Particle Transport In A Bottom-feed Separation Vessel

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ABSTRACT

A two-dimensional, axisymmetric numerical model of particle separation in a bottom-feed separation vessel is presented. The model includes six separate particle classes and assumes that the settling velocity of each particle class is sufficiently small when compared to the high inflow turbulence levels that the effect of the particles on turbulence can be neglected. Low particle settling velocities coupled with low particle volume fractions allow application of a drift-flux multi-phase model rather than a fully coupled multi-fluid model. Comparison of numerical results to measured plant data is in good agreement for all particle classes. Results of simulations show that bottom feeding results in a negatively buoyant, particle-laden jet being formed in the core of the vessel. The fraction of large particles that is carried out through the overflow is found to be critically dependent on the inlet velocity. The most effective way to reduce carry-over at the same time as maintaining through-put is to increase the diameter of the inlet feed pipe.

NOMENCLATURE

C_i	Volume fraction of particle class i
d_m	Cut-off particle size
$\mathbf{f}$	Body force
$\mathbf{i}_r$	Unit radial vector
$\mathbf{i}_k$	Unit axial vector
k	Turbulent kinetic energy
P	Pressure
S_ϕ	Source term for ϕ
$\mathbf{V}$	Liquid velocity
$\mathbf{V}_s$	Particle slip velocity
ϵ	Turbulent dissipation
μ_{eff}	Total effective mixture viscosity
ϕ	Turbulent scalar (either k or ϵ)
ρ	Liquid density
σ_{C_i}	Prandtl number of diffusion of particle class i
σ_ϕ	Prandtl number of diffusion of ϕ

1. INTRODUCTION

The separation of solids from liquid is an important part of many minerals processing applications and is undertaken in a wide variety of devices including hydro-cyclones, thickeners and classifiers. Often the object of separation is to remove particles of a certain size or density, leaving others with different size or density behind in the liquid. In practical applications there will almost always be a spectrum of particle sizes which makes numerical simulation difficult. Each different particle size must be treated separately which means that the particle size distribution must be reduced to a few representative particle classes (typically no more than two).

This study originated from the need to separate large particles from a particle/liquid suspension as their presence in the process stream had the potential to adversely affect downstream operations. Plant measurements had been made of particle concentration in underflow and overflow and were presented in terms of six particle sizes (all with the same nominal density).

The physical geometry of the vessel is such that the feed inlet is centrally located at the base of a cone and issues vertically into the vessel. Overflow exits the roof of the vessel through a number of overflow pipes. Underflow is pumped out of one side of the vessel through a pipe located near the inflow. For computation, the geometry is simplified by assuming axisymmetry. Thus the underflow pipe is treated as an annulus and the set of overflow pipes is replaced by a central pipe and an overflow annulus at approximately half the radius of the vessel. The computational domain is shown in Figure 1.

2. MATHEMATICAL MODEL

Because low particle volume fractions are expected in the vessel, a drift-flux multiphase model is chosen rather than a fully coupled multi-fluid model. A literature review showed that drift-flux models have been used successfully in the study of settling tanks and clarifiers ((Celik & Rodi 1989); (Adams & Rodi 1990); (Zhou & McCorquodale 1992)). A fully two-phase model was compared to the drift-flux model used in this study and, for a free-settling problem with low solid loadings, almost identical results were obtained. The drift-flux model used in this study has also been used to solve a rectangular settling tank problem, in which limited experimental results are available (Zhou & McCorquodale 1992). There is good qualitative agreement.

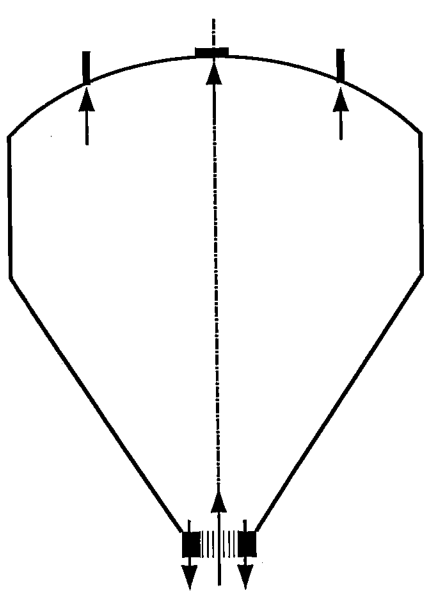

Figure 1: Computational domain for the particle separation vessel.

The advantage of the drift-flux model used here is that six different particle sizes are included in the model – this would have been computationally prohibitive with a fully multi-phase treatment.

In a vector form, the governing equations are written:

$$\nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}$$

$$\frac{\partial(\rho \mathbf{V})}{\partial t} + \nabla\cdot(\rho \mathbf{V} \otimes \mathbf{V}) = \nabla\cdot(\mu_{eff} \nabla \mathbf{V}) - \nabla P + \mathbf{f} \tag{2}$$

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla\cdot(\rho\mathbf{V}\phi) = \nabla\cdot(\frac{\mu_{eff}}{\sigma_\phi}\nabla\phi) + S_\phi \tag{3}$$

$$\frac{\partial(\rho C_i)}{\partial t} + \nabla\cdot(\rho(\mathbf{V}+\mathbf{V_s})C_i) = \nabla\cdot(\frac{\mu_{eff}}{\sigma_{C_i}}\nabla C_i) + S_{C_i} \tag{4}$$

where $\mathbf{V}$, P and $\mathbf{V_s}$ are the velocity vector, pressure and settling velocity vector respectively. C_i is the volume concentration of particle class i. The effective viscosity is μ_{eff} (and is the sum of molecular and turbulent viscosity) and the density is ρ. The body force $\mathbf{f}$ due to particle/fluid density difference is modelled by using a Boussinesq approximation. Turbulence is modelled using a standard $k - \epsilon$ model with wall functions applied at near wall surfaces. So ϕ in Equation (3) can be k or ϵ and the non-dimensional number σ_ϕ defines the diffusivity of ϕ. The effect of particles on turbulence has not been considered in the current study as it is believed that the low solids loadings and comparatively small particle settling velocities have only a very small effect when compared to the high inflow turbulence levels.

All variables are defined at the supply inlet. A zero-gradient condition is applied at the outlets and the liquid flow rates are distributed with a predetermined ratio through the outlets.

For a two-dimensional and axisymmetric flow, $\mathbf{V} = V_r\mathbf{i_r} + V_k\mathbf{i_k}$. A finite volume technique based on the SIMPLEC algorithm of Doormaal & Raithby (1984) was used to solve the time-averaged multi-phase

Navier-Stokes equations. The convection terms in the momentum equations are discretised using a second-order finite volume scheme (QUICK) for non-uniform grids (Li & Rudman 1995), and a first-order upwind scheme is used for solid-fraction equations and the governing equations for turbulent kinetic energy and dissipation rate.

There are several ways to incorporate Equation (4) into the SIMPLEC algorithm. The approach used here is to discretise Equation (4) directly and to include the settling velocity in the convection term. Note that the velocity field $(\mathbf{V} + \mathbf{V}_s)$ is not divergence free, so a continuity equation cannot be used in the discretisation of the convection/diffusion equation, as normally done, e.g. Patankar (1980).

3. VALIDATION

The numerical model was validated against data measured at the plant, and a comparison between numerical prediction and measured data for both underflow and overflow are presented in Table 1. The aim of the separation is to minimise the carry-over of particles with a size greater than d_m, and thus particle sizes are described below in terms of the maximum desirable particle size, d_m. The percentage for each size refers to the mass percentage of the total carry-over that is greater than (or smaller than for the smallest size class) a given size. In general there is good agreement between prediction and measurement except for the underflow of very large particles. It is known that the plant

Table 1: Comparison between measured and predicted percentages of solids in overflow and underflow for different particle sizes.

Particle size		$> 3d_m$	$> 1.5d_m$	$> d_m$	$> \frac{1}{2}d_m$	$> \frac{1}{3}d_m$	$< \frac{1}{3}d_m$	Tot. vol. frac.
Overflow	Meas. %	0.7	1.5	11.3	26.3	33.6	66.4	0.0269
	Pred. %	0.0	0.2	8.5	23.7	31.7	68.3	0.0256
Underflow	Meas. %	27.4	59.2	69.9	76.0	78.7	21.3	0.0852
	Pred. %	19.0	51.2	64.2	72.8	75.9	24.1	0.0746

measurement for this particle size class is in error, thus this discrepancy is not a serious problem. This data corresponds to standard operating conditions ir resulting flow is referre(flow. The distribution (the four larger particl(case are shown in Figu

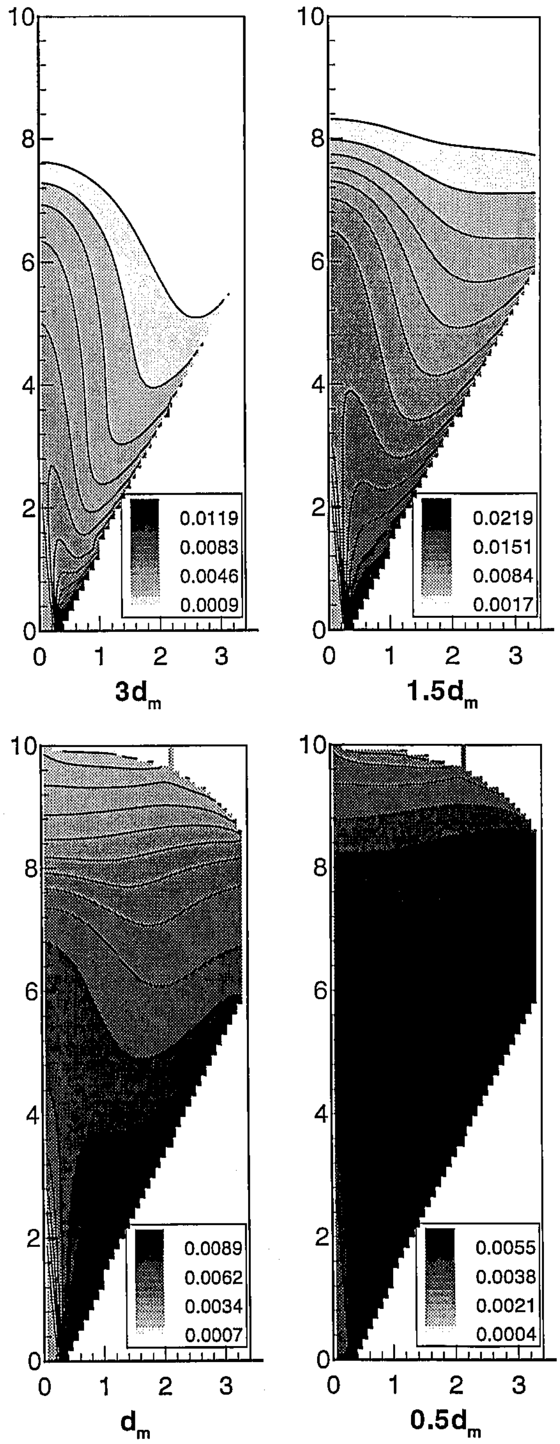

Figure 2: Distribution of volume fractions of the four largest particle size classess.

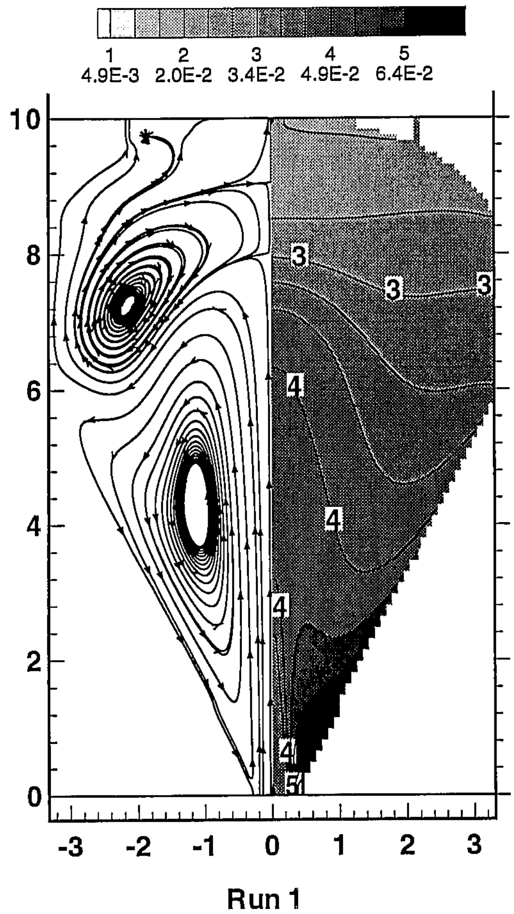

Figure 3: Flow streamlines and contours of total volume fractions of solids for the base case.

The volume fraction data for the two smallest classes show little variation throughout the vessel. Flow streamlines and total volume fractions of solids are shown in Figure 3, which illustrates the basic flow pattern observed for all flow configurations. The feed jet is laden with particles and is negatively buoyant with respect to the surrounding, particle-depleted fluid. Large particles settle out of the jet to the base of the cone and are withdrawn through the underflow, whereas smaller particles are more easily transported to the top of the vessel and out the overflow.

4. EFFECT OF DESIGN MODIFICATIONS

Three design modifications were investigated with the aim of reducing the carry-over of solids larger than d_m (referred to below as 'large particles'). The three modifications were: an increase in vessel height; an increase in vessel diameter; and an increase in feed-pipe diameter.

4.1 Effect of increasing vessel height

Increasing the vessel height has little effect on the basic flow pattern, as seen in Figure 4 in which the vessel height has been increased by 10%. Although the added height provides a longer 'upward journey' for particles and may be expected to give additional time for large particles to settle, results of carry-over suggest little difference, as seen in Table 2. In order to significantly decrease the carry-over of large particles by increasing the vessel height, a significant increase would be required.

Table 2: Percentage carry-over of large particles (size > d_m) and total volume fractions of solids in carry-over as functions of vessel height.

Geometry	% Part.> d_m	Tot. vol. frac.
Base	8.5	0.0256
Base + 5%	8.2	0.0255
Base + 10%	7.4	0.0252

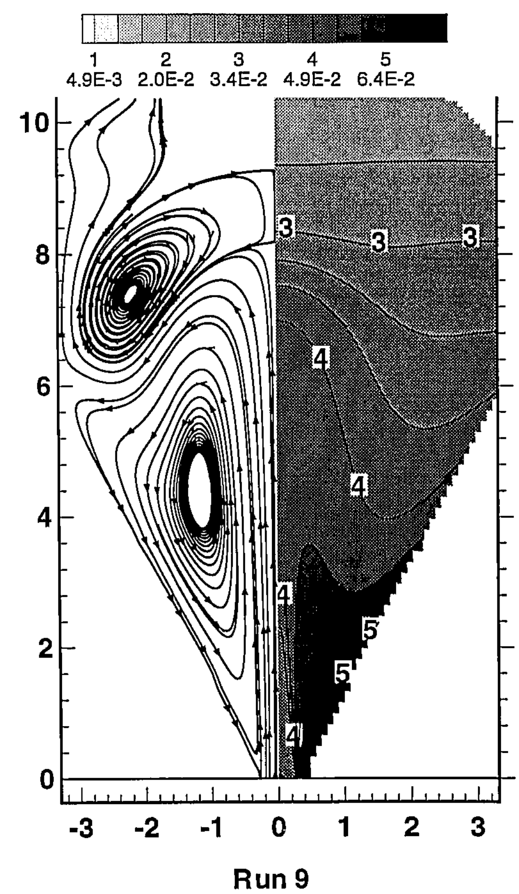

Figure 4: Particle streamlines and contours of total volume fractions of solids when vessel height is increased by 10%.

4.2 Effect of increasing vessel diameter

The vessel diameter was increased in such a way that the total vessel height and the angle of the base were kept constant. Once again, the basic flow pattern is not altered significantly by increasing the vessel diameter, as seen in Figure 5 which is for an increase of 15%. There is a small improvement in the carry-over of large particles when the vessel diameter is increased, (see Table 3).

Table 3: Percentage carry-over of large particles (size $> d_m$) and total volume fractions of solids in carry-over as functions of vessel diameter.

Geometry	% Part. $> d_m$	Tot. vol. frac.
Base	8.5	0.0255
Base + 15%	7.8	0.0253
Base + 30%	6.9	0.0250

Increasing the vessel diameter has the effect of reducing the mean upward velocity in the top of the vessel, and the effect of this is to reduce the carry-over of large particles and also total solids carry-over.

4.3 Effect of increasing feed-pipe diameter

Increasing the feed-pipe diameter has the most dramatic effect on the flow patterns and solids distribution, as seen in Table 4 nd Figure 6 (for an increase of 100%).

Table 4: Percentage carry-over of large particles (size $> d_m$) and total volume fractions of solids in carry-over as functions of feed-pipe diameter.

Geometry	% Part. $> d_m$	Tot. vol. frac.
Base	8.5	0.0255
Feed Diam. ×1.5	5.3	0.0244
Feed Diam. ×2.0	3.2	0.0237

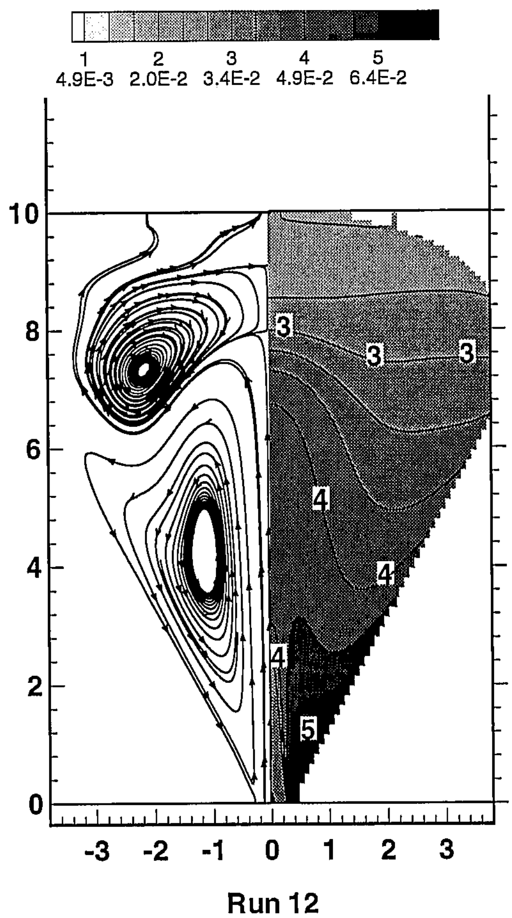

Figure 5: Particle streamlines and contours of total volume fractions of solids when the vessel diameter is increased by 15%.

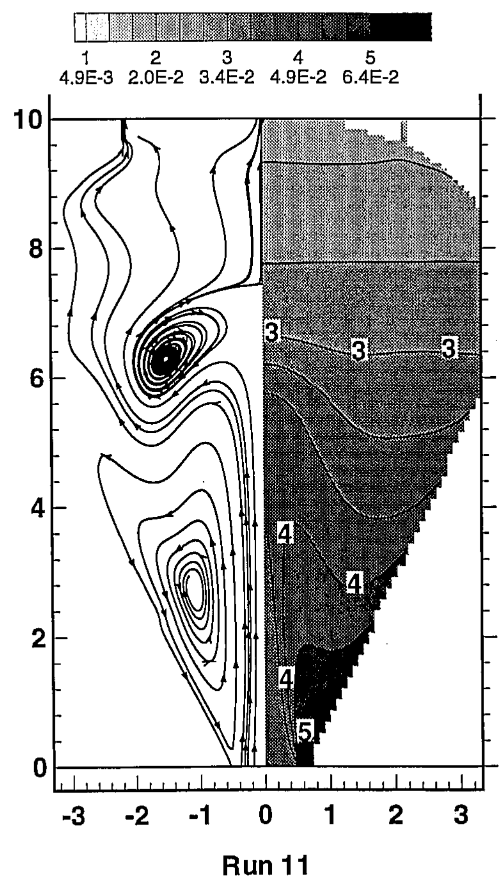

Figure 6: Particle streamlines and volume fraction contours with increased feed-pipe diameter.

The upper recirculation region is reduced considerably in size and the height that the negatively buoyant feed jet is able to attain is significantly reduced due to the lower supply velocity. This design alteration also significantly reduces the carry-over of large particles, (see Table 4). The reduction in height of the supply jet is the single most important factor in reducing the carry-over of large particles.

5. SUMMARY

The major findings of this numerical study are that the predicted flow patterns in the particleseparator show that the particle-laden supply flow stream is a negatively buoyant jet. The height this negatively buoyant jet attains is an important factor in determining the performance of the separator, with higher jets giving larger carry-over (poorer performance). The maximum jet height depends critically on the inlet velocity and the most effective way of reducing feed velocity (at the same time as keeping throughput constant) is to increase the inlet diameter. Increasing the overall height or diameter of the separator is less effective in reducing the carry-over (over the range of variation considered).

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