Novel on-Line Settling Velocity Transducer for 2-Phase Solid/Liquid Suspensions

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Abstract - The design and development of a novel vibrating reed technique for on-line measurement of the sedimentation kinetics of two-phase dispersions is described. The technique has been tested in conjunction with a variety of solid/liquid and liquid/liquid dispersions with dense phase concentrations in the range 0 - 50 % v/v. Typical output include settling velocities, solids flux profiles as well as solids throughputs. Additionally, the performance of a number of sedimentation kinetics models proposed for dilute systems (0 - 2.81 % v/v) are evaluated by comparison with data obtained using the device.

1. INTRODUCTION

Understanding and modelling the effects of various factors governing the stability of two-phase dispersions systems is vital since it influences the process design of appropriate chemical reactors, their subsequent downstream processing, storage and transportation. Central to this is the ability to make direct measurement of the sedimentation kinetics of such dispersions in an on-line manner.

In recent years, several sedimentation measurement techniques have been developed [1]. All involve monitoring the variation of some physical or chemical property over a defined sensing volume. The derived information is then used in conjunction with an initial calibration in order to determine the settling behaviour of a given suspension. However, the majority are unreliable since the type of calibration they require is suspension-specific. Consequently, few devices are capable of continuous on-line operation and, therefore, operators still have to rely on direct sampling methods in which samples are extracted for analysis in order to approximate the dynamic behaviour of the settling process. This approach is itself prone to errors and evidently non-representative since suspension composition may change rapidly with time.

In this study we report the design and development of a novel remote drive vibrating reed technique for the on-line monitoring of sedimentation kinetics that overcomes most of the above problems. The principle of operation of the device is simple and relies on the fact that the resonant frequency of a stiff reed performing simple harmonic motion in a fluid medium is directly related to the fluid hydrodynamic head. We make use of the fact that in the case of a settling dispersion, the hydrodynamic head decreases with time as the denser phase settles. Settling velocities and solids flux profiles may in turn be easily obtained by continuous monitoring of the resonant frequencies of a number of reeds positioned at set levels along the settling zone.

2. THE VIBRATING REED SENSOR

Fig. 1 shows, in perspective, a diagram of the vibrating reed sedimentation analyser designed based on finite element analysis [2] for maximum sensitivity in response. The instrument comprises a 110 mm long, 2.5 mm dia. reed (1) with a 0.06 mm thick and 40 mm diameter stainless steel disk (3) welded, at an intermediate point around its circumference. The remote span (longer end) of the reed is exposed to the test environment whilst the drive span is driven into transverse resonance vibration by an alternating current electromagnet (7). The remote span of the reed is mounted with a 20 mm diameter, 2 mm thick aluminium disk (2) which magnifies the effect of the test dispersion on the resonant frequency. The drive span on the other end is suitably threaded in order to take on a 5 x 10 x 2 mm thick mild steel plate (6) that serves to improve magnetic flux linkage with the electromagnet. The electromagnet is securely held in position by two suitably shaped aluminium brackets. These are in turn connected to a rectangular stainless steel support plate by four screws . The support plate is suitably machined in order to allow the mounting of the reed (1) to the wall of the settling tank (4) via the pinning disk using six equi-spaced screws. The pinning disk forms a liquid tight seal with the settling tank wall.

Vibrations are transmitted through the pinning disk and detected on the drive side by a photo-transistor comprising an infrared emitter and a photo-transistor detector (5). These are mounted at ca. 10 mm above the mild steel plate. The system automatically tunes to the first harmonic resonant frequency of the reed by operating on the basis of a regenerative feed back loop [3]. In this case, the vibration induced voltage signal picked up by the optical sensors is returned to drive the electromagnet via a 30 watt pulsating alternating current power amplifier thus forming a closed loop. A 50 watt transformer acts as the system power supply. The entire drive section of the reed is encapsulated in a suitably sized aluminium casing in order to block out light interference from surroundings. Sedimentation kinetic profiles are generated using a multiplex array of 4 reed units strategically position along the length of a 2.2 x 0.2 m cylindrical sedimentation tank.

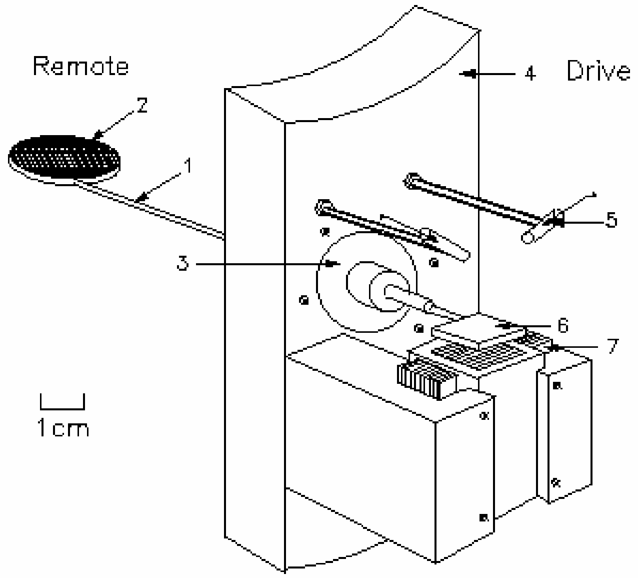

Figure 1. A perspective representation of the remote drive vibrating reed transducer viewed from the drive side showing the reed (1), remote side

attached mass (2), pinning disk (3), container wall (4), optical sensors (5), flux linkage plate (6) and electromagnet (7).

3. RESULTS AND DISCUSSION

Model dispersions: - Fig. 2 is a typical response showing the variation of resonant frequency with time for various concentrations of mono-size (200 - 212 μm) glass ballotini dispersions in the range 1.75 - 2.81 v/v %.

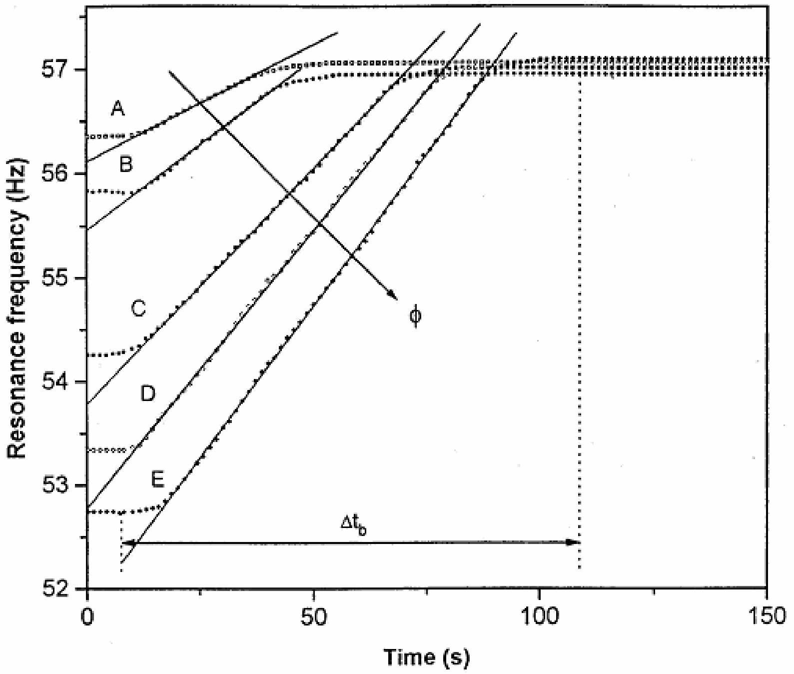

Figure 2

The variation of resonance frequency with time at reed position 1 (699 mm from top of settling zone) for monodisperse 200 - 212 μm glass ballotini spheres (density 2550 kgm^{-3}) settling in water @ 17 °C at various initial suspended solids volume concentrations, ϕ: curve A, $\phi = 1.75$ %; curve B, $\phi = 2.01$ %; curve C, $\phi = 2.35$ %; curve D, $\phi = 2.56$ % and curve E, $\phi = 2.81$ %

The initial flat region in the frequency response corresponds to steady state operation where the particles are still in a 'fluidised' state. The settling process is marked by a gradual increase in resonant frequency until all particles pass the reed's position following which data converge to approximately the same constant value. The corresponding time lapsed measured when two consecutive frequency measurements are within 99.9% of one another relative to the onset of settling is here referred to as the 'breakthrough time', Δt_b. This value increases with increase in particle concentration as well as the distance of each reed from the top of the settling zone. The linear variation of resonant frequency with time during the transition period indicates that for this special case of a nominally mono-disperse dispersion, all particles settle at approximately the same rate.

Fig. 3 shows the variation of the rate of change of resonant frequency with time profiles for different concentrations of 55 - 100 μm ballotini/water dispersions. The data have been obtained by differentiating the recorded frequency/time profiles of the type shown in fig. 2. As it may be observed, for a given initial solids volume concentration, the settling rate starts from a low, effectively zero value, goes through a peak and then reverts back to zero. This type of behaviour is highly indicative of size segregation and hence differential settling of the particles. It is often accompanied by the presence of a relatively diffuse suspension-supernatant interface. Also, according to the data, the maximum settling rate increases with increase in solids concentration. The breakthrough time corresponding to each solids concentration may be easily obtained from the intersection of each curve with the abscissa. It increases with the initial solids concentration. The analogous results obtained with other reeds stationed along the settling tank indicate that as the sensing zone moves away from the top of the settling zone, the peaks of the rate of change of resonant frequency with time profiles become progressively broader exhibiting a smaller degree of size segregation.

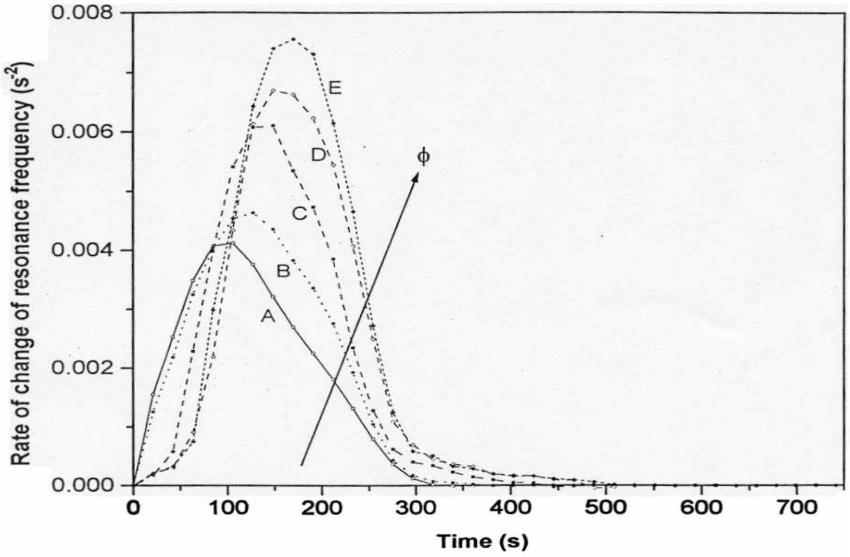

Figure 3
The variation of rate of change of resonance frequency with time at reed position 1 (699 mm from top of settling zone) for polydisperse 55 - 100 μm glass ballotini spheres (density 2550 kgm^{-3}) settling in water @ 17 °C at various initial suspended solids volume concentrations, ϕ: curve A, $\phi = 1.75$ %; curve B, $\phi = 2.01$ %; curve C, $\phi = 2.35$ %; curve D, $\phi = 2.56$ % and curve E, $\phi = 2.81$ %

Real Systems:- Fig. 4 shows the variation of normalised resonant frequency with time using the multiplex reed system sensing a 20 % v/v flocculated kaolin/water suspension at 17 °C. In this case, the resonant frequencies of reeds 3 (curve C) and reed 4 (curve D) decrease with time indicating an actual densification due to the build up of sediment in their proximity.

At the start of sedimentation, flocs are weak and irregular interconnected structures, which experience strong drag forces and therefore exhibit low settling rates [4]. This effect becomes more pronounced as the distance down the settling zone increases since the flow path of displaced fluid becomes more tortuous. In addition, the time required for the subsequent coalescence of flocs into more distinct faster settling spherical aggregates increases with distance down the settling zone. This explains the initial flat region (i) of curve C. As the settling process proceeds, a loosely packed sediment starts to form above reed 3. This increases in depth with time as the sediment-suspension interface rises and corresponds to region (ii) of curve C. During this interval, reed 3 is exposed to an increasingly more dense medium than the original suspension. Accordingly, the resonant frequency decreases with time. At the end of the settling process thin vertical channels start to appear in the sediment. These visibly increase in size with time and the sediment-supernatant interface begins to fall as compression and dewatering effects become more prominent. This process corresponds to region (iii) of curve C and is known as sediment consolidation [5]. The latter is characterised by the collapse of flocs and results in a more densely packed sediment. Accordingly, the resonant frequency continues to decrease in this interval. Region (iv) represents the end of sediment consolidation. Curve D shows that the system response obtained in conjunction with reed 4 follows a similar trend. In this case the reed is covered in sediment much earlier (region (ii)) since it is

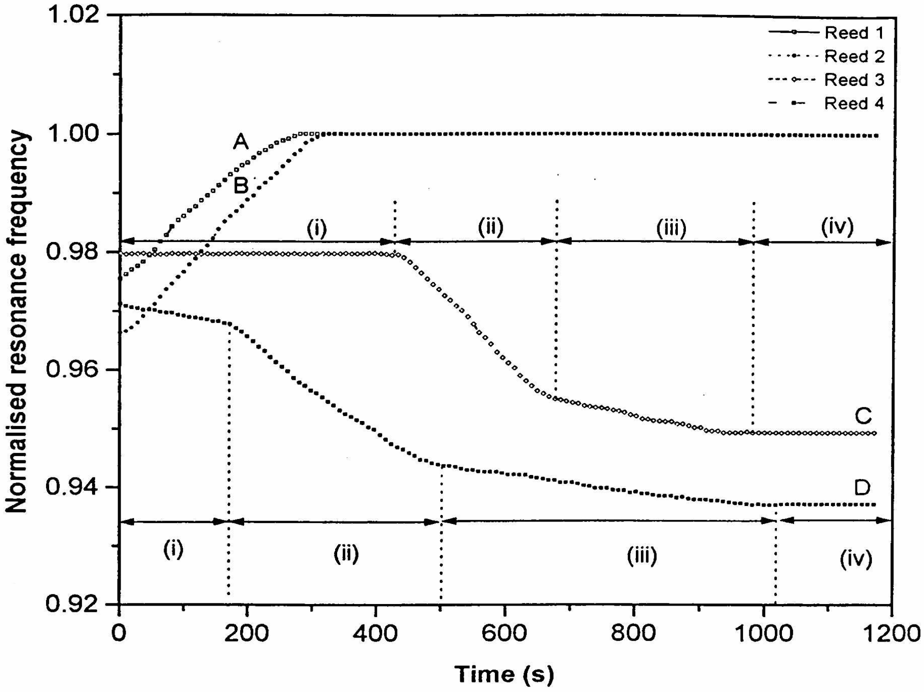

Figure 4
The variation of normalised resonance frequency with time for a 20 % v/v kaolin/water suspension (density 1370 kgm^{-3}) @ 17 °C at various reed positions relative to the top of the settling zone: curve A, 699 mm; curve B, 900 mm; curve C, 1096 mm and curve D, 1296 mm. Sedimentation is induced by adding 200 cm^3 of a 5 % wt/wt anionic flocculant (Magnafloc 155) solution to the suspension.

situated further down the settling zone. In addition, the compression and dewatering phase duration (region (iii)) is much longer due to a larger sediment volume.

Fig. 5 shows the variation of normalised resonant frequency with time for reeds 1 - 4 for a 30 % v/v oil (density 915 kgm^{-3}, viscosity 65 cP) and water emulsion at 17 ^{o}C. The data are normalised by dividing by the corresponding resonant frequency of each reed in pure oil at 17 ^{o}C. This experiment offers the possibility of evaluating the reed's response in conjunction with a system in which the hydrodynamic head relative to each reed actually decreases with time as phase separation proceeds. Considering curve A, region (i) represents the initial period in which the two phases are uniformly mixed. Region (ii) on the other hand, corresponds to the first stage of the phase separation process. This is characterised by the slow coalescence of fine oil droplets into larger entities which rise whilst the more dense aqueous phase settles. This is manifested in an increase in the resonant frequency. With time, a critical droplet size is reached following which rapid phase separation occurs. The latter corresponds to region (iii) whilst region (iv) represents complete phase separation.

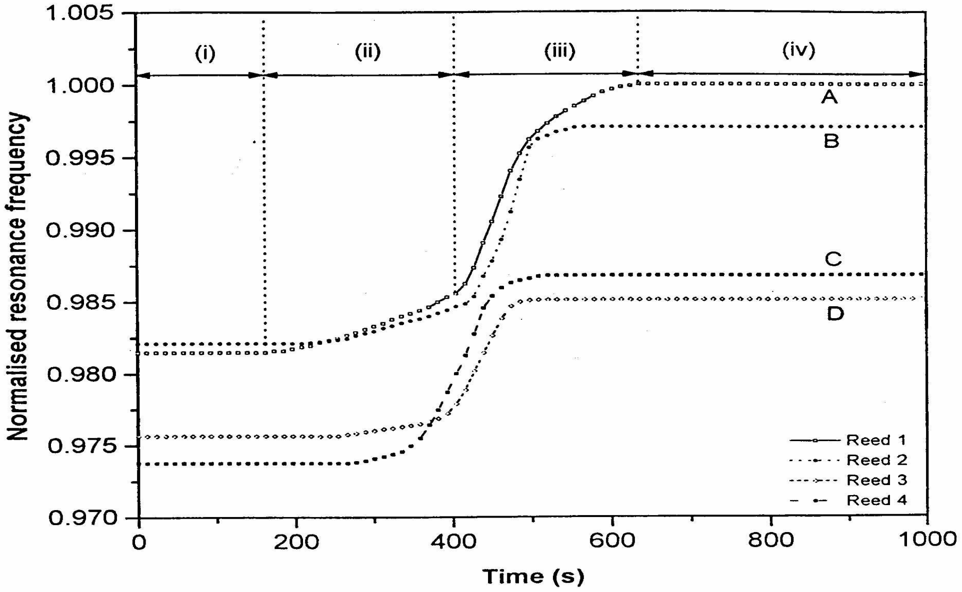

Figure 5

The variation of normalised resonance frequency with time for a 30 % v/v oil (density 915 kgm^{-3}, viscosity 65 cP) and water emulsion @ 17 ^{o}C at various reed positions relative to the top of the settling zone: curve A, 699 mm; curve B, 900 mm; curve C, 1096 mm and curve D, 1296 mm. The data shows how the two phases separate.

Evaluation of Hydrodynamic Correlations:- In contrast to mono-disperse systems, most of the hydrodynamic empirical correlations proposed for modelling the settling behaviour of poly-disperse systems (see for example Williams and Amarasinghe [6]) have been mainly confined to relatively concentrated systems (> 5% v/v). This is because as opposed to the dilute systems such as those encountered in the present study, these are easier to model since they are characterised by well defined interfaces the settling of which is largely representative of the bulk behaviour of the suspension. Accordingly all comparison between model and experiment presented here is confined to mono-disperse systems.

Figure 6 shows such data obtained in conjunction with different concentrations of the nominally mono-disperse 200 - 212 μm glass ballotini/water suspensions. Where appropriate, experimentally determined mean particle size (206 μm) and terminal settling velocity are used in conjunction with the models examined. As it may be observed, measured settling velocities are in especially good agreement with those predicted from empirical correlation. Although this correlation was originally developed in conjunction with solids volume concentrations in the range 10 - 40% v/v (the hindered settling regime) it can be applied to dilute systems (< 5% v/v) by using an appropriate value for the flow index, in turn calculated from the known particle Reynolds number [7]. The empirical correlation of is also in good accord with experimental measurements. In contrast, the hydrodynamic model of Reed and Anderson [9] appears to consistently underestimate settling velocities. This is probably due to overestimation of the influence of hydrodynamic and electrostatic phenomena on the settling behaviour of the particles. The hydrodynamic model of Batchelor [10] which was developed on a similar basis also underestimates particle settling velocities.

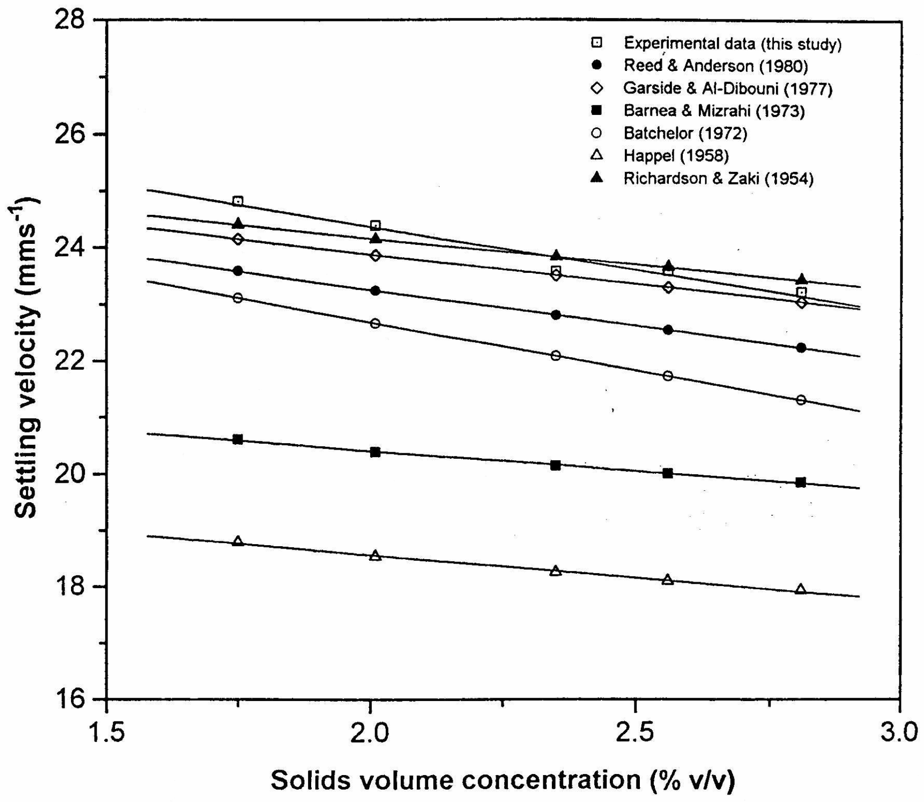

Figure 6

A comparison of experimentally determined settling velocities to those predicted from various theoretical models. The data relate to monodisperse 200 - 212 μm glass ballotini spheres (density 2550 kgm^{-3}) settling in water @ 17 °C at initial suspended solids volume concentrations in the range (1.75 - 2.81%).

4. CONCLUSION

In this paper we have reported the design and development of a novel technique for the on-line monitoring of the sedimentation kinetics of two-phase dispersions. The technique is robust as the only component entering the test medium is a stiff metallic reed. As the system operates by measuring the hydrodynamic head, requiring no bulk motion of the fluid, it is applicable to both Newtonian as well as non-Newtonian dispersions without the need for system specific calibration. Furthermore since the system's response is in a digital form, based on time, it can be monitored with a high degree of accuracy using relatively simple electronics.

We find little evidence of fouling during measurements, which in the event has negligible effect compared to the changes in the hydrodynamic head. From a modelling point of view, the technique has significant potential as a powerful tool for the development of semi-empirical and hydrodynamic correlations for simulating the behaviour of poly-disperse systems exhibiting complex sedimentation behaviour.

5. REFERENCES

1. R.A. Williams, C.G. Xie, R. Bragg, and W.P.K. Amarasinghe, Experimental Techniques for Monitoring Sedimentation in Optically Opaque Suspensions, *Colloids and surfaces*, **43**, 1, 1990.
2. H. Mahgerefteh and H.F. Al-Khoory, Predictive Criteria for the Optimisation of a Vibrating Reed Transducer, *Trans. Inst. Meas. Cont.*, **13**, 48, 1991.
3. S. Seely, Electron Tube Circuits, McGraw-Hill, New York, USA, 1958.
4. A.S. Micheals and J.C. Bolger, Settling Rates and Sediment Volumes of Flocculated Kaolin Suspensions, *I & EC Fundamentals*, **1**, 24, 1962.
5. F.M. Auzerais, R. Jackson, W.B. Russel and W.F. Murphy, The Transient Settling of Stable and Flocculated Dispersions, *J. Fluid Mech.*, **221**, 613, 1990.
6. R.A. Williams and W.P.K. Amarasinghe, Measurement and Simulation of Sedimentation Behaviour of Concentrated Polydisperse Suspensions, *Trans. Instn. Min. Metall. (Sec. C: Min. Process. Extr. Metall.)*, **98**, C68, 1989.
7. J.F. Richardson and W.N. Zaki, Sedimentation and Fluidization: Part I, *Trans. Instn. Chemical. Engrs.*, **32**, 35, 1954.
8. J. Garside and M.R. Al-Dibouni, Velocity-Voidage Relationship for Fluidization and Sedimentation in Solid-Liquid Systems, *Ind. Eng. Chem. Process des. Dev.*, **16**, 206, 1977.
9. C. Reed and J.L. Anderson, Hindered Settling of a Suspension at Low Reynolds Number, *AIChE J.*, **26**, 816, 1980.
10. G.K. Batchelor, Sedimentation in a Dilute Dispersion of Spheres, *J. Fluid Mech.*, **52**, 245, 1972.