Int. J. Multiphase Flow Vol. 16, No. 5, pp. 909–919, 1990
Printed in Great Britain.

0301-9322/90 $3.00 + 0.00

CONTINUOUS GRAVITY SEPARATION OF CONCENTRATED BIDISPERSE SUSPENSIONS IN AN INCLINED PLATE SETTLER

H. A. NASR-EL-DIN,[1,2] J. H. MASLIYAH[1] and K. NANDAKUMAR[1]
[1]Department of Chemical Engineering, University of Alberta, Edmonton, Alberta T6G 2G6, Canada
[2]Petroleum Recovery Institute, Calgary, Alberta T2L 2A6, Canada

(*Received 27 July 1989; in revised form 1 April 1990*)

Abstract—An experimental study for the continuous separation of concentrated bidisperse suspensions in an inclined plate settler has been conducted. The bidisperse suspension examined consisted of light polystyrene and heavy polyvinyl chloride beads in a salt solution. The effects of the feed total solids concentration, feed flow rate, angle of inclination and split ratio (defined as the ratio of either the underflow or the overflow to the feed flow rate) on the performance of the settler were examined. For a feed having high total solids volume fraction lateral non-homogeneities in the form of instabilities (fingers) were observed in the settler. The recovery of the heavy particles in the underflow stream significantly increased as the concentration of the light particles in the feed was increased. However, this had an adverse effect on the recovery of the light particles in the overflow stream at low feed flow rate and an angle of inclination of 30°. The enhancement in the recovery of the particles due to the presence of local instabilities for the vertical settler was much greater than that at an angle of inclination of 30°. A previous model due to Masliyah *et al.* was found to predict the experimental measurements for the dilute bidisperse suspensions. For high feed total solids volume fractions where strong instabilities were present, the model was used to assess the improvement in the settler performance as a result of these instabilities.

Key Words: bidisperse suspensions, inclined plate settler, fingering phenomenon

INTRODUCTION

Separation of bidisperse suspensions having light and heavy particles has been extensively studied since the early work of Whitmore (1955). Whitmore was the first to examine the effect of adding neutrally buoyant particles on the settling rate of heavy particles. Depending on the suspension total solids volume fraction, Whitmore identified two settling regimes. At total solids volume fractions <0.10–0.15, the settling rate is decreased by the addition of neutrally buoyant particles. This is due to the hindered settling effects. At total solids volume fraction >0.15, a significant increase in the initial settling rate occurs on the addition of neutrally buoyant particles. However, the enhancement in the initial settling rate diminishes when the total solids volume fraction exceeds 0.35–0.40. According to Whitmore (1955), the increase in the initial settling rate is due to the presence of vertical streams which are formed due to the lateral segregation of the two particle species.

Weiland & co-workers (Weiland & McPherson 1979; Fessas & Weiland 1981, 1982) extended Whitmore's work by using positively buoyant light particles. Similar to Whitmore's observations, they noticed local instabilities in concentrated bidisperse suspensions with the formation of vertical streams or fingers. They also found a significant increase (up to six-fold) in the initial settling rate as a result of the formation of these fingers. It should be mentioned that a higher settling rate reduces the settling time for only a limited period while the bidisperse suspension is present. Once the two particle species are disengaged, the settling time depends on their respective concentrations. Fessas & Weiland (1981) examined various factors affecting the time required to separate concentrated bidisperse suspensions. They found that the optimum conditions for accelerating the overall process for one particle species (low solids volume fraction of one species and a higher volume fraction for the other species) result in slow settling for the other species.

Fessas & Weiland (1982) studied the effects of the fluid density and the particle size of the light particle species on the initial settling rate of the heavy species. They found that the highest initial settling rate occurred when a light particle species having low density and large particle size was used. Later, Fessas & Weiland (1984) modelled the initial settling rate in the presence of these fingers. Their experimental data agreed well with their model predictions. Weiland *et al.* (1984) have also shown that these instabilities occur immediately after the cessation of mixing in batch systems. However, it takes about 20 s for these instabilities (fingers) to develop in some cases.

Although Whitmore and Weiland and co-workers examined the initial settling rate of concentrated bidisperse suspensions, the mechanism of formation of these local instabilities was not addressed. Three models were postulated to explain the lateral segregation of the two particle species. The first model is based on the presence of a lateral pressure gradient in the solid phase (Lin 1984). The second model is based on the presence of small concentration disturbances which grow in bidisperse suspensions having high total solids volume fraction (Batchelor & Janse van Rensburg 1986). The third model is based on particle–particle collisions with the maximum lateral displacement occurring between particles of different species (Cox 1987).

Modelling of settling rates in dilute bidisperse suspensions in batch and continuous modes has been considered by various researchers. For batch systems, Law *et al.* (1987) used the suspension zone concept to predict settling rates in a vertical column. They found that the models of Masliyah (1979), Selim *et al.* (1983) and Patwardhan & Tien (1985) predicted their experimental results fairly well. Shih *et al.* (1987) used a one-dimensional hydrodynamic model to predict settling rates that were experimentally obtained by Fessas & Weiland (1984). However, their model did not predict the streaming phenomenon (fingering) at high total solids volume fractions and it overpredicted settling rates at low total solids volume fractions. Stamatakis & Tien (1989) solved the particle conservation equations using the method of lines to predict settling rates. They found their results to be in good agreement with those of Law *et al.* (1987). Nasr-El-Din *et al.* (1988) studied both theoretically and experimentally the *continuous* separation of dilute bidisperse suspensions in a vertical settler. They found that the suspension zone model predicted their experimental results fairly well.

Unlike the separation of bidisperse suspensions in vertical settlers, studies on batch or continuous separation of bidisperse suspensions in inclined channels are sparse. Law *et al.* (1988) examined the separation of dilute bidisperse suspensions in inclined channels. At low solids volume fractions, flow visualization showed the presence of distinct zones separated by horizontal interfaces. MacTaggart *et al.* (1988) examined the separation of concentrated bidisperse suspensions in inclined plate settlers. They found fingering to have a dominant effect on the initial settling rate at small angles of inclination, whereas the Boycott effect has a dominant effect at large angles of inclination. Recently, Masliyah *et al.* (1989) examined the continuous separation of bidisperse suspensions having low total solids volume fraction in inclined plate settlers. They developed a kinematic model based on the continuity equations and the PNK model. The model was only tested for bidisperse suspensions consisting of light and heavy particles having rising and settling velocities of nearly equal magnitude. Consequently, there is a need to test their model for more general cases.

The objectives of the present study are:

(1) To examine the performance of an inclined plate settler for a feed having high total solids volume fraction where local instabilities develop.
(2) To study the effects of the feed flow rate, angle of inclination and split ratio on the settler performance in the presence of lateral non-homogeneities (instabilities).
(3) To test the Masliyah *et al.* (1989) model for the general case of unequal particles rising/settling velocities.

MATHEMATICAL MODEL

The mathematical model was detailed by Masliyah *et al.* (1989). A brief summary is given here. It is assumed that the inclined gravity settler consists of a uniform source zone extending the full length of the settler, as shown in figure 1. The solids and the carrier fluid are allowed to exit through the interfaces, but they are not allowed to enter the source zone except through the feed stream. The feed flow rate and composition together with the underflow rate are specified. The downstream direction is taken as positive.

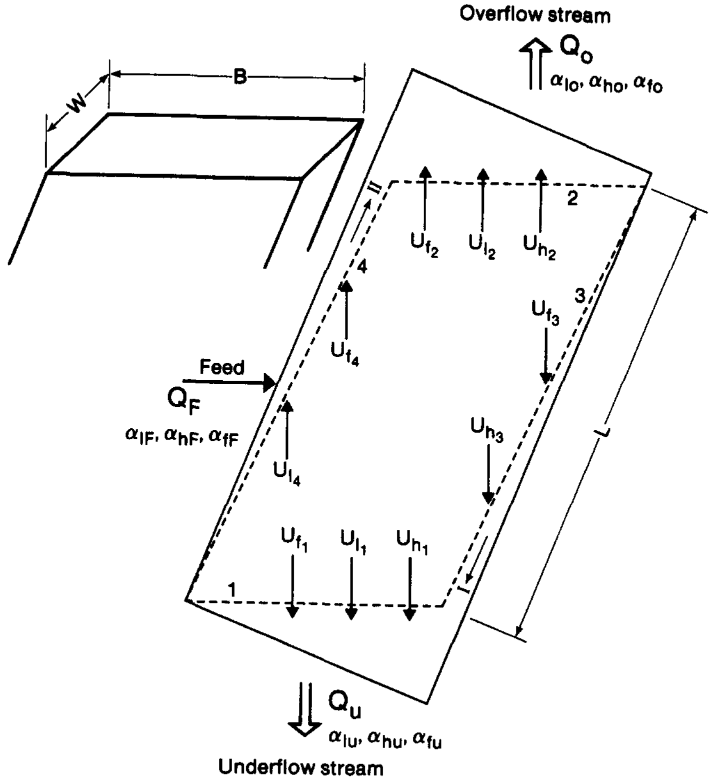

Figure 1. Schematic of the settler for the mathematical model.

The volumetric balance for a component c (fluid, light or heavy particle species) over the source zone is

$$Q_F \alpha_{cF} = \sum_{j=1}^{4} A_j U n_{cj} \alpha_c, \qquad [1]$$

where Q_F is the volumetric feed flow rate, α_{cF} is the feed composition of component c, Un_{cj} is the normal velocity of component c at an interface j, α_c is the volume fraction of component c in the source zone and A_j ($j = 1$ to 4) are the areas of the four interfaces (figure 1) and are given by

$$A_1 = A_2 = \frac{BW}{\cos\theta}$$

and

$$A_3 = A_4 = WL,$$

where W is the settler depth, B is the width of the settler, L is the length of the bidisperse suspension and θ is the angle of the inclination from the vertical.

It is also assumed that the light particles can only exit from the source zone through interfaces 1, 2 and 4. Similarly, the heavy particles can only exit through interfaces 1, 2 and 3. Therefore, one can write

$$Un_{l3} = Un_{h4} = 0. \qquad [2]$$

The fluid velocities U_{f3} and U_{f4} adjacent to the inclined interfaces between the source zone and the settler walls can be calculated according to the PNK model as

$$A_3 U_{h3} \alpha_h = -A_4 U_{f4} \alpha_f \qquad [3]$$

and

$$A_4 U_{l4} \alpha_l = -A_3 U_{f3} \alpha_f. \qquad [4]$$

The vertical velocity of a particle species i (light or heavy) at a boundary j ($j = 1$ to 4) is given by

$$U_{ij} = U_{fj} + K_{ij}, \qquad [5]$$

where U_{fj} is the vertical fluid velocity at boundary j and K_{ij} is the generalized relative velocity for a particle species i at boundary j. The relative velocity for spherical particles is given by Masliyah (1979) and Lockett & Bassoon (1979) as

$$K_{ij} = \frac{g d_i^2 (\rho_i - \rho_s) \alpha_f^m}{18 \mu_f (1 + 0.15\,\mathrm{Re}_{ij}^{0.687})}, \quad \text{for } \mathrm{Re}_{ij} < 1000, \qquad [6]$$

where ρ_s is the suspension density in the source zone and is given as

$$\rho_s = \rho_f \alpha_f + \rho_l \alpha_l + \rho_h \alpha_h, \qquad [7]$$

Re_{ij} is the Reynolds number of the ith particle species at boundary j and is given by

$$\mathrm{Re}_{ij} = |U_{ij} - U_{fj}| d_i \alpha_f \frac{\rho_f}{\mu_f}, \qquad [8]$$

ρ_f, ρ_h and ρ_l are the densities of the fluid, heavy and light particles, respectively, d_i is the mean particle diameter of a particle species i and m is related to Richardson & Zaki's exponent for hindered settling, n, where $m = n - 2$ (Masliyah 1979). The exponent n is a function of the particle Re and the ratio of particle diameter to settler width. Details of the solution of the model equations are given by Masliyah *et al.* (1989).

EXPERIMENTAL STUDIES

The experiments were conducted in a settler of $8 \times 0.53 \times 40$ cm inner dimensions. The settler was mounted on a steel stand that could be rotated from 0° to 90° and was made from Plexiglas to allow for flow visualization. The settler is a part of a closed loop detailed elsewhere (Masliyah *et al.* 1989). An angle of inclination of 30° was chosen in order to avoid any surface instability which normally occurs at 10°–15° (Herbolzheimer 1983; Shaqfeh & Acrivos 1987). In this manner, the effect of lateral segregation can be assessed.

The bidisperse suspensions used in the present study consisted of light polystyrene beads ($d_l = 0.039$ cm and $\rho_l = 1050$ kg/m^3) and heavy polyvinyl chloride beads ($d_h = 0.0137$ cm and $\rho_h = 1400$ kg/m^3) in a salt solution ($\rho_f = 1120$ kg/m^3 and $\mu_f = 1.41$ mPa · s at 20°C). Both particle species consisted of mono-sized spherical particles and they were prepared following the procedure described by MacTaggart *et al.* (1988). The settling velocities of the light and heavy particles at infinite dilution were −0.36 and 0.2 cm/s, respectively. The heavy particles were dyed red with Rhodamine B, using the procedure described by Fessas (1983), to aid in flow visualization. A few drops of Triton X-100 were used as a wetting agent.

In each experiment, the feed flow rate, feed composition and loop temperature were kept constant and the underflow split ratio (defined as the ratio of the underflow to the feed flow rate) was varied from 0.1 to 0.9. The feed flow rate was varied from 4.2 to 8.6 cm^3/s, which is equivalent to a total linear velocity of 0.99–2.03 (cm^3/s)/cm^2. The feed total solids volume fraction was varied from 0.08 to 0.30. After reaching overall steady-state conditions, the flow patterns at various split ratios were photographed. Three samples were collected for the feed, underflow and overflow streams. The solids concentrations were measured by separation and filtration. The details are given in Nasr-El-Din *et al.* (1988).

RESULTS AND DISCUSSION

Low total solids volume fraction

The first set of experiments was conducted for a feed having a low total solids volume fraction <0.1. Visual observation studies in the low concentration range did not show any lateral heterogeneity in the column. Similar to previous studies with symmetrical dilute bidisperse suspensions (Masliyah *et al.* 1989) the column has a zone of uniform bidisperse suspension, two convection currents: a descending convection current (convection current I in figure 1), consisting mainly of fluid and heavy species; and an ascending convection current (convection current II in figure 1), consisting of fluid and light particle species. As one approaches the end-point split ratios of zero and unity, a zone of monodisperse light or heavy suspension may appear. The sizes of these zones are functions of the split ratio, feed flow rate and composition.

Figure 2 shows the volume fractions of the light and heavy particle species in the product streams as a function of the underflow and overflow split ratio, respectively. The feed flow rate was 4.2 cm^3/s and the settler angle of inclination from the vertical was 30°. At low underflow split ratios (Q_u/Q_F), the downward fluid velocity is smaller than the rising velocity of the light particle species and, consequently, the light particles volume fraction in the underflow is nearly zero, as shown in figure 2. Once the downward fluid velocity exceeds the rising velocity of the light particles, the fluid carries some of the light particles into the underflow stream and consequently, the volume fraction of the light particles in the underflow increases with Q_u/Q_F. The light particles volume fraction in the overflow approaches that in the feed as the underflow split ratio approaches zero. One also observes that the heavy particle species volume fraction in the product streams behaves in a similar manner when it is plotted against the overflow split ratio, Q_o/Q_F. The volume fraction of the light particles in the overflow stream is higher than that of the heavy particles in the underflow stream. This trend is reasonable since the concentrations of the two particle species in the feed are nearly equal and the magnitude of the rising velocity of the light particles is larger than the settling velocity of the heavy particles. One should mention that a different trend can be obtained if the feed concentrations of the light and heavy particle species are significantly different.

Similar trends for the volume fraction of both particle species in the product streams were obtained at a higher flow rate of 8.6 cm^3/s, as shown in figure 3. However, the light particle species appears in the underflow stream at an underflow split ratio much lower than at the lower feed flow rate (figure 2). Also, the heavy particle species appears in the overflow stream at an overflow split ratio much lower than that at the lower flow rate. This is simply because the values of the flow rates of the underflow and overflow streams become larger at the higher feed flow rate, leading to more light particles being dragged downwards and more heavy particles dragged upwards. The solid lines shown in figures 2 and 3 represent the model predictions obtained at low and high flow rates, respectively. One observes that the model predicts the experimental measurements fairly well.

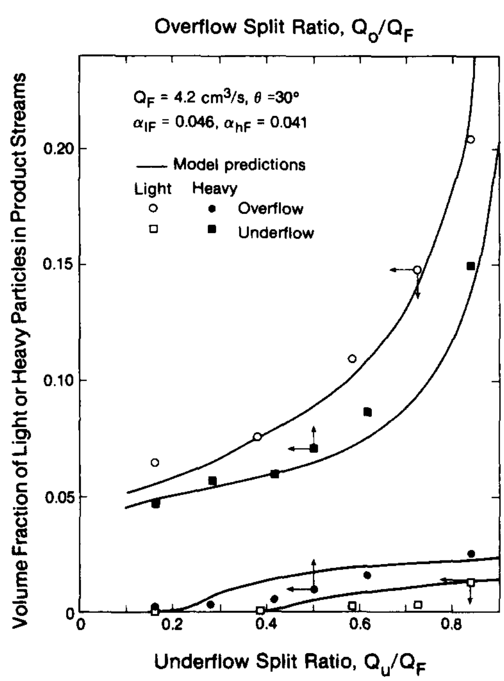

Figure 2. Volume fraction of the light and heavy particles in the product streams at $Q = 4.2\,cm^3/s$ and $\theta = 30°$.

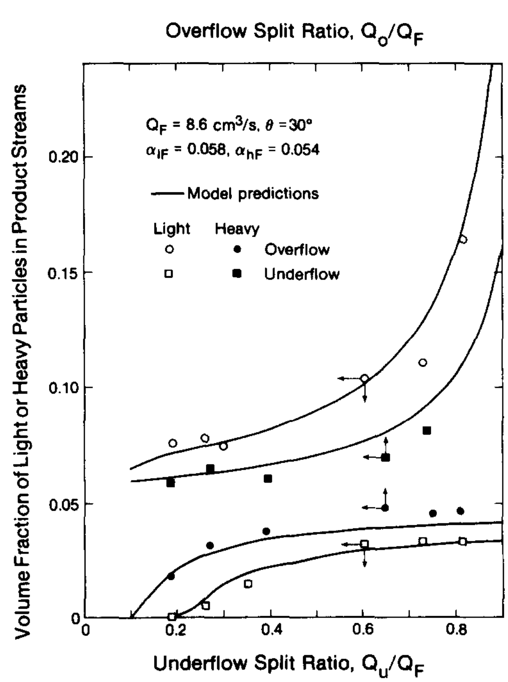

Figure 3. Volume fraction of the light and heavy particles in the product streams at $Q = 8.6\,cm^3/s$ and $\theta = 30°$.

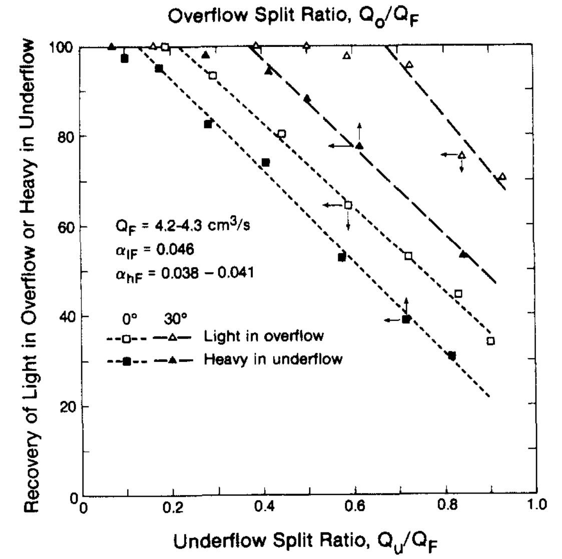

Figure 4. Recovery of the light and heavy particles for a feed having $\alpha_{tF} = 0.084$ to 0.087 at the low feed flow rate. The lines are a least-squares fit.

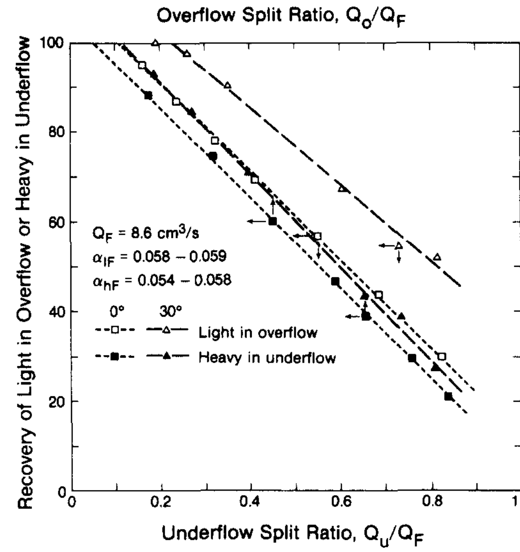

Figure 5. Recovery of the light and heavy particles for a feed having $\alpha_{tF} = 0.112$ to 0.117 at the high feed flow rate. The lines are a least-squares fit.

However, some discrepancies can be seen at low solids volume fractions, presumably due to larger experimental error in measuring such low solids concentrations.

Figures 4 and 5 show the effect of the settler angle of inclination from the vertical on the recovery of the light particles in the overflow and the recovery of the heavy particles in the underflow stream at feed flow rates of 4.3 and 8.6 cm^3/s, respectively. The recovery of a particle species in a product stream is defined as the fraction of the light or the heavy particles in the feed stream that has been collected in that product stream. For a given feed flow rate and settler angle of inclination and at a low underflow split ratio, the recovery of the light particles in the overflow stream is 100%. Similarly, the recovery of the heavy particles in the underflow stream is 100% for low values of Q_o/Q_F. At a critical value of the split ratio, the recovery of the light particles drops linearly with Q_u/Q_F. Similarly, the recovery of the heavy particles varies in the same manner with Q_o/Q_F. The recovery of the light particles in the overflow stream was higher than that of the heavy particle species in the underflow stream for the feed flow rates and settler angles of inclination given in figures 4 and 5. At low feed flow rate (figure 4), one also observes that the recovery of the light particles in the overflow or the heavy particles in the underflow stream are significantly increased by increasing the angle of inclination to 30°. This trend is reasonable and is due to the larger settling area at an angle of inclination of 30° (the Boycott effect). However, this effect diminishes at a higher feed flow rate of 8.6 cm^3/s, as shown in figure 5.

High total solids volume fraction

It is useful before discussing the experimental measurements to show some photographs of the flow patterns that were observed for a feed having a total solids volume fraction of nearly 0.30. Figure 6(a) shows various flow patterns for a feed having $\alpha_{lF} = 0.245$ and $\alpha_{hF} = 0.052$ at a feed flow rate of 4.5 cm^3/s and underflow split ratios (Q_u/Q_F) of 0.1, 0.5 and 0.7 at an angle of inclination of 30° from the vertical. The white color in this photograph represents the light particles, whereas the red color represents the heavy particle species. One observes a strong dependence of the flow pattern on the underflow split ratio. At low underflow split ratios, e.g. 0.1, the downward fluid velocity is not enough to drag any light particles into the lower half of the settler and, consequently, the lower half of the settler consists basically of a monodisperse suspension of the heavy particles. On the other hand, the upward fluid velocity is relatively high to drag a significant amount of the heavy particles into the upper half of the settler. Consequently, one observes lateral heterogeneities only in the upper half of the settler. The ascending convection current (II) contains only fluid in the region that corresponds to the monodisperse heavy suspension (lower half of the settler) and

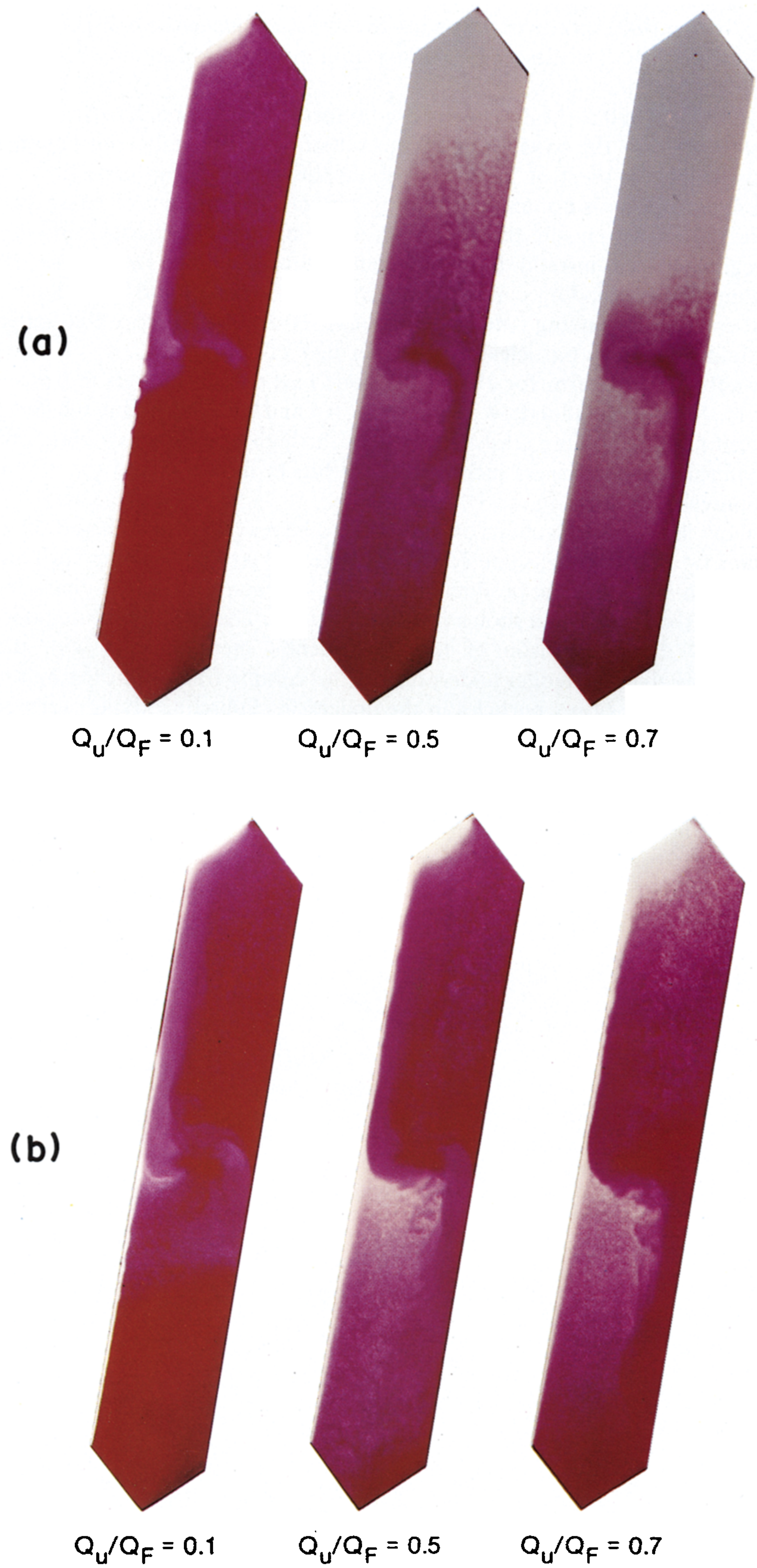

Figure 6. Flow patterns for a feed having: (a) $\alpha_{tF} = 0.297$ and $Q_F = 4.5\ cm^3/s$; and (b) $\alpha_{tF} = 0.292$ and $Q_F = 8.4\ cm^3/s$.

it contains fluid and light particle species in the region that corresponds to the bidisperse suspension (the upper half of the settler). The descending convection current (I) contains fluid and heavy particles throughout the settler.

At an underflow split ratio of 0.5, the downward fluid velocity is high enough to drag a significant amount of light particles into the lower half of the settler. Consequently, the region of local instabilities expands to include most of the lower half of the settler. At an underflow split ratio of 0.7, the upward fluid velocity is not enough to drag a significant amount of heavy particles to the upper half of the settler. As a result, the upper half has a monodisperse suspension of the light particles and the region of local instabilities is now confined to the lower half of the settler and around the feed point. The ascending convection current (II) contains fluid and light particles throughout the settler. The descending convection current (I) contains fluid in the upper section of the settler and fluid and heavy particles in the lower half of the settler.

Figure 6(b) shows the flow patterns for almost the same feed composition as in figure 6(a) but at a feed flow rate of 8.4 cm^3/s and underflow ratios of 0.1, 0.5 and 0.7. Comparing the flow patterns shown at the low feed flow rate [figure 6(a)] and those at the high feed flow rate [figure 6(b)], one observes that the intensity of the fingers increases at the higher flow rate and the monodisperse suspension zone diminishes.

Figures 7 and 8 show the volume fractions of the light and heavy particles in the product streams as a function of the split ratio for the same conditions given in figure 6(b). The variation of the volume fractions of both species in the product streams is, in general, similar to that observed at the low feed total solids volume fraction shown in figures 2 and 3. The most interesting observation in these two figures is the comparison of the experimental measurements with the model predictions. One observes that the model underpredicts the volume fraction of the light particles in the overflow and that of the heavy particles in the underflow. Subsequently, it overpredicts the volume fraction of the light particles in the underflow or that of the heavy particles in the overflow. The discrepancy between the model predictions and the experimental results is due to the exclusion of the fingering mechanism from the model. The fingering mechanism is only present at the high feed total solids volume fraction, as shown in figures 6(a, b). It is well-documented that the formation of local instabilities in bidisperse suspensions causes a significant increase in the magnitude of the initial settling or rising rates of the particles in batch systems (Fessas & Weiland 1981). As the settling or rising velocity of a particle species increases, its separation in the settler

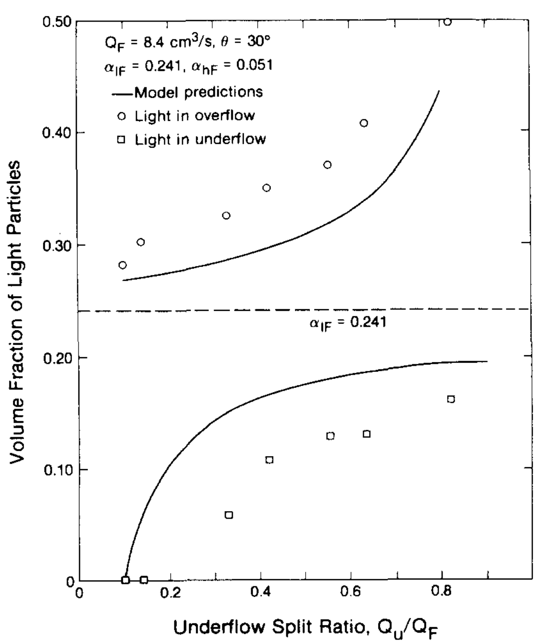

Figure 7. Effect of the underflow split ratio on the volume fraction of the light particles in the product streams at $\alpha_{lF} = 0.292$ and $Q_F = 8.4$ cm^3/s.

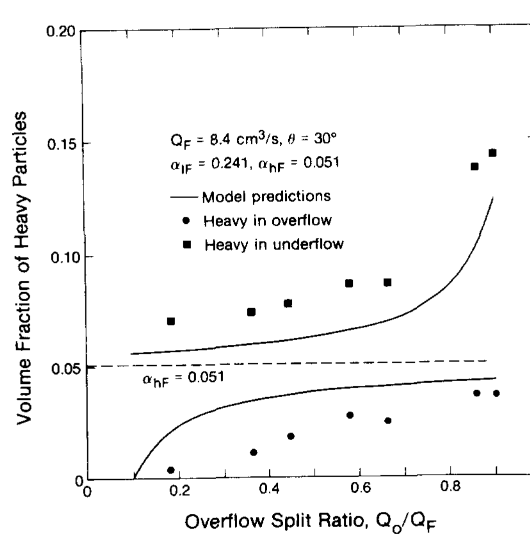

Figure 8. Effect of the overflow split ratio on the volume fraction of the heavy particles in the product streams at $\alpha_{lF} = 0.292$ and $Q_F = 8.4$ cm^3/s.

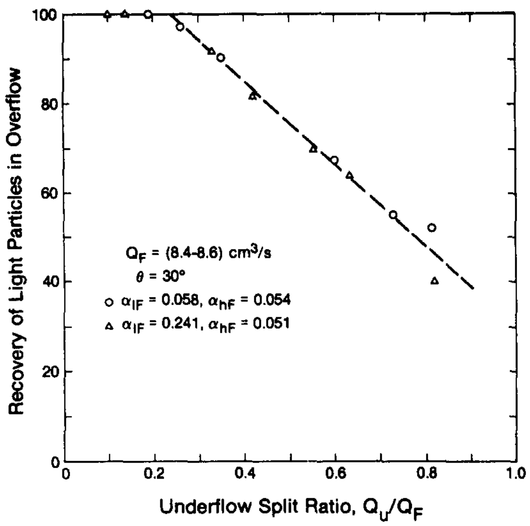

Figure 9. Effect of the feed total solids concentration on the recovery of the light particles in the overflow stream at $Q_F = 8.4$ to $8.6\,cm^3/s$ and $\theta = 30°$. The lines are a least-squares fit.

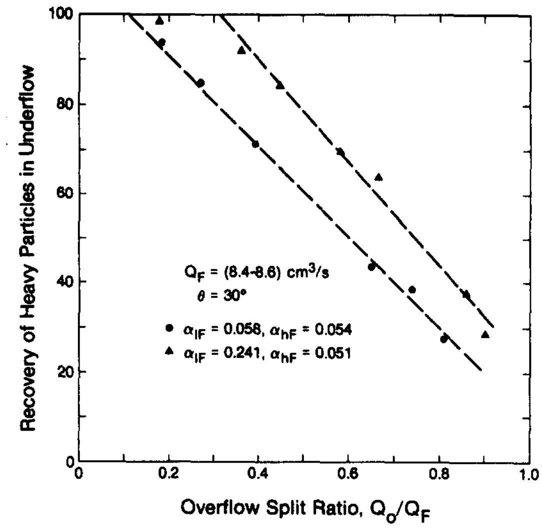

Figure 10. Effect of the feed total solids concentration on the recovery of the heavy particles in the underflow stream at $Q_F = 8.4$ to $8.6\,cm^3/s$ and $\theta = 30°$. The lines are a least-squares fit.

becomes more efficient and, consequently, the volume fraction of the light particles in the overflow or the heavy particles in the underflow will be higher than that predicted by the model.

Figures 9 and 10 show the recovery of the light particles in the overflow stream and the heavy particles in the underflow stream as a function of the split ratio, with the feed total solids concentration as a parameter. The concentration of the heavy particle species in the feed was kept constant at 0.054, the feed flow rate was 8.2–$8.6\,cm^3/s$ and the settler angle of inclination from the vertical was 30°. One observes in figure 9 that the recoveries of the light particles in the overflow stream at $\alpha_{tF} = 0.112$ ($\alpha_{lF} = 0.058$, $\alpha_{hF} = 0.054$) and $\alpha_{tF} = 0.292$ ($\alpha_{lF} = 0.241$, $\alpha_{hF} = 0.051$) are nearly the same. However, figure 10 shows a significant increase in the recovery of the heavy particles in the underflow stream for a feed having a total solids volume fraction of 0.292. These trends are due to the presence of the local instabilities, as was shown in figures 6(a, b).

The effect of the settler angle of inclination on the particle recovery in a product stream is of interest since the enhancement in settling rate depends on the Boycott effect and the intensity of the local instabilities (fingers). Both the Boycott effect and the instabilities are functions of the settler angle of inclination (MacTaggart *et al.* 1988). Figures 11 and 12 show the effect of the settler

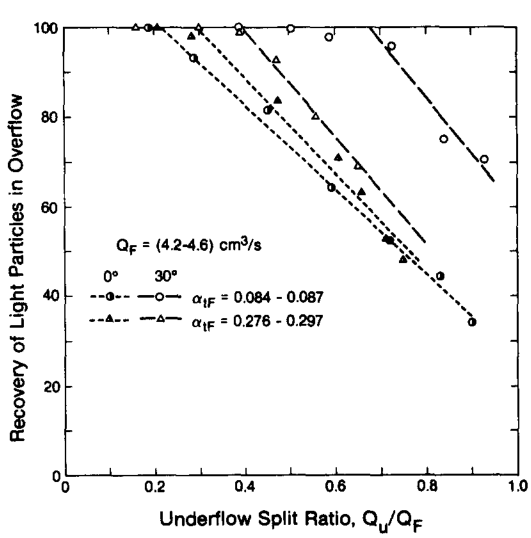

Figure 11. Effect of the angle of inclination on the recovery of the light particles in the product streams at $Q_F = 4.2$ to $4.6\,cm^3/s$. The lines are a least-squares fit.

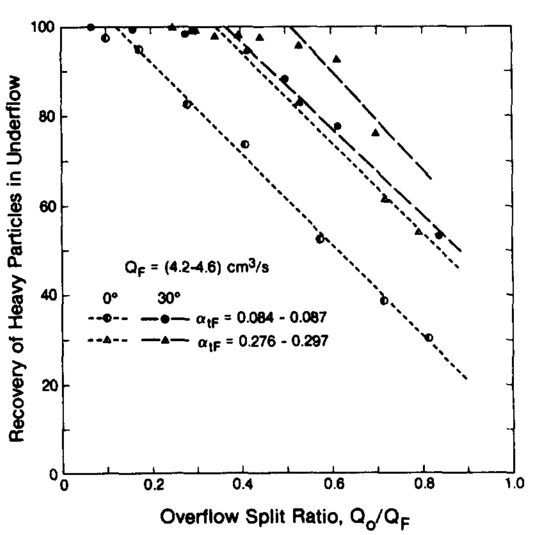

Figure 12. Effect of the angle of inclination on the recovery of the heavy particles in the product streams at $Q_F = 4.2$ to $4.6\,cm^3/s$. The lines are a least-squares fit.

angle of inclination on the recovery of the light particles in the overflow and the heavy particles in the underflow at a feed flow rate of 4.2–4.6 cm^3/s. The effect of increasing the concentration of the light particles in the feed on the recovery of the light particles is dependent on the settler angle of inclination. Figure 11 shows that at $\theta = 0°$ the recovery of the light particle species is nearly independent of the light particles concentration in the feed. At $\theta = 30°$, the recovery of light particles drops significantly as the light particle concentration in the feed is increased.

The effect of increasing the light particles concentration in the feed on the recovery of the heavy particles is different from that observed for the light particles in figure 11. One observes from figure 12 that the recovery of the heavy particles is enhanced at the higher feed solids concentration for both angles of inclination.

The results shown in figures 9–12 indicate that to enhance the recovery of the heavy particles, one has to increase the concentration of the light particles in the feed. One should also mention that by increasing the concentration of the light particles in the feed, the recovery of the light particles in the overflow stream will not change at the higher feed flow rate (figure 9) and will drop significantly at the low feed flow rate (figure 11). It is interesting to note that these trends are similar to those observed by Fessas & Weiland (1981) for batch systems.

CONCLUSIONS

For the continuous separation of the bidisperse suspensions examined in the present study, the following conclusions were obtained:

(1) Visual observation studies have shown that local instabilities (fingers) are present only for a feed having a high total solids volume fraction. At an angle of inclination of 30°, the intensity of these fingers increases as the feed flow rate increases.

(2) The recovery of the heavy particles in the underflow stream significantly increases as the concentration of the light particles in the feed increases. However, this has an adverse effect on the recovery of the light particles in the overflow stream at low feed flow rates and $\theta = 30°$.

(3) The enhancement in the recovery of the particles due to the presence of local instabilities at $\theta = 0°$ is much greater than that at 30°.

(4) Masliyah *et al.*'s (1989) model was found to predict the experimental measurements for dilute bidisperse suspensions. For high feed total solids volume fractions where strong instabilities are present, the model is used to assess the improvement in the settler performance as a result of these instabilities.

Acknowledgements—This study was made possible through an Alberta Oil Sands Technology and Research Authority contract (Agreement No. 515) to J. H. M. and K. N. Ms L. Holte assisted with the experiments.

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