Research on the Sedimentation of Spherical-Particle Aggregations

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Abstract. The sedimentation of spherical-particle aggregations is the common phenomenon in natural world. However, the related research is quite limited. In this study, the spherical particles with four different densities and three diameters were first used for preparing aggregations with two, three and four particles, respectively. And then the final settling velocity of the aggregations was measured using a visual vertical pipe column. It was found that the final settling velocity would increase with the density and the diameter of the unit particle, which is well in agreement with the Stokes’ theory. Furthermore, the geometry arrangement of the particles can also affect the settling velocity significantly, but no model available to consider its influence. With the increase of particle number, the final velocity presents increase tendency.

Key words: Aggregates; Final Sedimentation Velocity; Particle Geometry Arrangement; Stokes’ Theory.

1. Introduction

The sedimentation of particles is the common phenomenon in natural world. It has a wide range of application in the production and research in oil and gas filed development \cite{1}, such as the suspension and carry of drilling cuts with drilling mud in drilling process, the proppant was carried to fill the fracture with fracturing fluids in hydraulic fracturing process and the carry of packing material in gravel pack completion process. All the above processes refer to the sedimentation or suspension of solid particles \cite{2}. And the motion law of solid particles in liquid-solid two-phase flow plays an important rule on determining construction parameters \cite{3}. By now, the related research mainly focused on single particle \cite{4,5}. The final sedimentation of particles under different Reynold numbers can be accurately predicted with the Stokes’ equation and Oseen resistance coefficient \cite{6}. However, in the most cases, the sedimentation of particles in fluid belongs to the interfered sedimentation of multi-particles, some or all particles sink in groups, forming particle aggregations \cite{7,8}. Nowadays, the research on the sedimentation of particle aggregations is quite limited \cite{9}. Therefore, in this study, the sedimentation of typical particle aggregations was experimental investigated using a visual vertical pipe column, and then the effects of particles density, diameter, geometry arrangement and particle number were discussed.

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2. Experimental sections

2.1. Experimental Apparatus and Materials
The visual vertical pipe column with 2m length and 70mm inner diameter were used for measuring the sedimentation velocity of particles (see Figure 1). The top 1m section was used as the accelerate part and the following section was divided into five uniform observation parts, which was designed for obtaining the sedimentation velocity and determining whether the final velocity is achieved. In order to achieve visualization, the transparent glycerinum (Newtonian fluid) was selected for the test fluid. The viscosity is 560mPa.s and the density is 1.263 kg/m³ at room temperature, i.e., 20°C.

![Figure 1. Schematic of the visual pipe column](image)

Four kinds of materials particles, polyformaldehyde (POM), glass, silicon nitride and zirconia, were used for preparing the aggregation, the density of the materials were listed in Table1. And for every materials, three different diameters (1.588mm, 3mm, 5mm) were selected.

| Materials      | Density/kg/m³ |
|----------------|---------------|
| POM            | 1400          |
| Glass          | 2300          |
| silicon nitride| 3200          |
| zirconia       | 6000          |

2.2. Aggregates Preparation and Measurement Process
(1) The geometry arrangements of the particle-aggregates were first designed. As shown in figure 2, for two-particle aggregate, there is only one geometry arrangement, for three- particle aggregate, three kinds of geometry arrangements, 3-A, 3-B and 3-C, were designed while for three- particle aggregate, 4-A,4-B , 4-C and 4-D were designed. On the basis of the designed arrangements, the aggregates were prepared. The particles were connected using cementing agent. It was note that for every aggregate, the particles are uniform (same density and diameter).

(2) Before the experiment, the test aggregate was first immersed into the beaker filled with glycerinum. The soaking was kept at least 24h to make sure the surface of particles to be complete wetted and the impurities and air bubbles on particle surfaces were removed.
Figure 2. Designed geometry arrangements for different number aggregates

(3) The aggregate was first immersed below the liquid level using tweezers and then released along the center of the pipe column without initial velocity. The time for passing the observation sections was recorded using seconds counter. For every aggregate, the measurement would be repeated 15 times, and interval time is at least 10 min.

(4) With the information of settling time and length of observation sections, the sedimentation velocity of the aggregates can be calculated.

3. Results and discussions

3.1. Effect of Particle Density

Figure 3. Variations of aggregates’ final sedimentation velocity with unit particle density

Figure 3 shows the effects of particle density on the final sedimentation velocity. It suggests that for the two-particle aggregates, the final sedimentation velocity would increase linearly with the increase of particle density. For the aggregate with larger unit particle, the slope of the line is larger. These agree well with the Stokes’ theory. Furthermore, with the increase of particle number, the lines become steeper, which suggests density has more significant effects on large scale aggregates.
3.2. Effect of Particle Diameter

The effects of unit particle diameter on aggregate sedimentation velocity were shown in figure 4. It suggests that for all the aggregates, with the increase of unit particle diameter, the final sedimentation velocity would increase. The further quantitative analysis shows that the increase presents as a power law tendency. The power exponent would range from 1.70-2.0, which is close to the theoretical value, 2, in the Stokes’ equation.

3.3. Effect of Particle Arrangement

![Graph showing the effects of particle diameter on aggregate sedimentation velocity.](image)

**Figure 4.** Effects of particles diameter on aggregate sedimentation velocity

The effects of unit particle diameter on aggregate sedimentation velocity were shown in figure 4. It suggests that for all the aggregates, with the increase of unit particle diameter, the final sedimentation velocity would increase. The further quantitative analysis shows that the increase presents as a power law tendency. The power exponent would range from 1.70-2.0, which is close to the theoretical value, 2, in the Stokes’ equation.

![Graph showing variations of aggregates final velocity versus particle geometry arrangement.](image)

**Figure 5.** Variations of aggregates final velocity versus particle geometry arrangement
Figure 5 presents the effects of particle arrangement on sedimentation velocity. As shown in figure 5(a), for the three particle aggregates, the final velocity of the three designed arrangements varies with each other. The final velocity of 3-A is largest while that of the 3-B is the smallest. The relative difference can be up to 31.3%. The velocity variation between different arrangements was also observed in four particle aggregates. The largest difference is about 27.3%. The above analysis suggests that the geometry arrangement of the particle would have significant effect on the sedimentation velocity. However, in the Stokes’ equation, the effect of particle arrangement was not considered. Therefore, a new model needs to be proposed for considering the effect of particle arrangement in the future.

3.4. Effects of Particle Number

Figure 6 shows the effect of particle number on the aggregate final velocity. It suggests that with the increase of particle number, the sedimentation velocity of aggregates would present increase tendency in spite of the increase would be affected by the arrangement of the particles. In fact, in most of case, the increase of particle number means to the increase of aggregate scale. The previous figure has confirmed that the sedimentation velocity would increase with the size of unit particle. On the other hand, figure 3 suggests that the interfered between particles, resulting in aggregate, lead to large sedimentation velocity.

![Figure 6. Variations of final sedimentation velocity versus particle number (glass+3mm)](image)

4. Conclusion

This study aims to investigate the sedimentation of particle-aggregates. The final settling velocity of particle-aggregates with different materials, diameters, geometry arrangements and particle numbers were systematically measured. The experiments suggest that the final settling velocity would increase with the density and the diameter of the unit particles, which is well in agreement with the Stokes’ theory. Furthermore, the geometry arrangement of the particles can also affect the settling velocity, and with the increase of particles number, the velocity can also increase.

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