil industry which interested in particles of millimeter or centimeter size, settling in polymers or clay based fluids which can be easily and efficiently pumped [2,3].

The influence of shape on the terminal velocity of some regular geometric shapes has been studied such as sphere, disk, cylinder or isometric particles due to their advantages in the studies. Few studies have been done on irregularly shapes particles especially for settling these particles in non-Newtonian fluids.

Terminal Settling Velocity:

Consider a solid particle falling from a rest in a stationary fluid under the action of gravity. At first, the particle will accelerate as it does in a vacuum, but unlike in a vacuum, its acceleration will be retarded due to friction with the surrounding fluid. As frictional force increases with the velocity, this force will eventually reach a value equal to that of the gravitational force. From this point on, the two forces balanced and the particle continue to fall with constant velocity. Since this velocity is attained at the end of the acceleration period, it is called terminal settling velocity [3].

In practice, the acceleration period is of a very short duration, often of the order of a small fraction of a second. It is therefore customary to ignore this period in all practical problems concerned with settling

processes, and the terminal settling velocity then becomes the only important factor in this kind of problem. Its magnitude is closely related to the physical properties of the fluid and the particle [3].

Also the terminal settling velocity is considered the most important factor, which affecting relationship between the drag coefficient and particle Reynolds' number, since it is involving in the evaluation of these two quantities. Therefore, all the variables which affect terminal settling velocity can be correlated and clearly shown in drag coefficient-particle Reynolds' number relationship [4].

When the particle is at sufficient distance from the boundaries of the container and from other particles, so that the falling of a single particle is not affected by them, the process is called free settling [5].

The settling behavior at low Reynolds' number is known as laminar-slip and that of high Reynolds' number as the turbulent-slip between these two regimes is the transitional-slip regime. In laminar-slip regime, the settling velocity is affected by viscosity and rheology of fluid. While in the turbulent-slip regime, the settling velocity is affected mainly by the density of the fluid and the surface characteristics of particle [6].

The irregularly shaped particles settle at lower velocity than does the spherical particles because the lacked of the symmetrical and geometrical shaped, in other words; decrease in sphericity and increase in projected area will increase the drag so they tend to orient and take different trajectories in a preferred direction during their fall, this preferred orientation is not generally predictable, depending on the position of their center of gravity relative to the center of force since these two centers must fall on the same line of direction of motion, also increase roughness of particle surface increase drag [7, 8].

Experimental Apparatus and Materials

An experimental apparatus has been designed and built to measure the terminal settling velocity for solid particles. The test apparatus is consisting of vertical transparent Perspex pipe, with length of 160 cm, outside diameter of 8 cm and inside diameter of 7.8 cm to avoid wall effects as shown in figures below.

For careful determination of terminal settling velocity the pipe was divided into four sections as follows;

1. First section is inlet section L1. It is used for acceleration which defined as the distance that

particle should travel before reaching where an equilibrium of forces to get constant velocity (settling velocity). The first section must have sufficient settling length for accurate timing, so the inlet length used in this work was 85 cm.

2. Second section is test section L2. It is used for calculating the terminal settling velocity. The length was 50 cm, this section divided into two sections each of them 25 cm.
3. The third section is Drainage section L3. It is used for draining the fluid and avoids end effects.



Figure (1) Schematic diagram for experimental apparatus

Electrical Circuit

The precision of measurement of the velocity is directly related to the time taken by the particle to travel a known distance (after travel L1). Aiming to assure the precision of the time measurement and to eliminate the human error, a digital electronic circuit was designed with three photo-sensor nets; as shown in figures 2a, b and 3 these three nets are measured the time of particle falling in test section through fluid.

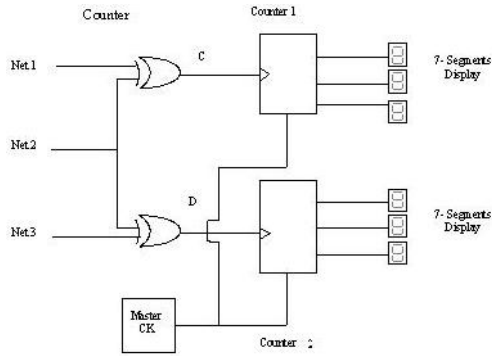


Figure 2a design of counter's circuit

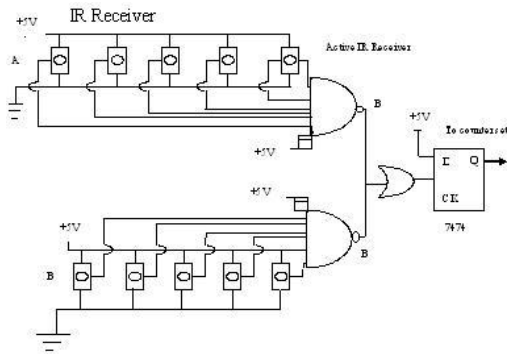


Figure 2b The design of the receivers

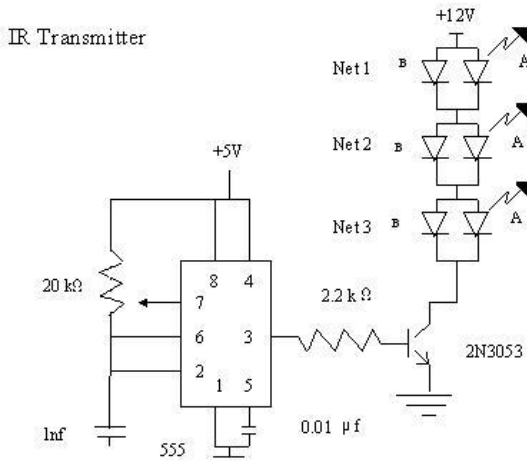


Figure 3 The design of the transmitter

Test Fluids

In order to get different rheological properties two polymers were used, CMC and polyacrylamide (Water Soluble Polymers) with different concentrations as non-Newtonian fluids. Seven different concentrations were prepared, four for

CMC and three for polyacrylamide, these values are given in table (1).

The densities of each test fluids used in this experimental work have been measured by pyknometer of volume 25 ml

Power-Law model was used to represent the flow behavior of non-Newtonian fluids. The rheological properties (n , k) of each non-Newtonian fluid used for settling velocity determinations measured by Fann VG meter model 35A rotational coaxial cylinder type

The parameters n and k can be determined approximately using a Fann-VG reading as follow;

$$n = 3.32 \log \frac{600}{300}$$

$$k = \frac{600}{(1022)^n}$$

Where; n_{600} = dial reading at 600 rpm, and

; n_{300} = dial reading at 300 rpm

Particle diameter's Measurements

a. Sphere Particles

Spherical particles are made of glass with different diameters; the diameters were measured by a vernier with an accuracy of 0.01mm. The weight of particles was measured by a digital balance and the volume was calculated using

$$\text{Vol.} = \frac{4}{3} D_s^3, \quad \text{while the area} = \pi D_s^2$$

Then, the density of the particle is the ratio of its weight to its volume; the physical characteristics of spherical particles are given in table (2)

b. Irregular Shaped Particles

The irregular shaped particles are formed from crushed rocks. The problem with these particles that they do not have standard diameters, so the concept

of the equivalent spherical diameter D_s was used, which represented the diameter has a volume of sphere. The volume of irregular shaped particles had been measured by displacement method using Kerosene; physical characteristics of irregular particles are given in table 3

Table (1) Concentrations of polymers and Power -Law constants

| No. | Polymer | Concentration, g./l | Power-Law constants |
|-----|----------|---------------------|---------------------|
| 1 | CMC | 3.71 | n=0.73,k=0.015 |
| 2 | CMC | 5 | n=0.71,k=0.091 |
| 3 | CMC | 15 | n=0.63,k=0.287 |
| 4 | CMC | 17.5 | n=0.61,k=0.566 |
| 5 | Polyacr. | 2 | n=0.58,k=1.016 |
| 6 | Polyacr. | 4 | n=0.51,k=1.135 |
| 7 | Polyacr. | 6 | n=0.39,k=3.320 |

Table (2) Physical characteristics of spherical particles

| D_s , cm. | Mass, g. | V_p , cm^3 | ρ_p , $g./cm^3$ | A_p , cm^2 |
|-------------|----------|----------------|----------------------|----------------|
| 0.22 | 0.014 | 0.0055 | 2.545 | 0.038 |
| 0.3 | 0.034 | 0.0141 | 2.411 | 0.071 |
| 0.4 | 0.082 | 0.033 | 2.484 | 0.126 |
| 0.6 | 0.299 | 0.113 | 2.646 | 0.283 |
| 0.8 | 0.675 | 0.268 | 2.518 | 0.503 |
| 1 | 1.338 | 0.524 | 2.553 | 0.785 |
| 1.43 | 3.825 | 1.531 | 2.498 | 1.606 |
| 2 | 10.841 | 4.189 | 2.588 | 3.141 |

Table (3) Physical characteristics of irregular shaped particles

| D_s , cm. | Mass, g. | V_p , cm^3 | ρ_p , $gr./cm^3$ | A_p , cm^2 |
|-------------|----------|----------------|-----------------------|----------------|
| 0.984 | 0.970 | 0.5 | 1.940 | 0.762 |
| 1.102 | 1.554 | 0.7 | 2.220 | 0.954 |
| 1.152 | 1.862 | 0.8 | 2.327 | 1.042 |
| 1.198 | 1.936 | 0.9 | 2.151 | 1.127 |
| 1.241 | 2.735 | 1 | 2.735 | 1.209 |
| 1.388 | 3.042 | 1.4 | 2.173 | 1.513 |
| 1.420 | 2.719 | 1.5 | 1.813 | 1.584 |
| 1.563 | 4.791 | 2 | 2.395 | 1.919 |
| 1.789 | 8.391 | 3 | 2.797 | 2.514 |
| 1.823 | 7.104 | 3.2 | 2.220 | 2.610 |
| 1.847 | 8.358 | 3.3 | 2.533 | 2.679 |
| 2.121 | 10.640 | 5 | 2.128 | 3.536 |

Procedure of Experimental Work

In order to get accurate results, great attention must be paid to each of the followings:

1. Firstly, all the used particles were washed in water and dried in oven, in order to avoid the error reading from dirty particles.
2. The temperature of the fluid was recorded of each run by a thermometer. The temperature remained at a room temperature therefore the fluid properties remained constant throughout the experiment.
3. The pipe was set exactly vertical by using a balance with a bubble, when the bubble in the center of the balance, that means, the pipe is in a vertical position.
4. 7 liters of each fluid was prepared in batches by shaker or mixer adding the necessary amounts of polymer in water.
5. After the test fluid prepared and the pipe was filled with a test fluid, a single particle was introduced into the top of the pipe. The particle should place in the center of the pipe just below the surface of the test fluid and leave it to settle freely.
6. The first inlet section L1 was neglected in order to ensure that the acceleration of particle is ended. When the particle crossed the test sections of L2, L3 the variation in signal will produce in each photo-sensor net as explained previously and the number of counts will appear in 7-segments displays in the board for each net, then the number of counts changed to time by multiplying with counters' factor, so the time required for falling particle in each sections L2, L3 will be known.
7. All particles dropped in same way and number of counts recorded. The falling times for each particle in test section (L2 and L3) were measured.
8. The terminal settling velocity of the particle is the measure of the total times along L2 and L3 that the particle required to settle through a known distance of 50 cm, which represented the total test section.

$$V_s = 50 / t$$
9. The time of falling of small spherical particles (0.2, 0.3) cm. was recorded manually by digital stop watch with accuracy of 0.01 sec. along test section of 50 cm.
10. The orientation of each falling particles were observed, to show the difference between the

falling of spherical particles and irregular shaped particles.

11. Then the test fluid was drained by the valve in iron base and particles were released by the second valve at the end of cone.
12. To minimize the error, each experiment repeated 3-4 times. An average time was used, thus average settling velocity was taken.
13. The effect of pipe wall on settling velocity was avoided by taking the ratio of particle diameter to pipe diameter less than or equals to 0.25.

Results and Discussion

From experimental work results, graphs were plotted to show the factors that affect settling velocity in each fluids for spherical and irregular shaped particles.

Factors Affect Terminal Settling Velocity

1- Particle Diameter Spherical Particles

As the particle diameter D_s increased the settling velocity V_s will be increased. As shown

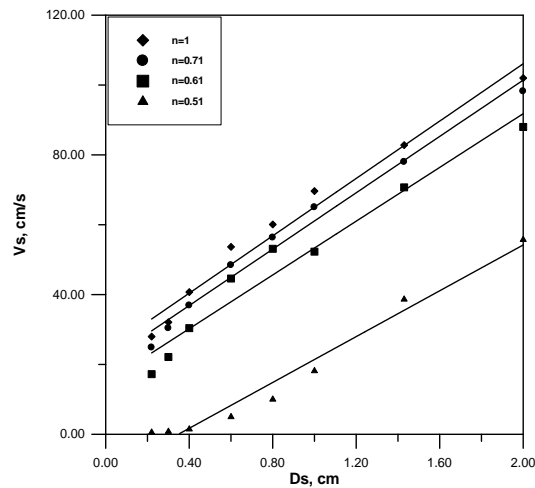


Figure (4) The effect of spherical particle diameter on settling velocity at different flow behavior

in figures below for each flow behavior (n) it's clear that as (n) decreased from unity the settling velocity will be slower. As shown in figure (4)

Irregular Shaped Particles

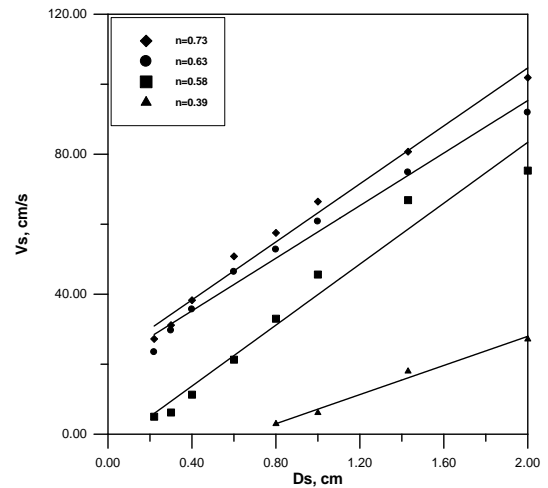
For irregular shaped particles, the effect of the volumes on their settling velocities was studied. Also, graphs have been plotted for each flow behavior (n). It is clear that as (n) decreased the settling velocity will be decreased with increasing of particle volume. As shown in figure (5)

2- Rheological Properties

It is clear that as the flow behavior (n) increased the settling velocity will be increased with increasing of particle diameter for spherical and irregular particles, as shown in figure (6).

3- Concentration

As the concentration for both fluids, CMC concentrations (3.75, 5, 15, 17.5) g/l and also for polyacrylamide concentrations (2, 4, 6) gr./lit increased the settling velocity will be decreased with increasing particle diameter for spherical and irregular shaped particles as shown in figures (7,8).



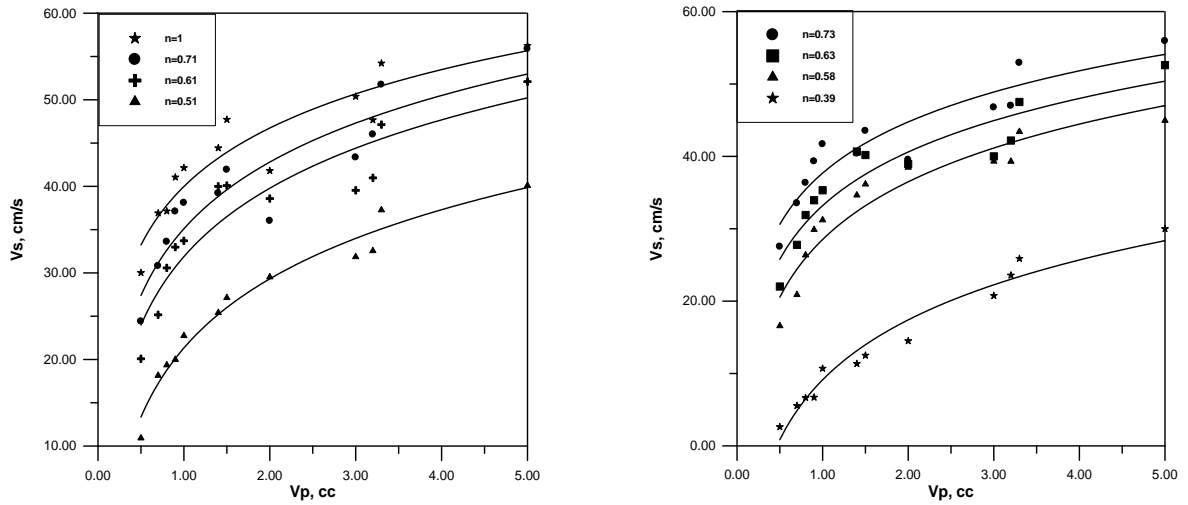


Figure 5 The effect of particle volume on settling velocity at different flow behavior

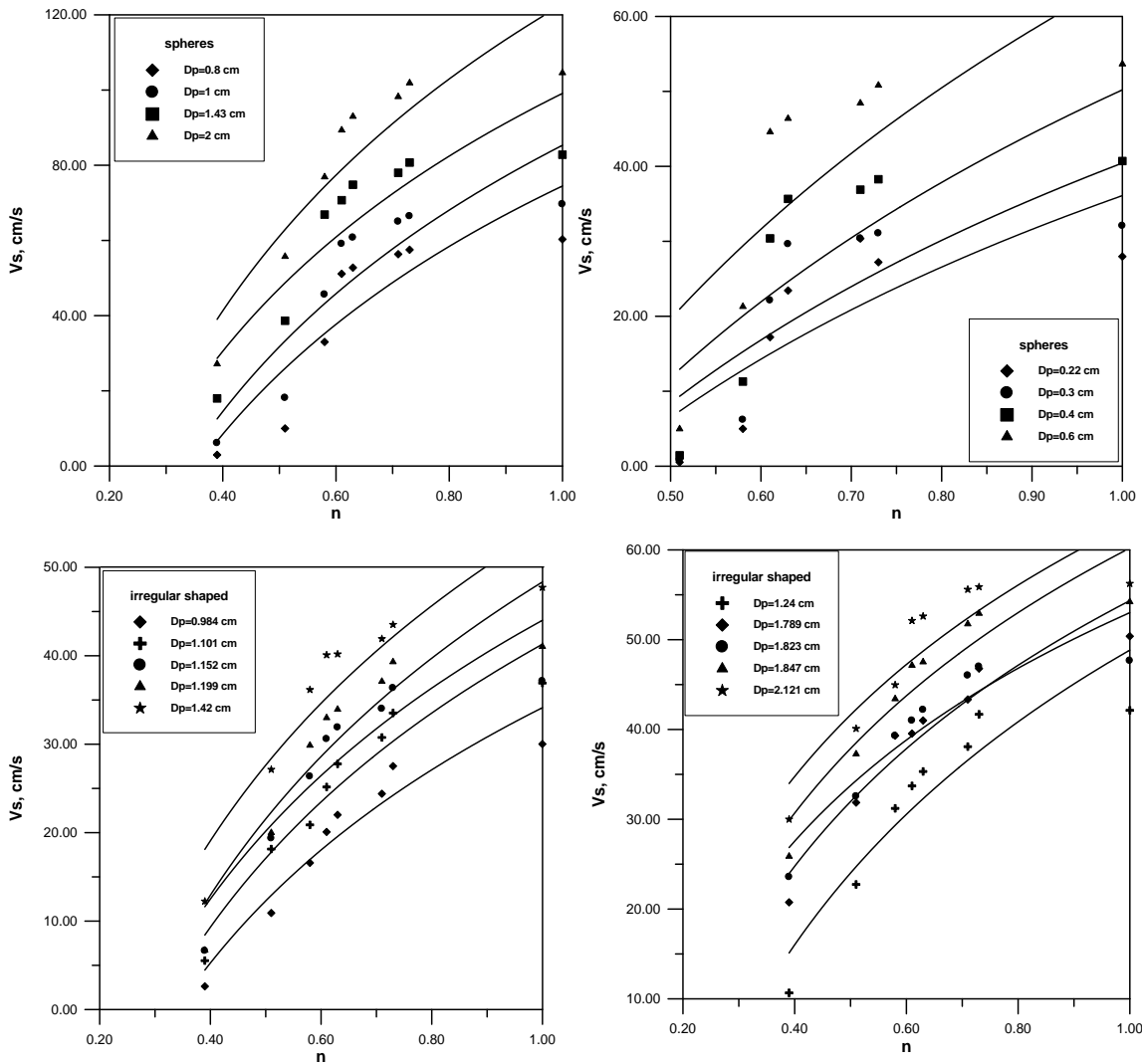


Figure 6 The effect of flow behavior index settling velocity for spherical and irregular shaped particles at different diameters

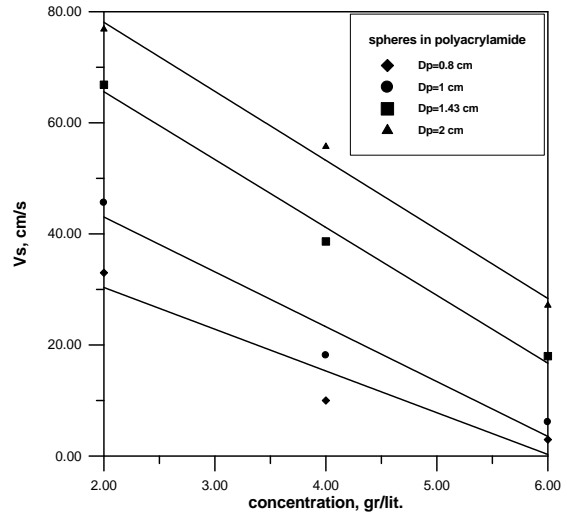
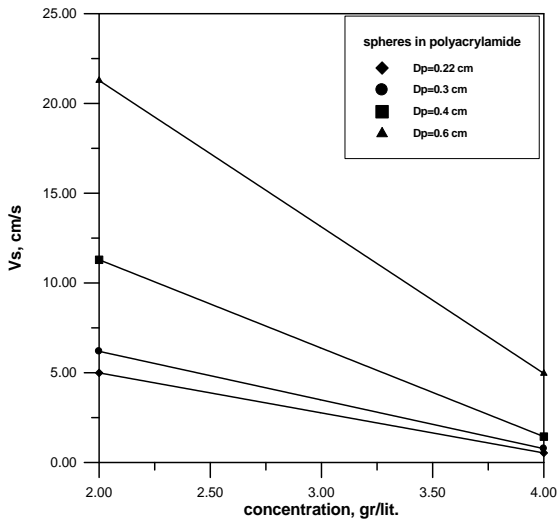
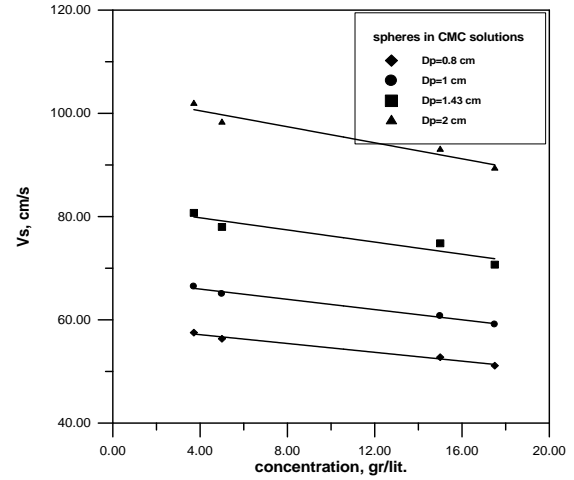
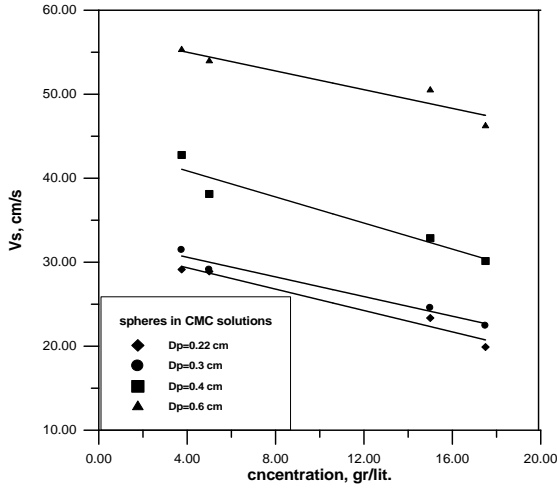
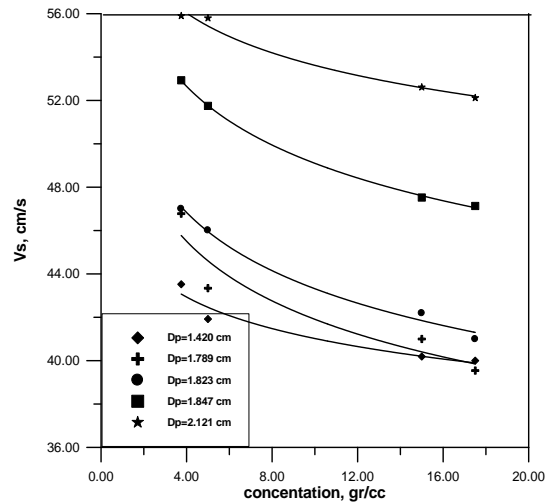
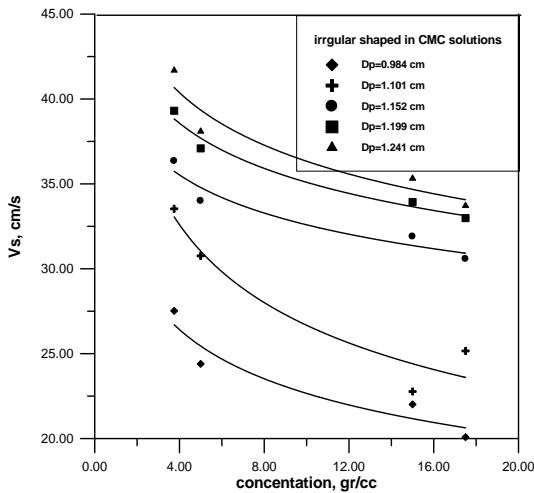


Figure 7 The effect of CMC and polyacrylamide concentration on settling velocity for spherical particles at different diameters



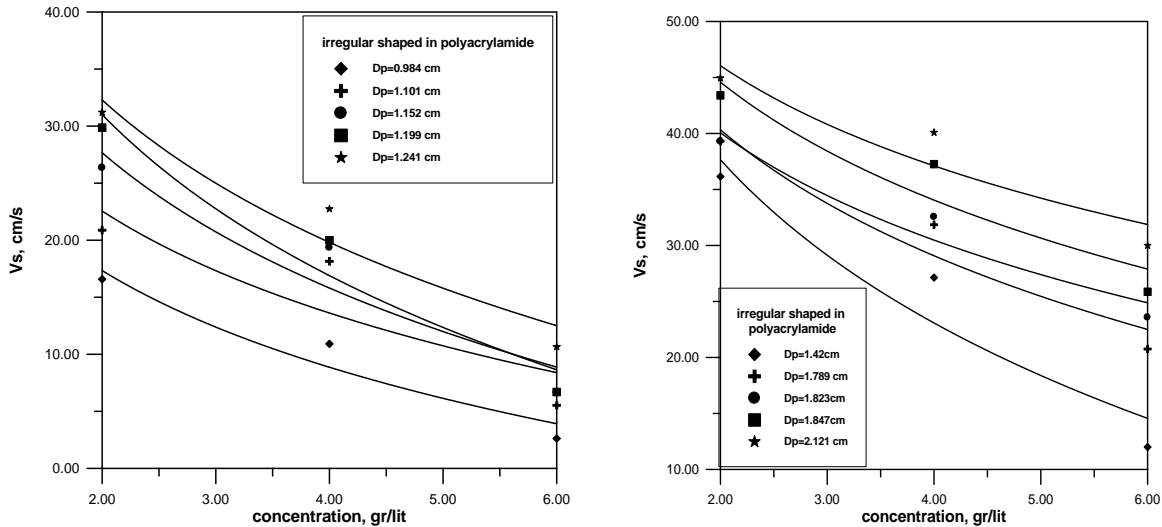


Figure 8 The effect of CMC and polyacrylamide concentration on settling velocity for irregular shaped particles at different diameters

Empirical Equations For Settling Velocity

1. A general formula was obtained for settling velocity (Y) versus CMC and Polyacrylamide concentrations (X) from our experimental work for spherical particles and irregular shaped particles

$$Y=B X+A$$

2. A general formula was obtained for settling velocity(Y) versus flow behavior index (X) from our experimental work for spherical particles and irregular shaped particles

$$Y=B X+A$$

3. A general formula was obtained for settling velocity (Y) versus diameter for spherical particles or volume for irregular shaped particles (X) from our experimental work

$$Y=B X+A$$

Where A, B are the constants of equation depends on the shape, diameters of particles and flow behavior indices.

Conclusions

1. Settling velocity of solid particle is greatly affected by a particle path during settling. It has been shown that the spherical particles follow the vertical path during settling, while the irregular shaped particles follow different paths and orientations like springing, circular, oscillating and unstable paths. This orientation will decrease the settling velocity of irregular shaped particles.

2. The particle size has a great effect on the settling velocity, as the particle diameter or volume increased the settling velocity will increase.
3. The rheological properties of non-Newtonian fluids have a great effect on the settling velocity, because as the fluid became far from Newtonian behavior, (flow index n far from unity), the settling velocity will be decreased.
4. The concentrations for both polymer fluids have effect on the settling velocity; it is shown that as the concentration of fluids increased the settling velocity of particles will be decreased.

Nomenclature

| <u>Symbol</u> | <u>Meaning</u> | <u>Unit</u> |
|---------------|--|---------------------------------|
| D_s | Diameter of particle has the same volume as a sphere | cm |
| F | Force. | dyne |
| k | Power-Law consistency index. | $\text{g.s}^n / 100\text{cm}^2$ |
| n | Power-Law flow behavior index. | dimensionless |
| V_P | Solid particle volume. | cm^3 |
| V | Velocity. | cm/s |
| V_S | Settling velocity. | cm/s |

Greek Symbols

| <u>Symbol</u> | <u>Meaning</u> | <u>Unit</u> |
|---------------|--|-----------------|
| $300, 600$ | Dial reading of Fann-VG meter rpm, at 300 rpm and 600 respectively | degrees |
| μ | Newtonian fluid viscosity. | cp |
| F | Density of fluid. | g/cm^3 |
| P | Density of particle. | g/cm^3 |

References

- Given on internet by Vassilios C. Kelessidis, "Terminal velocity of solid spheres falling in Newtonian and non Newtonian liquids"; (2003), at [http:// www.mred.tus.gr/puplications/18.pdf](http://www.mred.tus.gr/puplications/18.pdf)
- Reynolds P.A. and Jones T.E.R., "An experimental study of the settling velocities of single particles in non-Newtonian fluids"; Int. J. of Mineral Processing, 25, (1989).
- Michell S. J., "Fluid and particle mechanics", Pergamon Press LTD., (1970) p. 288- 301.
- Muhammad A.R. "The effect of particles shape and size and the rheological properties of non-Newtonian fluids on drag coefficient and particle Reynold's number relationship", Ph.D. Thesis, (1998).
- McCabe W.L., Smith J.C. and Harriott P. "Unit operation of chemical engineering" 5th edition, Mc Graw Hill, New York (1993), p.143-163.
- Chien S.F., "Settling velocity of irregular shaped particle"; SPE Drilling and Completion, Dec. (1994).
- Given on internet by Courtney K.Harris, "Sediment transport processes in coastal environments", (2003), at [http:// www.vims.edu/~ckharris/ms698-03/lecture-2pdf](http://www.vims.edu/~ckharris/ms698-03/lecture-2pdf)
- Jamil Malaika "Effect of shape of particles on their settling velocity", Ph.D. Thesis, (1949).

غير نيوتونية

مهند عبد الرزاق

جامعة النهريين/ الهندسة الكيماوية

:

إن هدف هذا البحث هو دراسة العوامل المؤثرة على سرعة الاستقرار الجسيمات الصلبة بأستخدام الموائع الغير نيوتونية مثل الخواص الريولوجية, تركيز الموائع غيرالنيوتونية, حجم و شكل الجسيمات الصلبة .
تم تصميم و بناء جهاز مختبري لقياس سرعة استقرار الجسيمات الصلبة يحتوي على أنبوب بيرسبكس بطول , كذلك تم تصميم دائرة الالكترونية لقياس زمن سقوط الجسيمات في السائل.
تم استخدام نوعان من الجسيمات الصلبة؛ كرات زجاجية وصخور غير منتظمة الشكل ذات أقطار مختلفة لكل منهما وقد تم استخدام نظرية القطر الكروي المكافئ لحساب قطر الجسيمات غير منتظمة الشكل.
تم تطبيق القانون الاسي لتمثيل السوائل غيرالنيوتونية وقد قيست سرعة استقرار الجسيمات الصلبة .
نوعان من البوليمرات هما كاربوكسي مثيل سيليلوز بتراكيز (/لتر و بولي اكرالامايد بتراكيز) / (.
بينت النتائج ان سرعة الاستقرار تقل عند ابتعاد المائع عن السلوك النيوتوني (عندما تقل قيمة (n))
يزداد تركيز الموائع غيرالنيوتونية (المحاليل البوليمرية). كما تزداد سرعة الاستقرار بزيادة قطر و حجم الجسيمات
تم أستنتاج ثلاث مجاميع من معادلات جديدة الاولى , يل سلوك جريان الموائع (n) والثانية تربط سرعة الاستقرار مع التركيز والثالثة تربط سرعة الاستقرار مع قطر الجسيمات الصلبة