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CHARACTERIZATION OF HINDERED SETTLING IN CONCENTRATED SOLID-LIQUID SUSPENSIONS

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ABSTRACT. In order to characterize the hindered effect which appears by sedimentation of concentrated suspensions new experiments with quartz sand having equivalent size d_{90} = 170 μm and concentration 10 – 30 %, in volume, in ethylene glycol and aqueous solutions carboxymethylcellulose (CMC) 0.5%, 1.0%, in weight, were carried out. The drag coefficient, C_D, as a parameter which quantifies the hindered effect, was calculated with particle terminal settling velocity. The hindered settling velocities predicted by Richardson-Zaki's equation were founded comparable with experimental results.

Keywords: *drag coefficient, particle terminal settling velocity, hindered settling velocity, Richardson-Zaki's equation, sedimentation exponent*.

INTRODUCTION

By interacting surfaces in relative motion, as in the case of a moving solid object through a surrounding fluid or a moving fluid which flows on a solid, appears the friction. In many practical applications it is need to know the fluid dynamic drag (friction) on solid particles in process equipments (e.g., slurry pipelines, fixed and fluidized beds).

In settling processes, the fluid drag generated by the moving of solid particles in suspending liquid influences the particle terminal settling velocity. There are two components which define the fluid drag force, F_D, on a moving particle: the skin friction or viscous drag (due to viscous friction) and the form drag (due to the boundary layer separation in the wake of the particle movement).

The fluid drag force is often expressed by the dimensionless friction factor or drag coefficient C_D [1]:

$$\mathbf{C_D} = \frac{\mathbf{F_D}}{\left(\frac{1}{2}\boldsymbol{\rho}\mathbf{w}^2\right)\left(\frac{\boldsymbol{\pi}\mathbf{d}^2}{4}\right)} \qquad (1)$$

where: ρ is the disperse liquid density (kg/m^3), w – the particle settling velocity (m/s) and d - the diameter of the solid particle (m).

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Experimental measurements and dimensional analysis have lead to the conclusion that the moving sphere in a Newtonian fluid shows a dependence of drag coefficient on particle Reynolds number Re [2], as:

$$\mathbf{C_D} = \frac{24}{\mathrm{Re}} \tag{2}$$

in Stokes regime Re < 1 (0,2);

$$\mathbf{C_D} = \frac{18.5}{\mathrm{Re}^{0.6}} \tag{3}$$

in Allen regime: $1 < \mathrm{Re} < 10^3$; and

$$\mathbf{C_D} = 0.44 \tag{4}$$

in Newton regime: $10^3 < \mathrm{Re} < 10^{5;}$

The particle Reynolds number is defined for Newtonian and Non-Newtonian fluids as equations (5) and (6) show [1]:

$$\mathrm{Re} = \frac{\boldsymbol{\rho} \cdot \mathbf{w_S} \cdot \mathbf{d}}{\boldsymbol{\eta}} \tag{5}$$

$$\mathrm{Re} = \frac{\boldsymbol{\rho} \cdot \mathbf{w}_s^{2-\mathbf{n}} \cdot \mathbf{d^n}}{\mathbf{k}} \tag{6}$$

where: w_S is the terminal particle velocity for Newtonian or non-Newtonian (power-law) fluids (m/s), d - the average particle size (m), ρ - the disperse fluid density (kg/m^3), η - the viscosity of Newtonian liquid (Pa·s), *k* – the fluid consistency coefficient ($Pa{\cdot}s^n$), *n* – the flow behavior index (-).

Dimensional analysis applied to the moving sphere in a Non-Newtonian fluid shows the dependence of drag coefficient on particle Reynolds number and on power-index [1]:

$$\mathbf{C_D} = \mathbf{f}(\mathrm{Re}, \mathbf{n}) \tag{7}$$

In creeping flow region (Re << 1) the numerical results shows that the drag coefficient obtained from Stokes' law may be expressed using a deviation factor, X(n) [1]:

$$\mathbf{C_D} = \frac{24}{\mathrm{Re}} \mathbf{X(n)} \tag{8}$$

The numerical values of X(n) show that: shear-thinning causes drag increase X(n) > 1, and shear-thickening causes drag reduction X(n) < 1.

Relationship between drag coefficient and particle Reynolds number can be used in characterization of particle motion in suspending liquid (frequently, the liquid phase may exhibit complex non-Newtonian behavior) and in determination of particle terminal velocity, important parameter in pipeline design for slurry transport.

In the present study, in order to characterize the hindered effect which appears in settling of concentrated suspensions, the drag coefficient was calculated considering the single particle terminal velocity obtained from experimental data.

Hindered settling velocity of particles in concentrated suspension (called also zone settling or mass settling) experimentally determined by the height of descending interface between suspension and the clear liquid followed in time was compared with the Richardson and Zaki predicted values.

In agreement with the equation of Richardson and Zaki [3] (equation 9), the most used expression of hindered settling velocity, the particle settling was graphically determined by extrapolation of the velocity to the voidage equal 1:

$$\mathbf{w}(\mathbf{c}) = \mathbf{w}_S (1 - \mathbf{C}_v)^z = \mathbf{w}_S \cdot \boldsymbol{\varepsilon}^z \tag{9}$$

where: *w(c)* is the hindered settling velocity (m/s), w_S - the single particle terminal settling velocity (m/s), C_v - the solid volume concentration (m^3/m^3), ε - the voidage or void fraction (m^3/m^3) and *z* – the sedimentation exponent (-).

Comparative to the single particle terminal settling velocity, graphically determined by extrapolation of yielded straight line log (w_{exp}) versus log (ε), by numerical simulation the terminal settling velocity of a spherical particle in Newtonian fluids, in creeping regime (Re_t < 2), can be evaluated by Stokes' equation:

$$\mathbf{w}_s = \frac{\mathbf{g} \cdot \mathbf{d}^2 (\rho_s - \rho)}{18 \cdot \eta} \tag{10}$$

where: *d* is the equivalent particle size of particles (m), ρ_s – the solid density (kg/m^3), ρ - the disperse fluid density (kg/m^3), η - the fluid viscosity (Pa·s), *g* - the gravitational acceleration (m/s^2).

The theoretical terminal settling velocity of a particle in non-Newtonian fluids following power-law is estimated by equation (11) [1]:

$$\mathbf{w}_s = \frac{\mathbf{g} \cdot \mathbf{d}^{n+1} (\rho_s - \rho)^{1/n}}{18 \cdot \mathbf{k} \cdot \mathbf{X}(\mathbf{n})} \tag{11}$$

where: k is the fluid consistency coefficient ($Pa \cdot s^n$), *X(n)* - the deviation factor, a function of flow index *n*.

As equations (1) – (11) show the settling behavior of particles, in sedimentation processes of solid-liquid suspensions, is influenced by: size and density of particles, the presence of other neighboring particles in concentrated suspensions; and rheological parameters of suspending liquid.

The literature data show that the variation of sedimentation velocity with concentration for non-spherical particles is similar to the behavior of spherical particles [4].

RESULTS AND DISCUSSION

Experimental hindered settling velocities

Gravity sedimentation, a simple and direct method, is used in the present work in order to characterize experimentally the particles settling. The method is based on measure the descendent solid-liquid interface as a function of time, as describe previously [5].

As in the case of sedimentation quartz sand in 0.5% CMC and 1.0 % CMC solutions, the hindered settling velocities in ethylene glycol is determined by sedimentation curves, considering concentrated suspensions (volume concentration C_v between 10 and 30 %, Figure 1).

The incipient hindered settling velocities calculated show clearly the decrease of velocities with the increase of solid particle concentration.

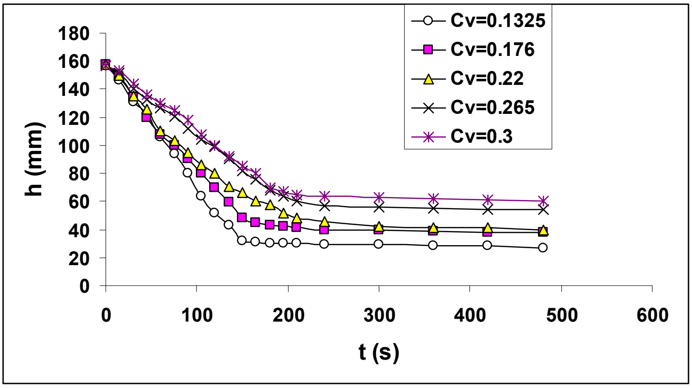
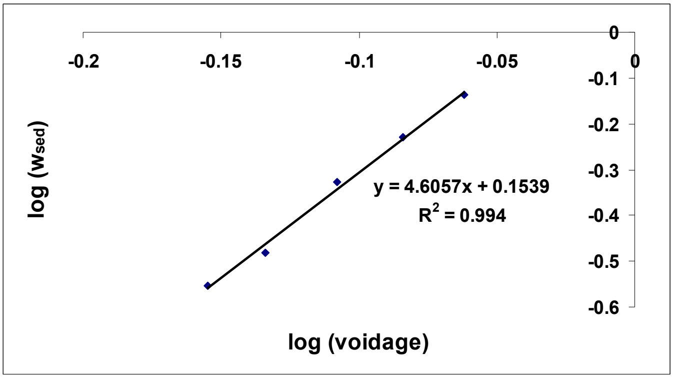


Figure 1. Sedimentation curves of quartz sand in ethylene glycol.

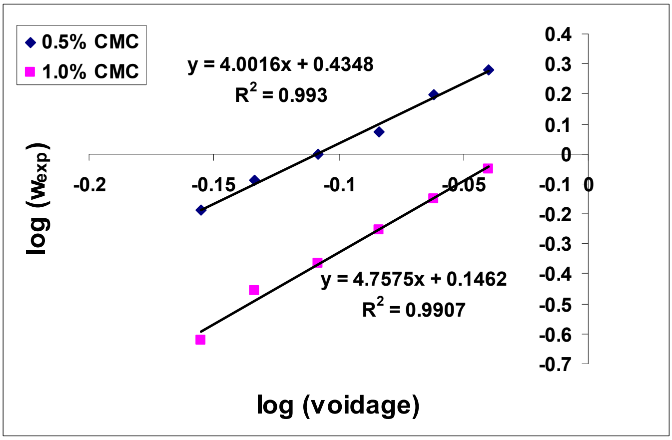
Single particle terminal settling velocity $w_{s(ex)}$ is determined by extrapolation to the voidage equal 1, when equation (9) is plotted on logarithmic coordinate (Figure 2). The obtained values are shown in Table 1.

As the slope of straight lines yielded in Figure 1 shows, the sedimentation exponent *z* determined by experimental data is comparable with Richardson-Zaki value (*z*=4.65).

Theoretical particle Stokes settling velocities $w_{S(s)}$ is calculated by Stokes' equation (10) or (11) for the equivalent size particle of d_{90} = 170 μm, and the liquid density and viscosity, or the rheological parameters *k* and *n* of suspending liquid shown in Table 1. The rheological parameters considered in the present work are from literature [6].



a.



b.

Figure 2. Log-log plot of experimental settling velocity and voidage in ethylene glycol (a) and in CMC solutions (b).

The ration between $w_{S(s)}$ and $w_{S(ex)}$ varies from 0.98 to 1.26. If in the case of ethylene glycol, a typical Newtonian liquid, and 0.5 % CMC the values are comparable, in the case of 1.0 % CMC, a typical shear-thinning liquid [7], the predicted value showing a clear influence of rheological parameters, is larger that those determined by experimental data (see Table 1).

All particle Reynolds numbers calculated by equation (5) or (6) with corrected particle velocity $w_{S(ex)}$ are smaller than 1, which indicates particle terminal settling in a creeping regime, as it was considered.

The calculated drag coefficient shows comparable values in the case of sedimentation of quartz sand in ethylene glycol and 0.5 % CMC, and a higher value in 1.0 % CMC, as is expected for shear-thinning fluids.

The theoretical hindered settling velocities predicted by Richardson and Zaki's equation, noted $\mathbf{w_{t1}}$ when theoretical Stokes' velocity $\mathbf{w_{S(s)}}$ and $\mathbf{w_{t2}}$ when single particle terminal velocity $\mathbf{w_{S(ex)}}$ is used, are compared with experimental hindered settling velocities as a function of voidage in Figure 3.

Table 1. Comparison of single particle terminal velocity using experimental data and Stokes' equation

Suspending medium	Liquid parameters	$w_{S(ex)}$ (extrapolation) (mm/s)	$w_{S(s)}$ (Stokes' equation) (mm/s)	Re_t	C_D
Ethylene glycol	ρ=1112 (kg/m^3) η=16.1 (mPa·s)	1.425	1.50	0.0167	1437
0.5 % CMC	ρ=1002 (kg/m^3) k=29.275(mPa·s) n=0.9295	2.70	2.61	0.0191	1382
1.0 % CMC	ρ=1002 (kg/m^3) k=110.76(mPa·s) n=0.871	1.40	1.77	0.0028	10276

It can be seen a good correlation between experimental and predicted settling velocities when ethylene glycol was used as suspending liquid and some differences for the other two cases.

In the same time, an improving of theoretical Richardson-Zaki's prediction was observed in the present study comparative with the previous, due to the new rheological parameters and appropriate equivalent particle size considered.

The difference which appears between experimental and theoretical hindered settling velocities in the case of quartz sand sedimentation in 1.0 % CMC seems to by caused by the rheological behavior of CMC solution as a shear-thinning liquid (see Table 1), which generally induces particle aggregation.

The larger value of drag coefficient in the case of 1.0 % CMC indicating a higher friction between particles and suspending liquid causes a higher hindered effect and induces smaller hindered settling velocities, as experimental data show.

CONCLUSIONS

The particles settling in hindered regime in the case of quartz sand suspensions in ethylene glycol, 0.5 % CMC and 1.0 % CMC was experimentally determined.

The single particle terminal settling velocity w_S was determined by extrapolation of the experimental velocity to voidage equal 1 and by numerical prediction using Stokes' equation.

An improving of theoretical hindered settling velocities in non-Newtonian fluids was obtained reconsidering the new values of rheological parameters necessary to determine the particle terminal settling velocity by Stokes' law.

The hindered settling velocity can be predicted by Richardson-Zaki's equation, considering an appropriate value for the sedimentation exponent z.

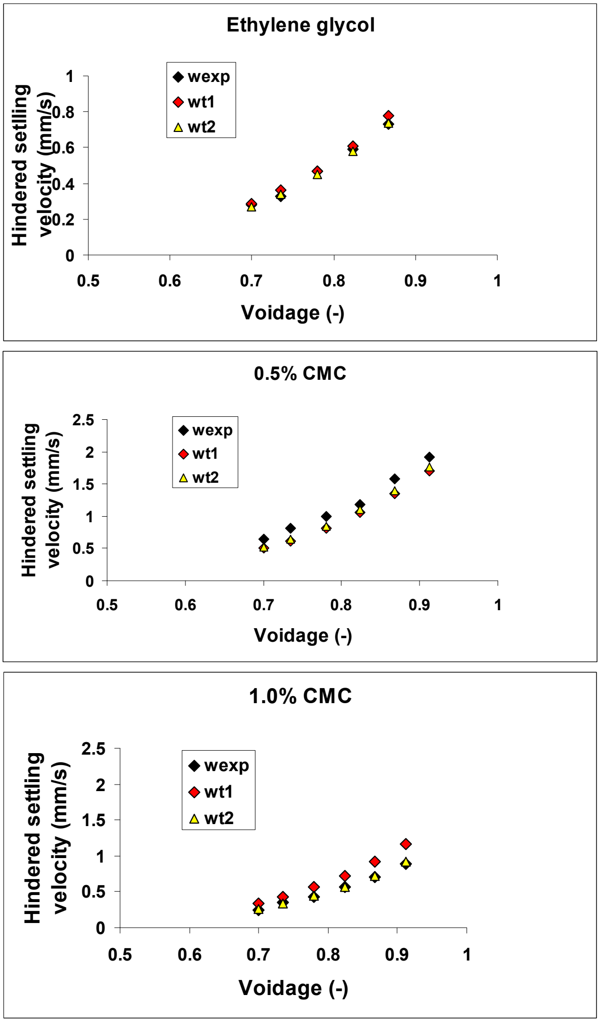


Figure 5. Experimental and theoretical hindered settling velocities vs. voidage.

The hindered effect on settling behavior was analyzed considering the drag coefficient. The drag coefficient and the hindered effect was higher in 1.0 % CMC, as for a shear-thinning fluid is expected.

EXPERIMENTAL SECTION

To get the particle size of sand quartz used for the experimental measurements, first a very narrow fraction of raw sand was prepared by sieving, and the sieve range 200 μm < d < 180 μm was removed. Sieve range refers to the range between material passing through 200 μm and retained on 180 μm. The separated fraction was than analyzed by wet sieving using the sieve series of 180, 163, 125, 90 and 71 μm, and compared with the analyze resulted using the Andreasen pipette which evaluated the particle settling velocities. By wet sieving and by sedimentation using the Andreasen pipette was determined the equivalent size of particle d_{90} =170 μm.

Experimental settling velocities were determined by collected data from batch settling tests. The suspensions with volume concentration between 10 % and 30 % have shown net sedimentation front during the whole settling process. The experimental runs were carried out in cylinders with internal diameter of 28 mm and 300 mm tall.

Prior each settling experiment, the blends were strongly mixed by shaking, directly in the cylinder were the tests are done, in order to obtain a well dispersed initial state. After mixing, the cylinder was allowed to stand, and the height of quartz sand was noted at regular intervals until no further sedimentation occurs. The boundary between the settling suspension and the supernatant phase were determined visually for each sample, as a function of time in order to establish the sedimentation curves. Each experiment was performed in triplicates.

REFERENCES

1. R.P. Chhabra, J.F. Richardson, "Non-Newtonian Flow in Process Industries. Fundamentals and Engineering Applications", Butterworth-Heinemann, Linacre House, Jordan Hill, Oxford OX2 8DP, **1999**.
2. R.B. Bird, W.E. Stewart, E.N. Lighfoot, "Transport Phenomena", 2nd edition, John Wiley & Sons Inc., New York, **2002**.
3. J.F. Richardson, W.N. Zaki, *Trans. Inst. Chem. Engrs.*, **1954**, *32*, 35.
4. R. Di Felice, R. Kehlenbeck, *Chem. Eng. Technol.*, **2000**, 23, 1123.
5. A. Ghirişan, S. Drăgan, *Studia UBB Chemia,* **2011**, *LVI*(2), 115.
6. M.A. Cancela, E. Alvarez, R. Maceiras, *Journal of Food*, **2005**, *71*(4), 419.
7. T.G. Mezger, "The Rheology Handbook", 2nd revised edition, Vincentz Network GmbH &Co. KG, Hannover, **2006**.