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SEDIMENTATION OF DILUTE SUSPENSION IN INTERMEDIATE REGION

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Abstract: *The present paper describes the results of experimental investigation of the continuous sedimentation of a dilute model of fine-grained suspension in the intermediate region of settlement. The effects of particle size (glass beads of average diameter 150–850 μm), concentration, and inclination of the vessel axis on particle fall velocity were evaluated. It was confirmed that the local relative particle-liquid velocity has a practically constant value across the vessel cross-section. The settling pattern is strongly affected even by a very gentle slope of the vessel axis, which causes an asymmetrical absolute velocity profile and significant increase of the local concentration and absolute fall velocity of particles near the upward-facing wall of the vessel.*

Keywords: ***sedimentation, intermediate settlement, particle size, concentration, vessel inclination.***

1. Introduction

The particle fall velocity is one of the main hydrodynamic parameters of solid-liquid mixture flow in natural conditions, for example sediment transport in rivers and channels, as well as in technical applications for water or waste – water treatment, chemical and civil engineering, pipeline hydraulic transport, or dredging. The fall velocity is a common integral parameter describing the mutual interaction between the particles and the carrier fluid. However, a reliable method of determining the fall velocity of particles of general shape is still not available, and in fact there is still a significant lack of experimental data and theoretical solutions for the sedimentation of clouds of solid particles in the intermediate region of sedimentation.

The paper describes the experimental results of dilute model suspension sedimentation in the intermediate region of sedimentation, for particle Reynolds number Re_p varying from 3 to 140 in a vertical and slightly inclined sedimentation vessel.

The fall velocity of a particle moving in suspension in a container is generally determined by the particle diameter d, shape b, and density ρ_p, the volumetric concentration of the suspension C_v, the distance from the container wall y, and the density ρ_o and viscosity μ_o of the carrier liquid. It is also dependent on the dimension D of the horizontal cross-section and shape B of the container, and, as will be shown below, on the inclination of the container walls α. The particle fall velocity (Ah Chin et al., 1986) can be generally described by Eq. (1)

$$w_c = (d,\ b,\ \rho_p,\ C_v,\ y,\ \rho_o,\ \mu_o,\ D,\ \alpha). \qquad (1)$$

The effect of the selected parameters of Eq. (1) on particle fall velocity will be discussed in the following paragraphs. The absolute local velocity of the settling particles and carrier liquid were measured for different volumetric concentrations and sedimentation vessel inclinations, and thus relative particle-water velocities were also determined. The effects of the particle concentration of the suspension and the vessel inclination on the particle velocity and the internal structure of sedimentation will be described.

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2. Experimental equipment and procedure

Several experimental methods are suitable for measuring continuous sedimentation, for example the radiometric tracer method, PIV (Particle Image Velocimetry), and LDA (Laser Doppler Anemometry). The LDA or PIV methods are suitable for very dilute transparent suspensions and make it possible to determine both local particle and liquid velocities. The radiometric tracer method allows the absolute particle velocity of different species of suspended solids to be measured, but for higher concentrations of relatively fine particles, problems with accuracy can arise (Vlasak et al., 1994). For this reason, we used LDA for measuring the local velocities, but for higher particle concentrations a method based on the increment of hydrostatic pressure due to the increase in suspension density was developed. This method makes it possible to measure the mean fall velocity in suspensions with a relatively wide range of concentrations.

The volumetric concentration is generally given as

$$C_v = (\rho_s - \rho_o)/(\rho_p - \rho_o), \tag{2}$$

where ρ_s is the density of suspension. Because the particles which enter the elementary volume V_C at time $t_o = 0$ and fall in the suspension with velocity w_c reach, during the time interval t the distance $l = w_c\, t,$ the elementary volume is given as

$$V_C = w_c\,.\,t.\,S_D = l.\,S_D, \tag{3}$$

and the volumetric concentration of the suspension can be determined as the ratio of the volume of the particles V_p and of the suspension V_s in the elementary volume V_C

$$C_v = V_p / V_C = (q_p\,.\,t) / (w_c\,.\,t.\,S_D), \tag{4}$$

where q_p is the flow rate of solid particles, and S_D is the cross-sectional area of the sedimentation vessel.

The increase in hydrostatic pressure in the column of the suspension compared to the hydrostatic pressure of the carrier liquid alone is

$$\Delta p = h.\,(\rho_s - \rho_o).\,g, \tag{5}$$

where h is the height of the column. From Eqs. (2 – 5) the mean fall velocity w_c of suspended particles can be expressed as

$$w_c = 4\,g.\rho_p\,.\,h\,.\,(\rho_p - \rho_o) / (\pi\,.\,\Delta p.D^2), \tag{6}$$

To determine the local absolute particle velocity w_p of the individual particles and also the local velocity of displaced water, $v_{o,}$ the LDA technique was used (Vlasak et al., 1991). The LDA apparatus consists of a laser and optical parts from a DISA system (beam divider, Bragg-cell, optics, photomultiplier working in the lateral forward diffraction regime). The Doppler signal detected in the photomultiplier was processed by a frequency synthesizer and evaluated by a counter. The primary experimental data, Doppler frequencies in the form of 12 bit words, were statistically processed and as a result pairs of velocity data distributions on the velocity histogram were obtained. One group of bins of the velocity distribution in the higher velocity range represents the absolute particle fall velocities in suspension, w_c, and the second one, close to the zero velocity values, represents the local velocities of the displaced waver, v_o. To investigate the effect of concentration and sedimentation vessel axis inclination on the inner structure of the suspension during the settlement process, visualization was also used.

To measure the particle fall velocity in the model suspensions, equipment consisting of a sedimentation vessel (a glass tube of inner diameter $D = 0.05$ m and length $L = 2.3$ m), a particle dosing device, and measuring devices were used. The particle dosing device maintained the continuous uniform supply of particles and ensured a constant concentration of the measured suspension.

Water was used as the carrier liquid, and narrow sized glass beads of different mean diameters (average particle diameter varied in range d_{50} = 150, 280, 350 and 850 μm) were used as model particles. The temperature of the suspensions was in range $T = 20 \pm 2$°C. It was possible to operate the equipment continuously over a sufficiently long time period to obtain a stationary regime. A schematic diagram of the equipment is presented in Fig. 1.

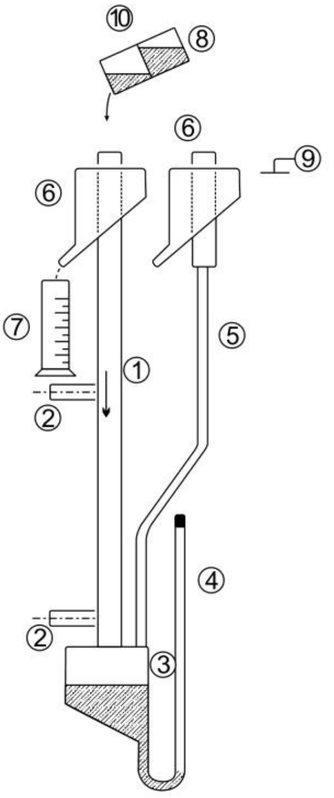


Fig. 1. Experimental equipment (1 – sedimentation vessel, 2 – γ-detector, 3 – sedimentation tank, 4 – let out hose, 5 – coupling hose, 6 – control and out-let set-up, 7 – calibrated vessel, 8 – particle dosing device, 9 – level of suspension, 10 – particles)

3. Results and discussion

The absolute local particle fall velocities and local water velocities were measured for different volumetric concentrations C_v of the suspension and three values of the sedimentation vessel axis inclination α. The effects of concentration and vessel inclination on the particle fall velocity and particles distribution in the vessel cross-section were evaluated.

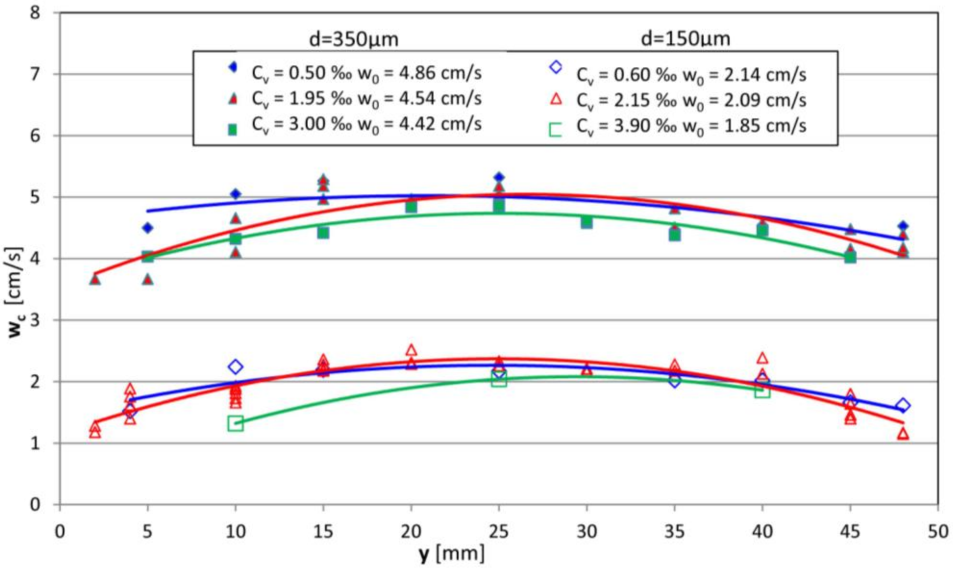


Fig. 2. Absolute fall velocity profiles in the vertical sedimentation vessel

The absolute particle fall velocities in a vertical vessel are shown in Fig. 2. For the smaller particles (mean diameter d_{50} = 150 μm) the velocity profiles are relatively flat and symmetrical. Velocity profiles are slightly asymmetrical, more so for particles with mean diameter d_{50} = 350 μm. The curvature of the velocity profiles is steeper in the area near the vessel walls, while a relatively flat plateau can be seen in the central part of the vessel cross-section. The maximum local velocity values are located 5 to 10 mm from the column axis; the profile asymmetry increases with decreasing concentration. The reason for the velocity profile distortion is probably an imperfect circular shape or imperfect verticality of the vessel.

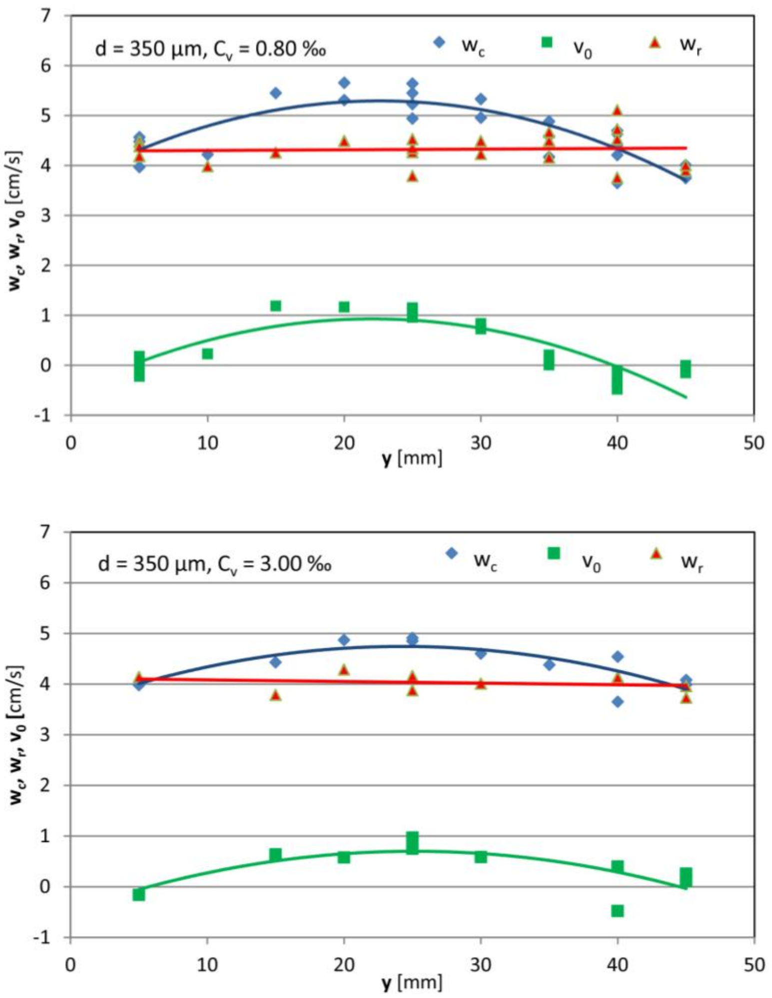


Fig. 3. Relative and absolute particle velocities and water velocity profiles in the vertical sedimentation vessel

The measured profiles of displaced water show very similar shapes to absolute particle fall velocity profiles, with the opposite direction, of course. This indicates, that it may be useful to introduce the relative particle fall velocity:

$$w_r = w_c - v_o, \qquad (7)$$

where w_r is the relative particle fall velocity and v_o is the local velocity of displaced water with respect to the sedimentation vessel.

While the absolute fall velocity profiles are arch-shaped, the relative particle-water velocity values are nearly constant, independently of the position in the vessel (see Fig. 3). This indicates that the difference in the absolute fall velocities is due to the different velocities of displaced water. In the vertical sedimentation vessel, upward flow of the displaced water was observed near the wall, while downward flow of the displaced water was observed in the central area. This explains why the local absolute fall velocity of particle w_c is observed to be even higher than the fall velocity $w_{p,\infty}$ of the same single particle in the unbounded liquid medium. This inner flow structure in the sedimentation vessel was also confirmed by visualization of the sedimentation process. In the central area and in the vicinity of vessel walls the flow lines are smooth and straight; at the boundary of these areas, with opposite flow directions, wavy trajectories and even swirls can be observed (see Fig. 4).

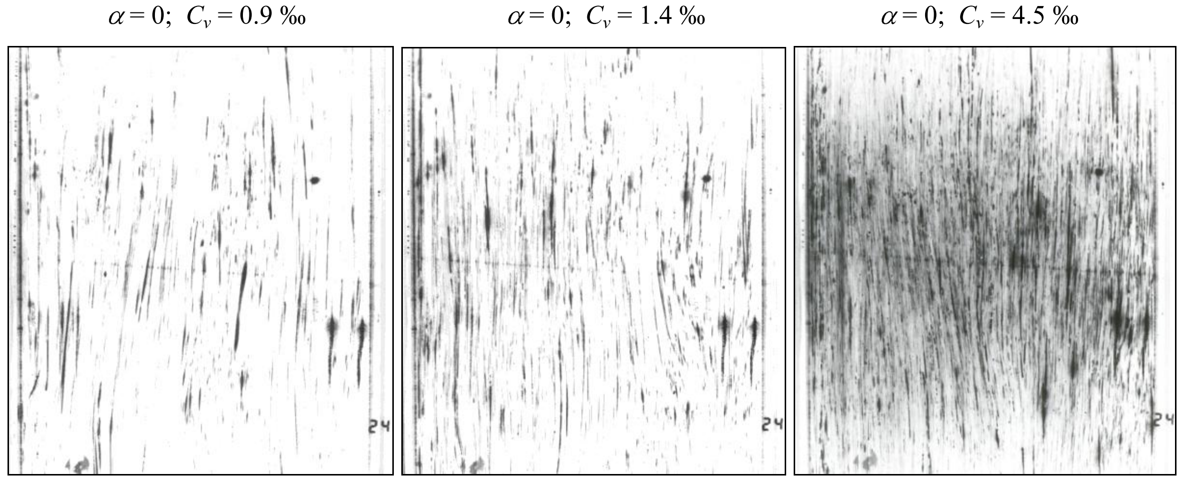

$\alpha = 0$; $C_v = 0.9$ ‰ $\alpha = 0$; $C_v = 1.4$ ‰ $\alpha = 0$; $C_v = 4.5$ ‰

Fig. 4. Structure of sedimentation in vertical sedimentation vessel.

In the sedimentation vessel, during continuous sedimentation the suspension divides into channels in which the velocities of the particles and water can be in the same direction (the so-called co-current regime) and the particles apparently move faster than a single particle in unbounded calm liquid. On the other hand, other channels exist where a counter-current regime of the particles and liquid occurs and the absolute fall velocity of the particles is lower than that of a single particle.

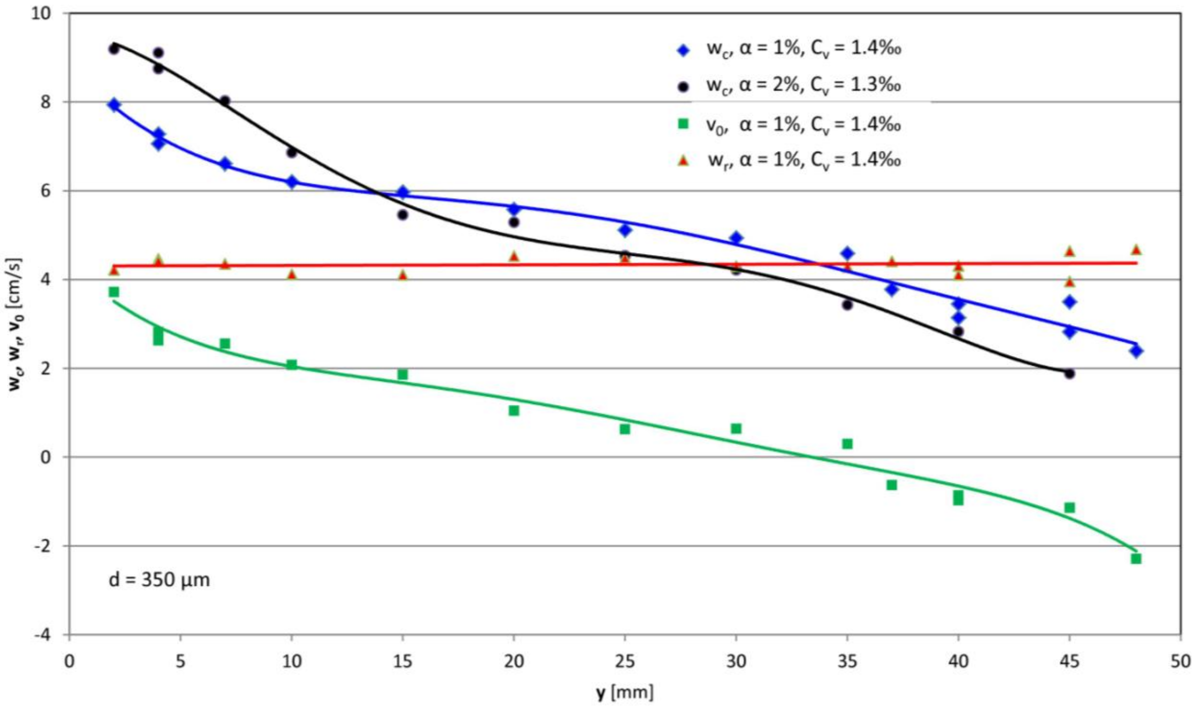
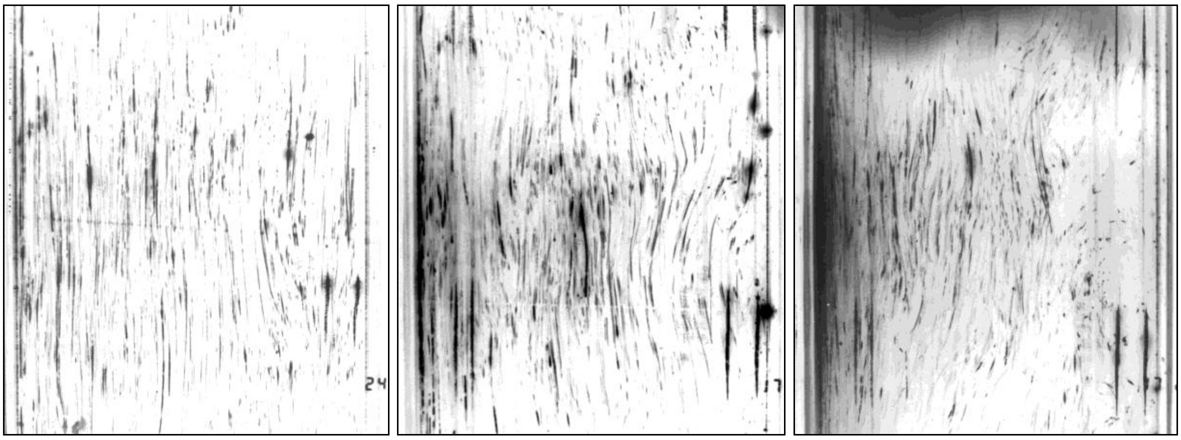


Fig. 5. Relative and absolute particle velocities and water velocity profiles in the inclined sedimentation vessel

The sedimentation process is highly sensitive to the inclination of the sedimentation vessel; even very small inclination causes a considerable change in the inner structure of the sedimentation process. If the axis of the sedimentation vessel is slightly inclined, the absolute particle velocity profiles become significantly asymmetric (see Fig. 5). Higher particle fall velocities are attained near the upward-facing wall, which is located at co-ordinate $y = 0$. In the vicinity of the upward-facing wall the co-current regime of the particles and carrier liquid was observed in combination with a significant increase in the local particle concentration. In contrast, near the downward-facing wall of the vessel a counter-current flow regime of the particles and water and lower particle concentration were observed. Nevertheless, the relative particle-water velocity reached an almost constant value over the whole cross-section. In the central part of the vessel between the co-current and counter-current flow regimes, wavy trajectories and even local swirls were observed (see Fig. 6). If the inclination of the vessel axis increases the transverse migration of the particles in the direction of the upward-facing wall becomes significant, while near the downward-facing wall the occurrence of particles is entirely random.



$\alpha = 0$; $C_v = 1.4$ ‰ $\alpha = 1$ %; $C_v = 1.9$ ‰ $\alpha = 2$; $C_v = 1.9$ ‰

Fig. 6. Structure of sedimentation in inclined sedimentation vessel.

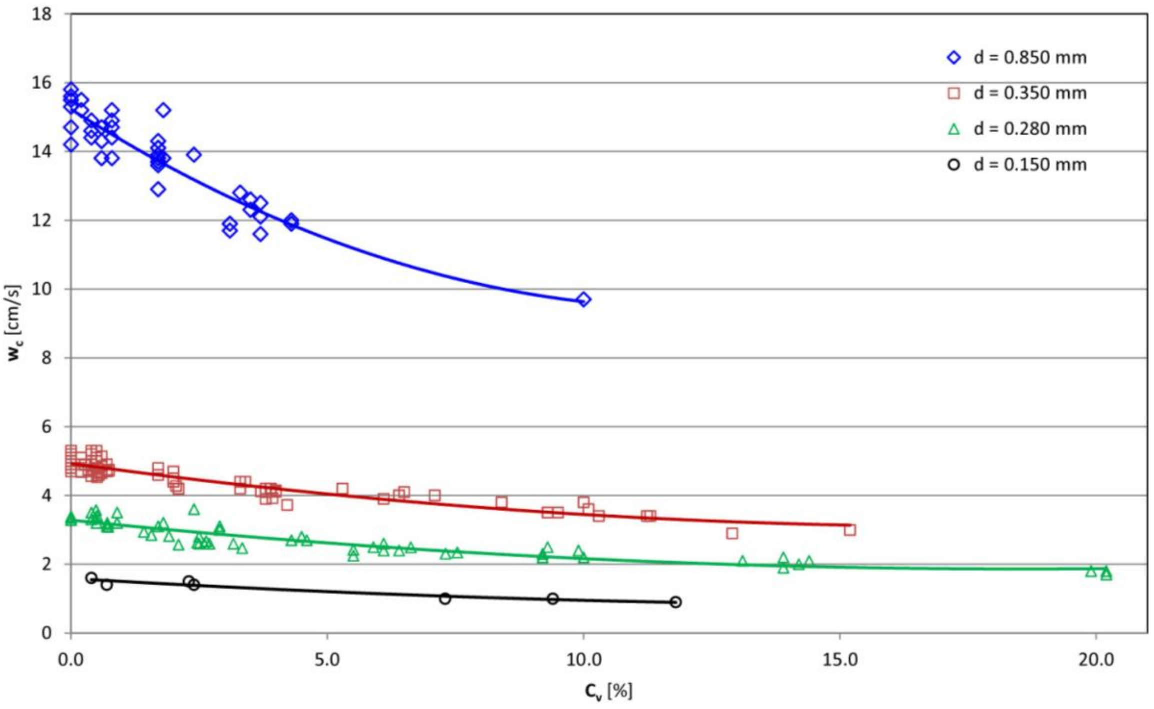


Fig. 7. Effect of concentration on particle fall velocity in a vertical sedimentation vessel

It is generally known that the value of absolute particle fall velocity decreases with increasing concentration. Many relations have been proposed to solve this effect, but unfortunately their validity is limited by certain conditions. They are usually suitable for small concentrations or concentration above 10%. If we compare our experimental data with the proposed relations, rather wide scattering can be observed. Based on our experimental data obtained by the hydrostatic pressure method and the radiometric tracer method measurement (Vlasak et al., 1994; Vlasak & Chara, 1995), the relation

$$w/w_c = (1 + 4.92\, C_v)^{-1}, \tag{8}$$

similarly to the model of Burgers (1942), is proposed (see Fig. 7).

4. Conclusions

The results of an experimental investigation of continuous sedimentation of a suspension of glass beads in water in a vertical or inclined sedimentation vessel confirm the significant impact of sedimentation-induced flow of the displaced liquid on the absolute particle fall velocity. The absolute particle velocity is affected by the particle diameter and concentration, the inclination of the sedimentation vessel axis, and the distance of the particle from the vessel wall.

The value of particle fall velocity decreases with increasing concentration.

The distribution of the local absolute particle fall velocity exhibits arch-shaped profiles; however the values of local particle-liquid relative velocity are nearly constant across the cross-section of the sedimentation vessel.

The sedimentation process is highly sensitive to the inclination of the sedimentation vessel axis. Even an inclination in the range 1% causes considerable change in the structure of the sedimentation process, with a tendency to form an asymmetric absolute particle fall velocity distribution. An upward flow of displaced liquid took place near the downward-facing surface of the vessel, and significantly more concentrated down ward flow was observed near the upward-facing wall.

If the inclination of the sedimentation vessel axis exceeds 1%, a significant transversal migration of the suspended particles combined with an increase in the local concentration is observed near the upward-facing wall, as well as wavy trajectories and swirl areas in regions where the downward flow of the suspension and upward flow of the displaced liquid are in contact.

Acknowledgements

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Symbols

b	shape of particle
B	shape of sedimentation vessel
C	concentration
d	particle diameter
D	diameter of sedimentation vessel
h	height
l	distance
L	length
p	pressure
q	flow rate
Re	Reynolds number
S	area
S_D	sedimentation vessel cross-sectional area
t	time
T	temperature
v	liquid velocity
V	volume
V_C	elementary volume
w	particle fall velocity
y	coordinate
α	angle, slope of sedimentation vessel axis
μ	viscosity
ρ	density
Δ	increment

Subscripts

c	cloud of particles
o	liquid
p	particle
r	relative
s	suspension
v	volumetric
50	mean diameter
∞	unbounded