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PARTICLE SEGREGATION IN SLURRY FLOW THROUGH VERTICAL TEES

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Abstract—An experimental study has been conducted of particle segregation in slurry flow through vertical tees. Water–sand slurries with solids concentrations to 25% by volume were used with tees of various sizes and angles. The experiments showed that the branch concentration is less than the upstream value for all the branches studied at velocity ratios less than unity. The separation ratio was found to be a function of upstream conditions, velocity ratio, branch size and angle. For lateral branches, the inertia effect is dominant at low velocity ratios, whereas the gravity effect becomes important at high velocity ratios. A two-dimensional model explains the results qualitatively.

INTRODUCTION

Two-phase flow through a tee is commonly used in industrial operations. One application occurs in sampling of solid–gas or slurry flow through an opening flush with the pipe wall. Another common example occurs when distributing solids through networks. Because of the difference in inertia between the phases, some separation occurs on passing through a bifurcation point. The degree of separation depends, among other factors, on the densities of the two phases. As the difference between the densities increases, the separation increases.

The degree of separation is usually expressed as the ratio of the quality or concentration of the dispersed phase in the branch to that upstream. This ratio is known as the separation factor, separation ratio or sampling efficiency.

Previous studies of phase separation at a tee have considered gas–liquid, gas–solid and liquid–solids systems. In gas–liquid systems, where the density difference is large, Fouda & Rhodes (1972, 1974) found the gas fraction in the branch to be higher than that in the upstream flow. They also found that using a deflecting baffle of 0.75 D improves gas distribution. Henry (1981) studied the phase separation phenomenon for air–water systems using a branch of 0.04-area ratio. He found that as the branch velocity increased the branch quality increased and then levelled off. He also found that the separation depended on the upstream flow pattern. A similar result was also found by Azzopardi & Whalley (1982). Zetzmann (1984) found that the separation factor increased as the ratio of branch flow to total flow increased. It increased to a maximum, greater than unity, and then decreased gradually to one. This rather surprising result probably reflected a nonuniform distribution of the phases upstream of the tee. He also found that increasing the branch angle from 45° to 90° had no significant effect on the separation factor. A similar result was also found by Honan & Lahey (1981). Zetzmann also found that separation increased as the branch size decreased at a given branch flow rate. This effect of the branch size was also found by Azzopardi (1984). Azzopardi also pointed out that the phase separation for lateral branches is affected by the axial length of the branch rather than the branch diameter. Saba & Lahey (1984) studied two-phase (air–water) separation in a tee both theoretically and experimentally. A physically based empirical model was developed. They found a very high degree of separation in their system.

Previous studies of gas–solid systems can be divided into two groups. The first group considered flow through large branches and was mainly concerned with pressure losses across the branch. Included in this group are the studies of Morikawa *et al.* (1974), Morimoto *et al.* (1977) and Morikawa *et al.* (1978). The second group considered small branches of the type used for sampling to measure solids concentration and particle size distribution in pipelines. Examples of these are the studies of Raynor (1970), Lundgren *et al.* (1978), Durham & Lundgren (1980), Laktionov (1973) as reported by Durham & Lundgren (1980), Masuda *et al.* (1981) and Davies & Subari (1982). All found that the separation ratio increases as the branch velocity increases and decreases as the particle size or the upstream bulk velocity increases. Various empirical equations relating separation ratio (sampling efficiency) to velocity ratio and particle inertia parameter were given.

Zebel (1978) studied the problem theoretically. Assuming Stokes' law for the drag and using an analytical approximation for two-dimensional planar potential flow, he found that the sampling efficiency is a function of the particle inertia parameter. Unlike the experimental results, according to his arguments, separation ratio (sampling efficiency) should be independent of the velocity ratio.

Unlike gas–liquid and gas–solid systems, the amount of work done with solids–liquid systems is meagre. Iwanami & Suu (1969) were first to study the pressure losses for slurry flow through tees. Bugliarello & Hsiaso (1964) studied phase separation for neutrally buoyant particles in a laminar flow. They found the separation ratio to be independent of the branch angle. Also, the smaller the branch size, the higher was the branch concentration.

Most of the experimental results obtained with slurries refer to sampling through small branches. Torrest & Savage (1975) studied particle collection from vertical downward flow through small side ports. They found that the separation ratio increased linearly as the branch velocity increased. For particles with settling velocities greater than 20 cm/s, at a given flow rate, the separation ratio increased as the branch size decreased. This effect did not occur for particles of lower settling velocities.

Moujaes (1984) found that the branch concentrations were consistently lower than the upstream values for slurries of 60/80 mesh sand. Higher concentrations were obtained with 140 mesh particles in the same system. He also found that the branch concentration increased as the branch size decreased. The branch concentration seemed to be insensitive to the upstream flow conditions. More recently, Nasr-El-Din *et al.* (1985) measured solids concentration and particle-size distribution through a small hole flush with the wall of a vertical pipe. They found that the branch concentration was lower and that the mean particle diameter was smaller than the corresponding values in the upstream flow.

The object of the present investigation was to study solid segregation in branches of larger area ratio and at different angles to the flow. Although the investigation was primarily experimental, interpretation of the results is facilitated by a simple mathematical model.

MATHEMATICAL MODEL

Before considering the model, a list of the assumptions is necessary. The particles are assumed to be rigid and uniformly distributed over the cross-section at a large distance upstream from the branch inlet. At this location they are assumed to move with the same velocity as the fluid. Inertia is considered the predominant mechanism in the collection of particles.

The equations of motion are used in the space-average form of Jackson (1963) and Wallis (1969) as

$$\partial(1-c)/\partial t + \nabla\cdot[(1-c)\,v_f] = 0 \quad , \qquad [1]$$

$$\partial c/\partial t + \nabla\cdot[c\,v_s] = 0 \quad . \qquad [2]$$

where c, v_s and v_f are the local volume fraction solids, particle velocity and fluid velocity.

The momentum equations for the two phases are, for the i-direction,

$$\rho_p a_{fi} = -\nabla p + \rho_f g_i + f_{fsi} + f_{fwi} \quad , \qquad [3]$$

$$\rho_s a_{si} = -\nabla p + \rho_s g_i + f_{sfi} + f_{swi} \quad , \qquad [4]$$

where a is the instantaneous acceleration, p is the fluid pressure, f_{fs} is the drag force of the solids on the fluid, f_{sf} is the corresponding force of that fluid on the solid. f_{fw} is the force on the fluid which arises from the presence of a wall, and f_{sw} is this force for solid particles. g_i is the component of gravity acceleration.

Since the interfacial forces per unit system volume must vanish, we have the reciprocity relationship

$$c f_{sfi} + (1 - c) f_{fsi} = 0 \quad . \tag{5}$$

The interfacial drag force can be calculated with use of Rowe's generalization, given by Wallis (1969) as

$$f_{sfi} = \frac{3}{4} C_{DS} (\rho_f / d_s) [|v_f - v_s| (v_f - v_s)_i]/(1 - c)^n \quad , \tag{6}$$

where the drag coefficient (C_{DS}) depends upon the local particle Reynolds number (Re_s) defined as

$$\mathrm{Re}_s = \mathrm{Re}_b [(v_{fx} - v_{sx})^2 + (v_{fy} - v_{sy})^2]^{1/2} (1 - c)/U_b$$

and

$$\mathrm{Re}_b = (\rho_f d_s U_b) / \mu_f \quad . \tag{7}$$

For the sand particles used in the experiments, C_{DS} values were inferred from terminal falling velocities of single particles and expressed piecewise as values of a_1 and b in

$$C_{DS} = a_1 \, \mathrm{Re}_s^b \quad . \tag{8}$$

These values are shown in table 1. They differ considerably from the values for spheres at higher Re_s values. n was taken as 2.5 from the results of high concentration and hindered settling experiments conducted with fine sand.

Equation [8] gives C_{DS} values for steady flow and the need for corrections in accelerating flows was noted by Torobin & Gauvin (1959). Recently, Temkin & Mehta (1982) found the transient drag to be different from that at steady state at the same Reynolds number, but the difference depends on whether the flow is accelerating or decelerating. Since the transient C_{DS} values are not available, [8] will be used as an approximation. However, the added mass contribution of Zuber (1964) and Wallis (1969) was included.

To find the particle trajectories and separation ratio, the fluid velocity should be known. This can be obtained from the mixture mass-average velocity, defined as

$$\rho_m v_m = \rho_f (1 - c) v_f + \rho_s c \, v_s \tag{9}$$

and

$$\rho_m = \rho_f (1 - c) + \rho_s c \quad .$$

The mixture mass average velocity can be obtained from [3] and [4]. We first remove the gravity and wall friction forces since they are usually much smaller than the interfacial drag force. Multiplying [3] by $1-c$ and [4] by c and adding, we get the equation of motion for the mixture

$$\rho_m \mathrm{d}v_m / \mathrm{d}t = - \nabla p \quad . \tag{10}$$

Table 1. Coefficients in C_{DS} expression

Re_s	a_1	b
$\mathrm{Re}_s < 1.0$	24	−1
$1.0 < \mathrm{Re}_s < 2.151$	24.022	−0.883
$2.151 < \mathrm{Re}_s < 46.33$	20.3695	−0.6226
$\mathrm{Re}_s > 46.33$	1.556	0.04792

The particle trajectories can be obtained from [4]. We first evaluate the drag force from [6] and substitute for the fluid velocity in terms of the mixture mass-average velocity according to [9]. Normalizing the distance by dividing by the branch diameter d, the velocity by the upstream bulk velocity U_b, the time by d/U_b and the pressure by $\rho_m U_b^2/2$, the particle equations of motion in the x- and y-directions can be written as

x-direction:

$$\mathrm{d}v'_{sx}/\mathrm{d}\tau = -(\rho_m/2\rho_s)(\partial p'/\partial x') + (C_{DS}\,\mathrm{Re}_s/24K_d)(\rho_m/\rho_f)[v'_{mx} - v'_{sx}]/(1-c)^{n+2} \quad ; \qquad [11]$$

y-direction:

$$\mathrm{d}v'_{sy}/\mathrm{d}\tau = -(\rho_m/2\rho_s)(\partial p'/\partial y') + (C_{DS}\,\mathrm{Re}_s/24K_d)(\rho_m/\rho_f)[v'_{my} - v'_{sy}]/(1-c)^{n+2} \quad , \qquad [12]$$

where $\tau = tU_b/d$ and $K_d = (\rho_s d_s^2 U_b)/(18\mu_f d)$.

Three basic steps are required to calculate the separation ratio:

(1) Establishing the flow pattern of the mixture upstream the branch inlet. In principle this can be obtained from [10]. However, the flow field for a flow through a branch is a three-dimensional one. In such circumstances six differential equations are required to describe the particle motion. The problem can be greatly simplified by approximating the velocity field as a flow into a slot with the flow direction perpendicular to the slot axis.

A second simplification is to neglect density variations for the mixture in this analysis, a reasonable approximation for most liquid–solid mixtures. Solution of [10] for steady-state irrotational, two-dimensional flow is the potential flow given by

$$\nabla^2\Psi = 0 \quad . \qquad [13]$$

Equation [13] is an elliptic partial differential equation, which is converted into a set of algebraic equations by the central finite difference formulas. This is then solved numerically using the successive over-relaxation method. The usual grid size was $\Delta x/d = \Delta y/d = 0.1$.

(2) Determining the particle trajectories, which are obtained by solving the particle equation of motion. A fourth-order Runge–Kutta method was used to integrate these equations. The dimensionless time increment used was 0.1. During the integration, the mixture velocity components and the pressure gradients must be known. The mixture velocity components are obtained from the definition of the stream function as

$$\begin{aligned} v_{mx} &= -\partial/\Psi/y \quad , \\ v_{my} &= \partial\Psi/\partial x \quad , \end{aligned} \qquad [14]$$

whereas the pressure gradients can be determined from the mixture velocity.

Also, to determine particle trajectories, the upstream particle Reynolds number (Re_b), particle inertia parameter (K_d), solids concentration (C_v), densities of the two phases and initial position should be known.

(3) Calculating the separation ratio from the limiting particle trajectory. This separates the particles that enter the branch from those that miss it. The separation ratio can be calculated from a mass-balance relation

$$C/C_v = (x_0/d)(U_b/U) \quad , \qquad [15]$$

where x_0 is the x-coordinate of the limiting trajectory in the undisturbed condition far upstream, and d is the branch diameter. U and U_b are the branch and upstream bulk velocities, and C and C_v are the branch and upstream solids concentrations.

MODEL PREDICTIONS

The flow field ahead of a branch was obtained by solving [13]. Figure 1 shows streamlines for $U/U_b = 0.6$ and branch angle of 45°. The streamlines correspond to dimensionless stream function values of 0.5, 0.75, ... and 2.0. The streamline $\Psi' = 1.0$ separates mixture (or fluid for infinite dilution) entering the branch from that missing it. The figure shows that deflection of the streamlines begins about one branch diameter upstream. Other results show that as U/U_b approaches zero or unity, regions of reverse flow appear. As U/U_b approaches zero, reverse flow out of the branch occurs, and the stagnation point lies on the upper inclined wall. On the other hand, as U/U_b approaches unity, reverse flow into the branch appears and the stagnation point lies on the vertical wall above the branch corner.

Figure 2 shows streamlines for $U/U_b = 0.6$ and a branch angle of 135°. For this case, the stagnation point is shifted from the upper corner of the branch to a point inside the branch itself and a part of the mixture which enters the branch exits again (reverse flow). From figures 1 and 2, one observes that the position of the stagnation point is a function of the branch angle. As the branch angle increases the stagnation point moves away from the corner and consequently, the reverse flow increases. Also, the deflection of the streamlines increases as the branch angle increases. Of course these potential flows are only approximations and neglect the complications which arise from viscous effects arising at the boundaries.

Figure 3 shows particle trajectories for velocity ratio of 0.2 and branch angle of 90° with $\rho_f = 1000\ \mathrm{kg/m^3}$ and $\rho_s = 2650\ \mathrm{kg/m^3}$. The solid lines show the mixture streamlines and the dotted lines represent the particle trajectories. As shown in this figure, particle trajectories coincide with the mixture streamlines far from the slot, whereas close to the slot the particle can not change its direction as the fluid does.

Other results show that particle deflection depends, among other factors, on the drag coefficient relationship. For a given Reynolds number, the greater the drag coefficient, the greater is the particle deflection.

The branch concentration can be determined from the limiting particle trajectory. In the presence of reverse flow, the stagnation point was used to determine the limiting particle trajectory as recommended by Addlesee (1980) in his study of probe sampling.

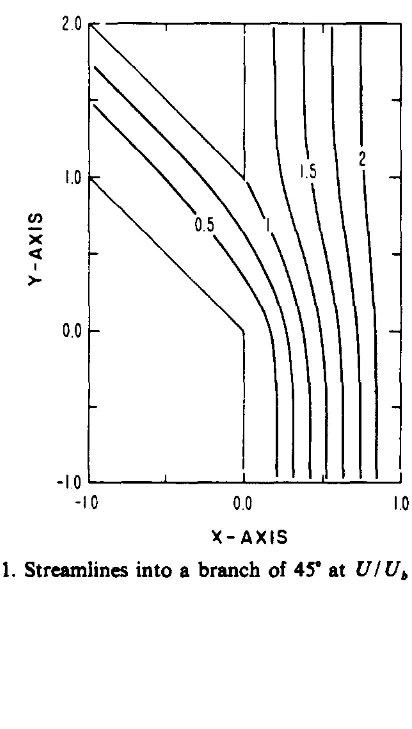

Figure 1. Streamlines into a branch of 45° at $U/U_b = 0.6$.

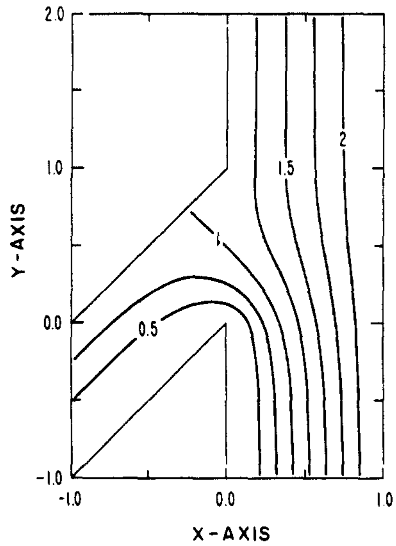

Figure 2. Streamlines into a branch of 135° at $U/U_b = 0.6$.

Figure 4 shows the predicted effect of particle inertia parameter on separation ratio for a sand–water slurry. A solids concentration of 10% was used in these calculations. Various K_d values were obtained by changing the particle diameter d_s, and the corresponding particle Reynolds numbers were accordingly recalculated. As shown in this figure, at a given velocity ratio, the branch concentration is high for small K_d and decreases with increasing K_d. This result is reasonable because small particles can follow the fluid streamlines and can change direction much easier, and consequently the separation ratio will be high. On the other hand, particles with high inertia parameters are affected much less by the fluid streamlines and the separation ratio is lower. Figure 4 also shows the effect of branch velocity on the separation ratio. At a given inertia parameter, as the velocity ratio increases, the separation ratio increases. The separation ratio approaches zero as the velocity ratio approaches zero, and of course it approaches unity as the velocity ratio approaches the limit. This result is reasonable, because as the branch velocity increases, the drag force acting on the particle increases, causing more particles to enter the branch. This result is not in agreement with the only previous theoretical work (Zebel 1978), but it agrees with

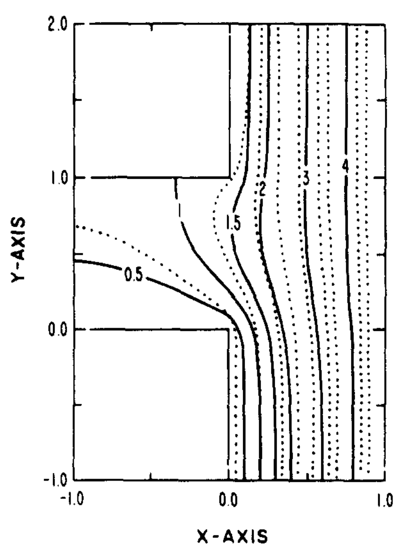

Figure 3. Particle trajectories for 90° tee, $K_d = 16.88$, $C_v = 0.1$, $U/U_b = 0.2$ and $Re_b = 3886.0$.

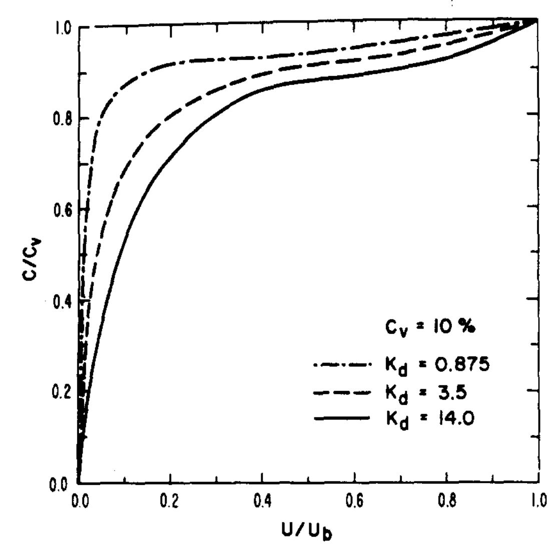

Figure 4. Effect of particle inertia parameter on branch concentration, predicted values from simulation.

the previous experiments in gas–solid systems (Raynor 1970; Davies & Subari 1982). Although the density ratios are different in gas–solid and liquid–solid systems, it seems that the mechanisms are the same. One also observes that the rate of increase of the separation ratio is high at a low branch velocity and starts to decrease as the branch velocity increases.

Figure 5 shows the predicted effect of discharge solids concentration on the separation ratio. C_v in this case is the upstream solids concentration, which is of course constant in this theoretical study. By removing the concentration correction from the drag force expressions in [6] and [7], a solution can be obtained for the case of infinite dilution. This is the situation of interest in dilute gas-phase systems. Figure 5 shows that as the concentration increases, particle segregation decreases. This result is reasonable because as the concentration increases, the drag force on the particles also increases. As this force increases, the tendency for the particles to follow the fluid increases and the branch concentration increases.

From figures 4 and 5, one can observe that in contrast to the findings of Bugliarello & Hsiao (1964) and Moujaes (1984), the separation ratio is a function of the upstream conditions (solids concentration and bulk velocity) in addition to other factors.

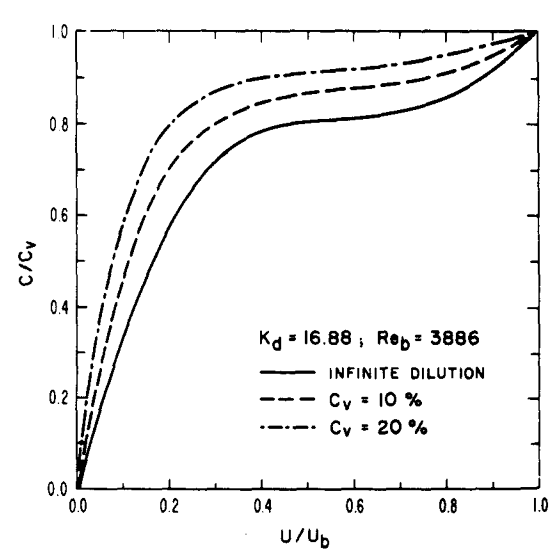

Figure 5. Effect of upstream solids concentration on branch concentration, predicted values from simulation.

EXPERIMENTAL PROCEDURE

In the absence of any previous work on particle segregation in slurry flow through tees, and because the theoretical predictions use an oversimplified two-dimensional model, it was necessary to conduct an experimental study to evaluate the degree of segregation and to find the conditions for minimum separation. Vertical flows have much more uniform concentration distributions than horizontal flows, and this made the former the logical ones to study.

The tee was installed in a vertical section of a 24.3-mm pipeline shown schematically in figure 6. The vertical section is a part of a 52-mm loop described elsewhere (Nasr-El-Din *et al.* 1984). A reducer was used after a 90° elbow to connect the vertical section with the loop. The tee was 100 cm downstream of the reducer. Tees with various dimensions and angles were tested in this study. The branch was constructed from a transparent hose to allow visual observations. The flowrate of the mixture through the branch was controlled by a pinch valve. Samples were collected over short timed intervals (± 0.1 s) so that branch velocities and concentrations could be calculated from the volume and weight of the sample. Slurry temperature was maintained constant at 20 ± 1°C by a heat exchanger (not shown).

The dispersed phase used in this study was silica sand particles of density $\rho_s = 2650$ kg/m^3, whereas the continuous phase was tap water of density $\rho_f = 998$ kg/m^3 at 20°C. Three sands of 0.165-, 0.326- and 0.72-mm surface mean-diameter and narrow-size distribution were used in the experiments. Hereafter, these sands will be reffered to as fine, medium and coarse, respectively. The experiments covered the effect of discharge solids concentration, particle size, branch velocity, diameter and angle on the measured concentration and size distribution. Table 2 summarizes the ranges of the various parameters covered in this study.

During the course of the experiments, the bulk velocity and solids concentration were kept constant. Samples of the total pipeline flow were withdrawn to allow the bulk velocity U_b and discharge concentration C_v to be determined.

EXPERIMENTAL RESULTS

Figure 7 shows the separation ratio C/C_v as a function of the velocity ratio U/U_b for the fine and medium sands at a discharge concentration of 7%–8%, bulk velocity 5.3–5.4 m/s, branch angle 90° and area ratio of unity. It is apparent from these results that as the branch velocity increases the separation ratio increases, and for all velocity ratios less than

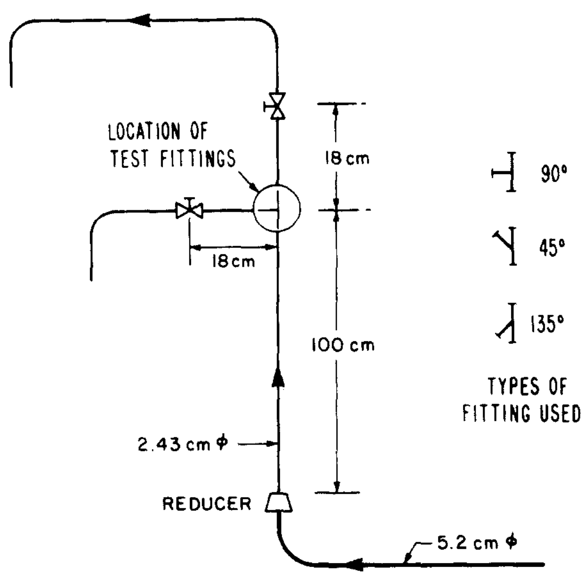

Figure 6. Test loop.

Table 2. Parameters studied

Parameter	Symbol	Range
Discharge concentration	C_v	3%–26%
Branch diameter	d	8–24.3 mm
Branch velocity	U	0–5.4 m/s
Branch angle	θ	45°–135°
Bulk velocity	U_b	4.8–5.4 m/s
Area ratio	M	0.11–1.0
Mean particle diameter	d_s	0.165–0.72 mm
Particle inertia parameter	K_d	0.86–16.88
Free stream particle Reynolds number	Re_b	862–3886
Pipe diameter	D	24.3 mm

unity, the separation ratio is less than one. It starts from zero at zero branch velocity (branch valve is fully closed) and increases gradually to unity. The figure also shows that the separation ratio is a function of the particle size. At a given velocity ratio, the larger particles show lower separation ratios. This is the K_d effect shown in the model predictions of figure 4. One also observes that the rate of change of the separation ratio with respect to velocity ratio is highest at low velocities and differs substantially for these two particle sizes.

Figure 8 shows the effect of slurry mean concentration on the separation ratio C/C_v for a branch angle of 90° and area ratio of unity. The fine and medium sands were used in this experiments at various discharge concentrations and a bulk velocity of 5.2–5.3 m/s for the fine sand and 4.8–5.4 m/s for the medium one. The figure shows that in both cases, increasing the mean concentration increases the separation ratio, and this confirms Moujaes' suggestion and the model predictions of figure 5. This effect can be attributed to the increased drag force which arises from the higher solids concentration at a given mean flow.

Results shown in figures 7 and 8 show that the common assumption that the branch and upstream concentrations are equal should be used carefully. According to these results, this assumption can be used with less than 10% error for fine particles with low inertia parameter, especially at high solids concentrations.

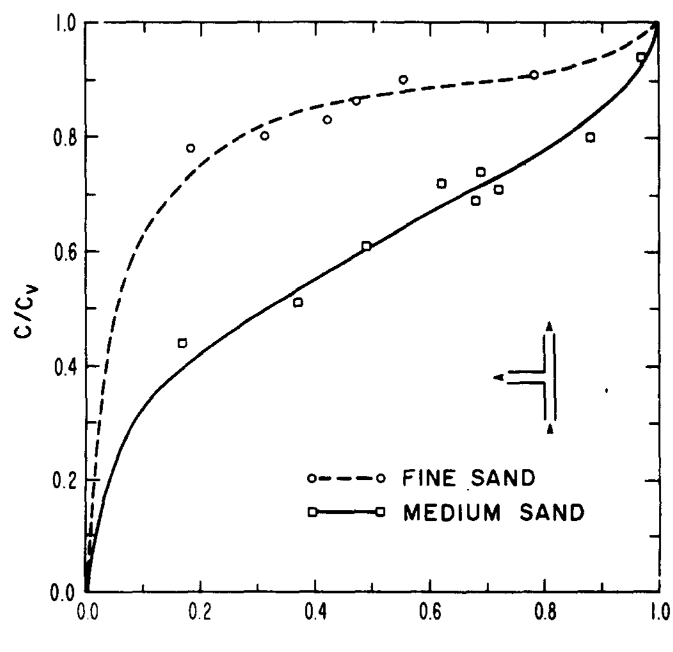

Figure 7. Effect of particle size on separation ratio, $M = 1.0$, $\theta = 90°$ and $C_v = 7\%–8\%$.

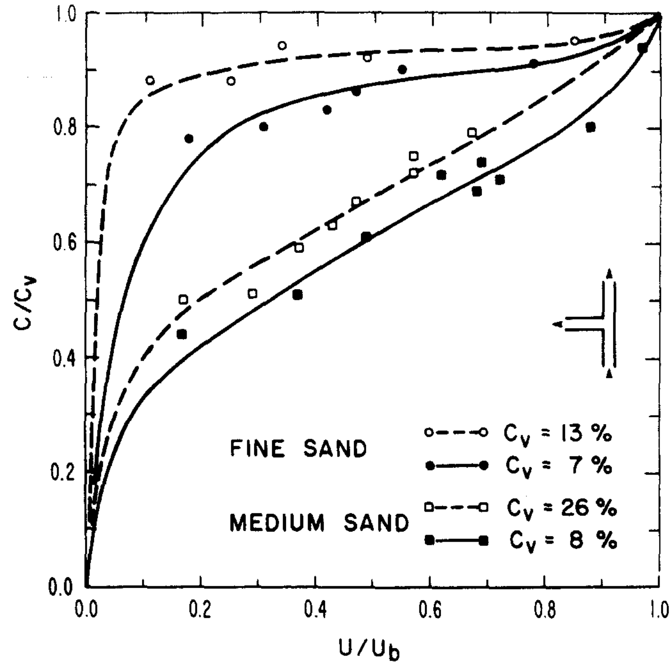

Figure 8. Effect of solids concentration on separation ratio, $M = 1.0$ and $\theta = 90°$.

Figure 9 compares the separation ratios for the medium sand using 90° branches of 0.11-, 0.42- and 1.0-area ratio. Discharge concentrations of 8%–9.5% bulk velocities of 5.1–5.4 m/s were used in this experiment. As the diameter of the branch decreases, the separation ratio decreases at a given velocity. This result is reasonable, because as the aperture decreases, the time available for the particle to change its direction is correspondingly reduced. It would be expected that the effect of using small diameter holes would be severe if coarse particles were used. One also observes that although the settling velocity of the medium sand is in the range of 20 cm/s which was mentioned by Torrest & Savage (1975), the effect of reducing the branch size is significant. Other results for the fine sand (lower settling

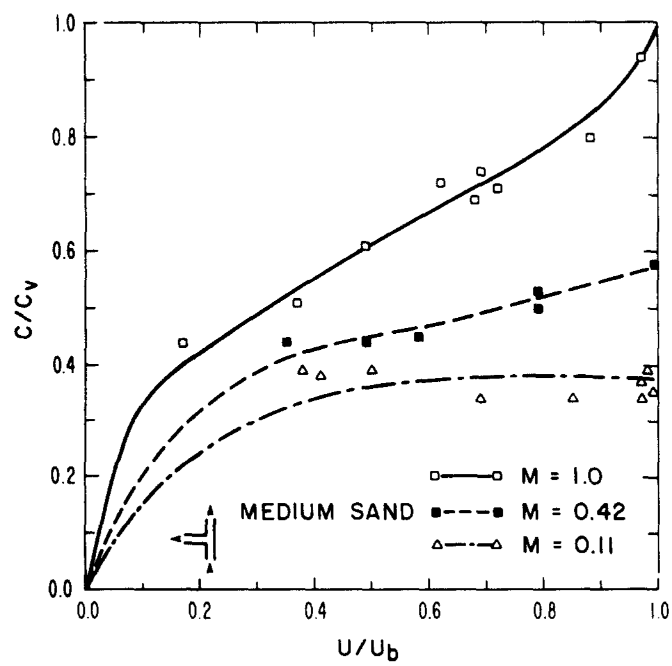

Figure 9. Effect of area ratio on separation ratio, $C_v = 8\%–9.5\%$ and $\theta = 90°$.

velocity) showed similar trends to those of the medium sand. It should be mentioned that an increase in branch concentration with decreasing branch size, originally found by Bugliarello & Hsiao (1964) and confirmed by Moujaes (1984), is opposite to the trend of the results of the present study. A comparison with the results of Bugliarello & Hsiao was not possible because their results were obtained for neutrally buoyant spheres (for which the inertial segregation could be neglected) in experiments conducted with laminar vertical flow. However, it is likely that there were considerably different concentration and velocity distributions across the pipe in their experiments.

Figure 10 shows the effect of particle size for a branch of 45° angle and area ratio of unity. The fine and medium sands were used at discharge concentrations of 9.9%–13.7% and bulk velocities 5.2–5.4 m/s. From figures 9 and 10, one observes that, as with the results obtained for a 90° branch, the difference between the separation ratios for the two sands is substantial for all the velocity ratios. The difference between the results obtained at 45° and 90° is largest at low velocity ratios and decreases as the velocity ratio increases, especially for the medium sand. Also, one notes that at a given velocity ratio, the separation ratios for both sands are lower for branches of 90° than those for a 45° branch. This result is reasonable, because for the former, a particle has to change direction by 90° to be captured, whereas for the latter, it has to change direction by only 45°.

Figure 11 shows the effect of particle size for a branch of 135° angle and area ratio of one. For the medium sand, the discharge concentration was 8.3% and the bulk velocity was 5.5 m/s, whereas for the fine sand, these values were 7% and 5.3 m/s, respectively. Here the difference between the separation ratios for the two sands is significantly smaller than those obtained with 45° and 90° branches. The maximum difference occurs at U/U_b 0.05 to 0.1, and it disappears at U/U_b near 0.5. These results suggest that the separation ratio is not only a function of particle inertia but is also affected by the gravity force especially at velocity ratio greater than 0.5. At these high velocity ratios, the velocity in the vertical branch is relatively small, and particle settling is significant, especially for the medium sand. This settling increases the separation ratio for the medium sand, and the difference between the separation ratios for the two sands diminishes. This effect was not observed for the 45° or 90° angles, probably because it is easier for the particles to slide into a 135° branch.

Figure 12 shows the effect of branch angle on the separation ratio for the coarse sand at a discharge concentration of 3.2%–3.4% and bulk velocity of 5.3–5.5 m/s. Two important

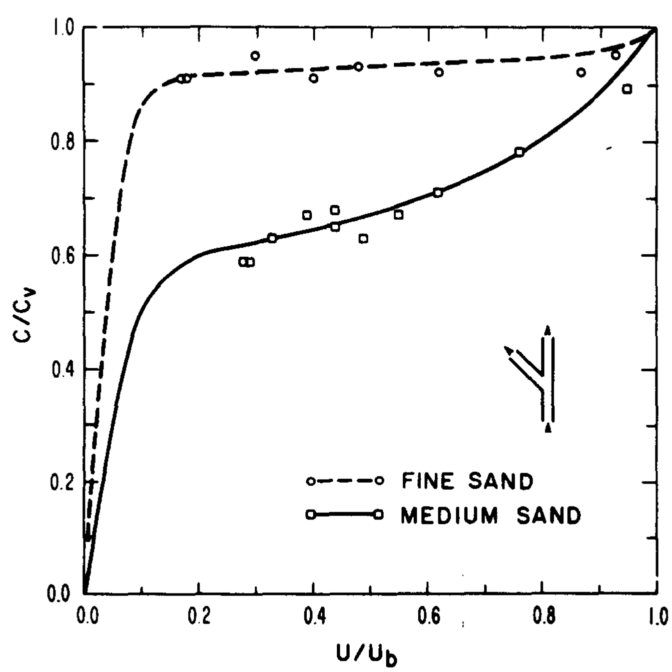

Figure 10. Effect of particle size on separation ratio, $M = 1.0$, $\theta = 45°$, and $C_v = 9.9\%–13.7\%$.

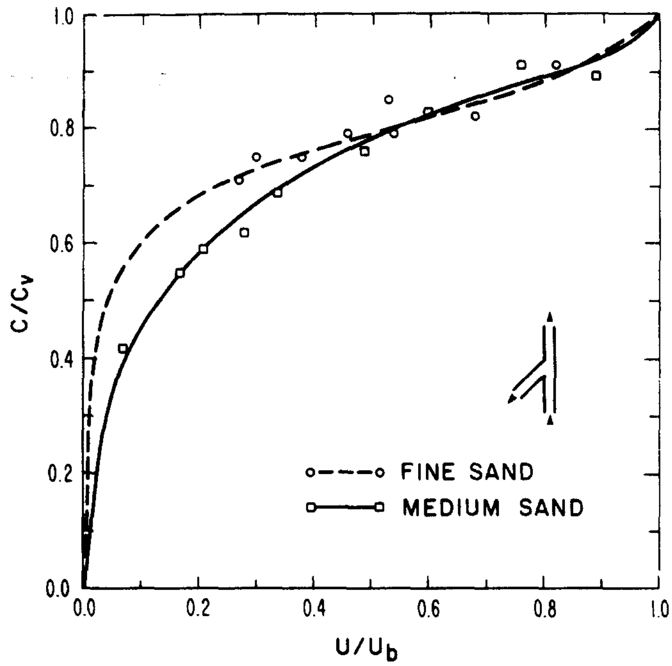

Figure 11. Effect of particle size on separation ratio, $M = 1.0$, $\theta = 135°$ and $C_v = 8.3\%$.

phenomena can be observed from this figure. First, the separation ratios for the 90° branch are less than those for the 135° branch. This result was not expected, because at a given velocity ratio, as the branch angle increases, one would expect the separation ratio to decrease because of the inertia effect. This contradiction can be explained as follows: To have the same area ratio for branches at 45° or 135°, the major axis of the intersection ellipse must be 41.4% longer than the diameter of a 90° branch. This means that for the 135° branch, a particle has much more time to change direction and enter the branch. Consequently the separation ratio for the 135° branch will be higher than that for the 90° branch. This result can be also interpreted with the particle intertia parameter K_d. For a

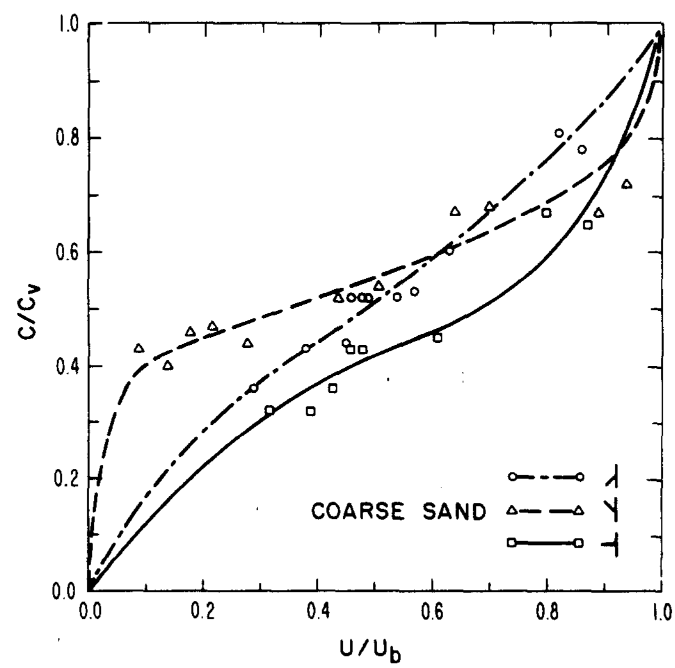

Figure 12. Effect of branch angle on separation ratio, $M = 1.0$ and $C_v = 3.2\%–3.4\%$.

lateral with angle θ, the K_d value for the lateral branch is lower than that for a tee by $\sin\theta$, and consequently the separation ratio for the lateral at a given velocity ratio is higher. The effect of K_d is shown in figure 4.

The second observation is that at low velocity ratios the separation ratio for 45° is higher than that for 135°. This was expected because of the inertial effect. At higher velocity ratios, the separation ratio for the 135° is higher than that of the 45° branch. This result can not be explained in terms of the inertia effect but can be attributed to the gravity effect.

Figure 13 shows the effect of increasing the slurry concentration for the fine sand at a branch angle of 135°, area ratio of one, solids concentrations of 7% and 14% and a bulk velocity of 5.3 m/s. The effect is similar to the results obtained for 90° branch shown in figure 8 and to the model predictions. One also observes that the increase in separation ratio with concentration is high at low velocity ratios and decreases as the velocity ratio increases.

Figure 14 shows the effect of reducing the branch size for the medium sand at a discharge concentration of 8.3%, a bulk velocity of 5.1–5.5 m/s and branch angle of 135°. One observes that for all velocity ratios, reducing the branch size reduces the corresponding separation ratio and this agrees with the results obtained for branches of 90°.

Figure 15 compares the separation ratio for the medium sand at 8.3%–9.5% discharge concentration, a bulk velocity of 5.1 m/s and branches of 90° and 135°. Again, for all the separation ratios, the values corresponding to the 135° branch are higher than those for the 90° branch. This confirms the results obtained for the coarse sand which were shown in figure 13. This conclusion also confirms that of Azzopardi (1984) that for lateral branches the axial length should be considered rather than the branch diameter.

Figure 16 shows the effect of particle size on the separation ratio for branches of 90° angle and an area ratio of 0.11. Three sands were used at a discharge concentration of 3.0%–3.4% and a bulk velocity of 5.1–5.3 m/s. The figure shows that the separation ratio is a function of the particle size and this similar to the results obtained for the larger branches shown in figure 7. The figure also shows that, unlike larger branches, the separation ratio is almost independent of the velocity ratio at higher velocity ratios. The rate of increase of separation ratio at zero velocity ratio is lower than that for the larger branches, and the rate of increase is independent of the particle size at high velocity ratios. This was not observed for the larger branches. Finally, one observes that the relation between the sep-

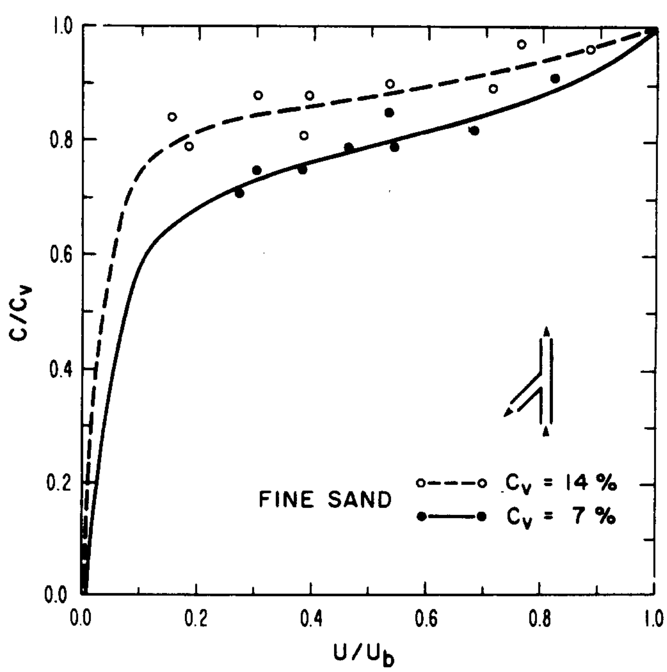

Figure 13. Effect of solids concentration on separation ratio, $M = 1.0$ and $\theta = 135°$.

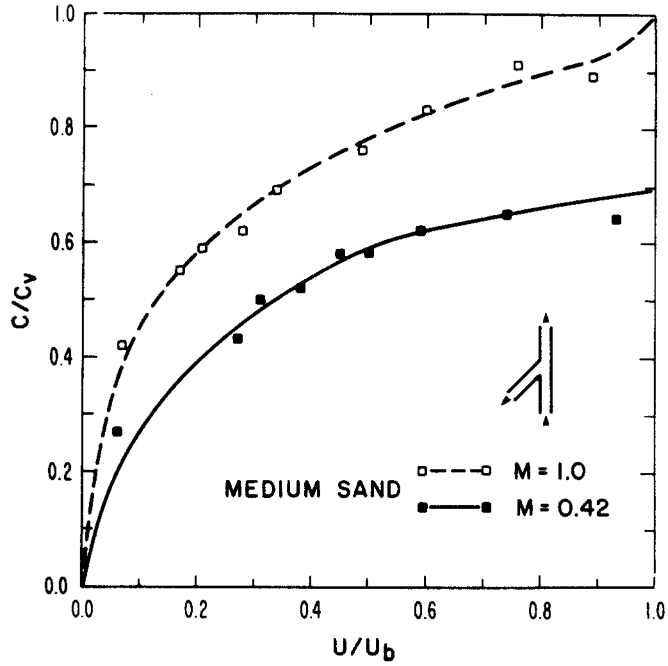

Figure 14. Effect of area ratio on separation ratio, $C_v = 8.3\%$ and $\theta = 90°$.

aration ratio and the branch velocity at constant bulk velocity is only linear, as suggested by Torrest & Savage, to a certain value before it levels off.

Samples for all the branches studied were collected to determine the effect of various parameters on particle size distribution. The results showed the mean particle size of the branch to be generally lower than the upstream value. For branches with area ratio of unity, the effect was insignificant. For smaller branches, the effect was pronounced and depended on the velocity ratio. As the velocity ratio increases, the branch particle mean diameter approached the upstream value. These trends agree with the results of Nasr-El-Din *et al.* (1985) obtained for branches with very small area ratio.

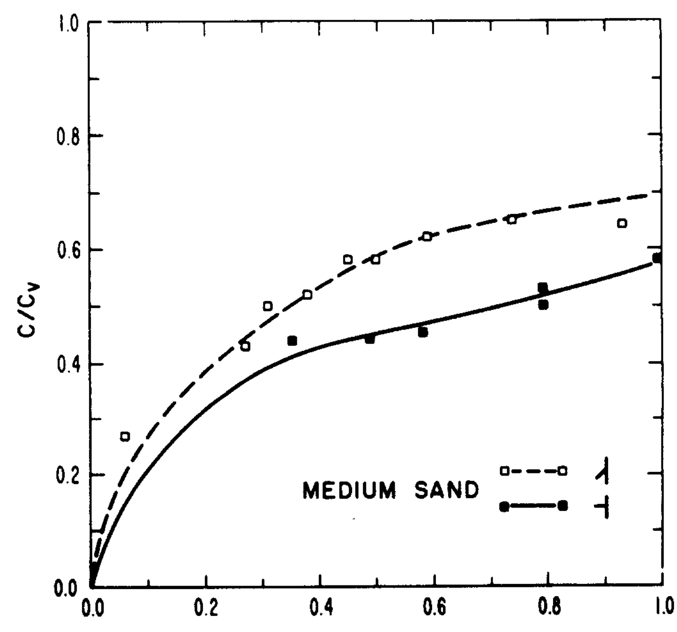

Figure 15. Effect of branch angle on separation ratio, $M = 0.42$ and $C_v = 8.3\%–9.5\%$.

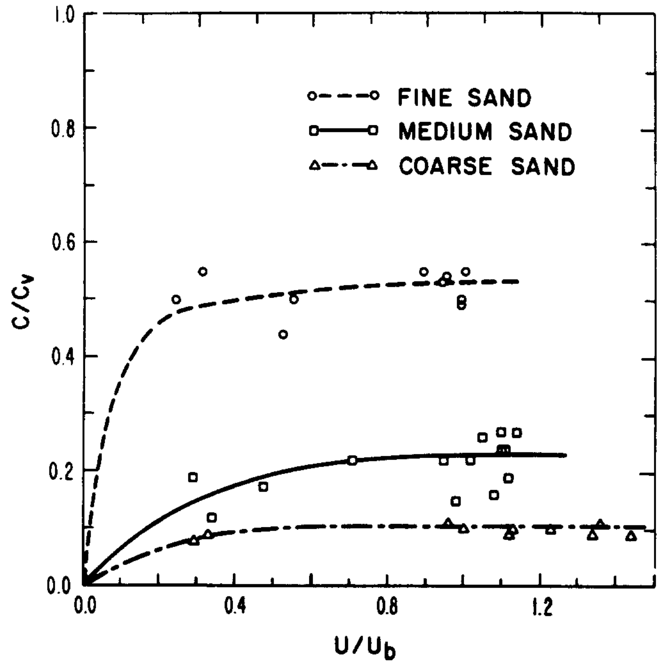

Figure 16. Effect of particle size on separation ratio, $M = 0.11$, $C_v = 3.0\%–3.4\%$ and $\theta = 90°$.

Although a two-dimensional model was introduced to explain the results qualitatively for the finest particles, a fair agreement with some experimental data was obtained. Figure 17 shows a comparison between the predicted and the measured separation ratios for the fine sand at a discharge concentration of 7%. For the medium and the coarse sands, the model predictions exceed the experimental results significantly. It is believed that this difference results from the simplifications involved in the model. These are likely to be approximating the problem with a two-dimensional flow, using the slip condition at the boundaries and using the steady state drag relationship.

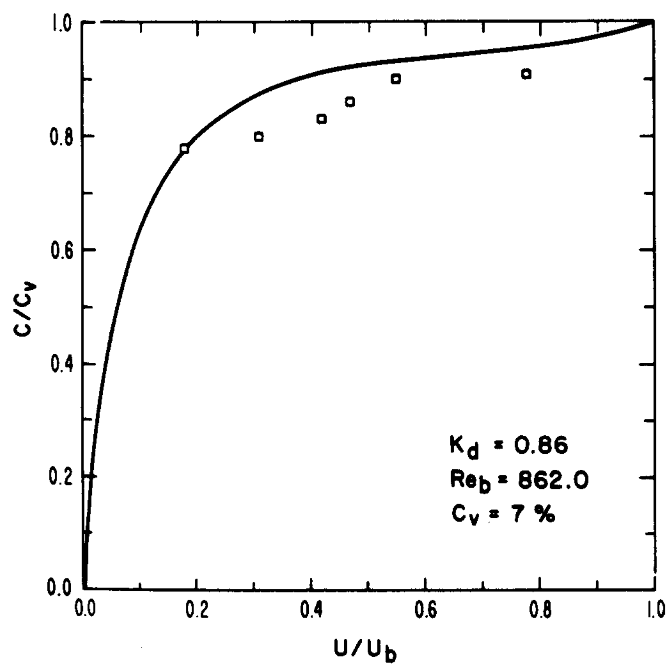

Figure 17. Predicted and measured separation ratios, fine sand, $M = 1.0$ and $\theta = 90°$.

Visual observations during the experiments indicated strong swirling secondary components in several of the branch flows. Similar observations were reported by Iwanami *et al.* (1969). These suggest a flow complexity which would be a further cause of discrepancies between model predictions and experimental observations. They would also complicate analyses of the pressure changes produced by these flow bifurcations.

CONCLUSIONS

(1) The present study shows that for all branches studied, because of the inertial effect, the branch concentration is less than the upstream one for all velocity ratios less than unity.

(2) The separation ratio depends upon upstream conditions. It increases as the upstream solids concentration increases and decreases as the upstream bulk velocity, particle size and/or density increase.

(3) The separation ratio is also a function of velocity ratio, branch size and orientation. At a given velocity ratio, no matter what the branch angle, the separation ratio decreases as the branch size decreases. For most branch sizes studied, the separation ratio increases as the velocity ratio increases. For branches of small size, the separation ratio is almost independent of the velocity ratio at relatively high velocity ratios.

The separation ratio is also a function of the branch angle. This study shows that the separation ratio for a 90° branch is lower than those for branches of 45° or 135° which have the same area ratio. At low velocity ratios, and because of inertia, the separation ratio for a 45° branch is higher than that for a 135° branch. On the other hand, at high velocity ratios, because of gravity, the separation ratio for a 135° branch is slightly higher than that for a 45° branch for the medium sand. This effect is more pronounced for coarser sands.

These results indicate that care is required in designing slurry piping networks. Dividing a slurry using a tee or a wye will generally produce a lower branch concentration and smaller mean particle diameter than the upstream values. Also, if the slurry consists of solids of different densities, one would expect a higher concentration of lower density solids in the branch. Although the present study has considered only a simple case, the same principles govern segregation in more complex systems such as manifolds.

For horizontal flows, the effect of the density gradient would complicate particle segregation. Also, because of the gravity effect, the location of any smaller-diameter branch will be very important. However, the same general trends would be expected to occur.

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REFERENCES

ADDLESEE, A. J. 1980 Anisokinetic sampling of aerosols at a slot intake. *J. Aerosol Sci.* **11**, 483–493.

AZZOPARDI, B. J. 1984 The effect of the side arm diameter on the two-phase flow split at a *T* junction. *Int. J. Multiphase Flow* **10**, 509–512.

AZZOPARDI, B. J. & WHALLEY, P. B. 1982 The effect of flow patterns on two-phase flow in a *T* junction. *Int. J. Multiphase Flow* **8**, 491–507.

BUGLIARELLO, C. & HSIAO, C. 1964 Phase separation in suspensions flowing through bifurcations: A simplified hemodynamics model. *Science* **143**, 469–471.

DAVIES, C. N. & SUBRAI, M. 1982 Aspiration above wind velocity of aerosols with thin-walled nozzles facing and at right angles to the wind direction. *J. Aerosol Sci.* **13**, 59–71.

DURHAM, M. D. & LUNDGREN, D. A. 1980 Evaluation of aerosol aspiration efficiency as a function of Stokes number, velocity ratio and nozzle angle. *J. Aerosol Sci.* **11**, 179–188.

FOUDA, A. E. & RHODES, E. 1972 Two-phase annular flow stream division. *Trans. Instn. Chem. Engrs* **50**, 353–363.

FOUDA, A. E. & RHODES, E. 1974 Two-phase annular flow stream division in a simple tee. *Trans. Instn. Chem. Engrs* **52**, 354–360.

HENRY, J. A. R. 1981 Dividing annular flow in a horizontal tee. *Int. J. Multiphase Flow* **7**, 343–355.

HONAN, T. J. & LAHEY, R. T., Jr. 1981 The measurement of phase separation in wyes and tees. *Nucl. Eng. Design* **64**, 93–102.

IWANAMI, S., SUU, T. & KATO, H. 1969 Study on flow characteristics in right-angled pipe fittings: 1st report: on case of water flow. *Bull. JSME* **12**, 1043–1050.

IWANAMI, S. & SUU, T. 1969 Study on flow characteristics in right-angled pipe fittings: 2nd report: on case of slurries in hold up flow. *Bull. JSME* **12**, 1051–1061.

JACKSON, R. 1963 The mechanics of fluidized beds part I: The stability of the state of uniform fluidization. *Trans. Instn. Chem. Engrs* **41**, 13–21.

LUNDGREN, D. A., DURHAM, M. D. & MASON, K. W. 1978 Sampling of tangential flow streams. *Am. Ind. Hyg. Assoc.* **39**, 640–644.

MASUDA, H., YOSHIDA, H. & IINOYA, K. 1981 Dust sampling for particle mass concentration measurement. *J. Soc. Powder Tech. Japan* **18**, 177–183.

MORIKAWA, Y., KOBAYASHI, Y., TAKEDA, M. & UEURA, Y. 1974 Pressure losses of air-solid mixtures in the branching of pneumatic conveying. *Bull. JSME* **17**, 1272–1277.

MORIKAWA, Y., KONDO, T. & HIRAMOTO, T. 1978 Pressure drop and solids distribution of air-solids mixture in horizontal unsymmetric branches. *Int. J. Multiphase Flow* **4**, 397–404.

MORIMOTO, T., YAMAMOTO, A., NAKAO, T., TANAKA, S. & MORIKAWA, T. 1977 On the behavior of air-solids mixture in a pipline for pneumatic conveyance with a single or double T-branches. *Bull. JSME* **20**, 600–606.

MOUJAES, S. F. 1984 Measurements of slurry concentration and flow rate in shell and tube heat exchangers. *Can. J. Chem. Engng.* **62**, 62–67.

NASR-EL-DIN, SHOOK, C. A. & ESMAIL, M. N. 1984 Isokinetic probe sampling from slurry pipelines. *Can. J. Chem. Engng.* **62**, 179–185.

NASR-EL-DIN, H., SHOOK, C. A. & ESMAIL, M. N. 1985 Wall sampling in slurry systems. *Can. J. Chem. Engng.*, **63**, 746–753.

RAYNOR, G. S. 1970 Variation in entrance efficiency of a filter sampler with air speed, flow rate, angle and particle size. *Am. Ind. Hyg. Assoc.* **31**, 294–304.

SABA, N. & LAHEY, R. T. Jr., 1984 The analysis of phase separation phenomena in branching conduits. *Int. J. Multiphase Flow* **10**, 1–20.

TEMKIN, S. & MEHTA, H. K. 1982 Droplet drag in an accelerating and decelerating flow. *J. Fluid Mech.* **116**, 297–313.

TOROBIN, L. B. & GAUVIN, W. H. 1959 Fundamental aspects of solids-gas flow, Part III: Accelerated motion of a particle in a fluid. *Can. J. Chem. Engng.* **37**, 224–236.

TORREST, R. S. & SAVAGE, R. W. 1975 Particle collection from vertical suspension flows through small side ports—A correlation. *Can. J. Chem. Engng.* **53**, 699–701.

WALLIS, G. B. 1969 *One-Dimensional Two-Phase Flow*. McGraw-Hill, New York.

ZEBEL, G. 1978 Some problems in the sampling of aerosols. In *Recent Developments in Aerosol Science (Symposium on Aerosol Science and Technology)*, 167–185.

ZETZMANN, K. 1984 Phase separation of an air-water flow in a vertical T-junction. *Ger. Chem. Engng.* **7**, 305–312.

ZUBER, N. 1964 On the dispersed two-phase flow in the laminar flow regime. *Chem. Engng. Sci.* **19**, 897–917.