THE MIXING AND SEPARATION OF PARTICLE SUSPENSIONS USING OSCILLATORY FLOW IN BAFFLED TUBES

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We report experimental observations on the way in which particles that would normally sediment in a liquid, can be maintained in suspension by the use of oscillatory flow in baffled tubes. In one regime of operation, a near uniform suspension of particles can be obtained and the intensity of the particle mixing varied by control of the frequency and amplitude of oscillation. In another regime, particle concentration profiles along the tube are observed and it is shown that this effect could be used to separate particles with different sedimenting characteristics. The experimentally observed particle concentration profiles are modelled using a simple numerical scheme.

INTRODUCTION

In this paper we demonstrate that it is possible to maintain particles in suspension by using chaotic liquid phase mixing produced by oscillatory flow in baffled tubes. The effect could be of benefit to a number of process engineering applications and our objective here is to describe the main factors that control the mixing process both in terms of a physical mechanism and in relation to the effect of process variables.

The intimate mixing of particles in a liquid phase is both important and in some circumstances difficult. The impeller driven stirred tank is a traditional method for suspending particles in a liquid: numerous correlations exist to describe which states of agitation are required to keep particles of different sedimenting conditions in suspension (Zweitering, 1958, Harnby, 1985 and Nienow, 1985). An alternative possibility is the use of turbulent flow in smooth walled tubes to effect suspension and again this is well correlated: (See for example Wasp *et al.*, 1979, Okuda, 1981 and Zandi, 1971). A rule of thumb calculation typically indicates that mean tube velocities of ~3 m/s are required to maintain the suspension of sand particles. Finally, fluidization is now a widely used technique for maintaining particles in suspension within a liquid phase. An upward liquid flow maintains the particles in suspension provided a minimum fluidization velocity is achieved (see for example Davidson and Harrison, 1971). As the superficial velocity is increased above the minimum fluidization velocity, U_{mf}, the fluidized bed voidage progressively increases and in general, fluidization superficial velocities in the range U_{mf} to $3 \times U_{mf}$ are used for commercial applications.

Stirred vessels, pipe flow and fluidization all utilize steady externally applied mechanics, although rotor speeds and pumps could in principle be pulsed. In this work we wish to exploit the benefits of applying unsteadiness to the flow together with flow separation associated with the flow around sharp edges. The nuclear and other industries has for some time utilized pulsed plate columns for solvent extraction (see for example Long, 1967, Baird, 1966 and Lo *et al*, 1992) and in this paper we used a related effect associated with oscillatory flow in baffled tubes (Dickens *et al.*, 1989). If liquid is oscillated in a periodically baffled tube under appropriate conditions it is possible to generate an eddy structure that can lead to a chaotic flow within each baffle cavity (Dickens *et al.*, 1989, Howes *et al.*, 1991) and under certain conditions each cavity can behave as though it was a perfectly mixed tank. Chaotic flows, as defined by Ottino, 1989, are flows where adjacent fluid elements would separate exponentially, rather than linearly as in the case of a steady, simple shearing flow (Roberts, 1992). In order to generate a chaotic flow in a baffled tube the oscillatory Reynolds number Re_0 must exceed of order 150 where.

$$Re_0 = \frac{\omega x_0 D}{\nu} \tag{1}$$

D is the tube diameter (typically 25 mm), ω is the angular frequency of oscillation, (typically 20 rads/s) x_0 the centre to peak amplitude of oscillation, (~3 mm) and ν the kinematic viscosity ($\sim 10^{-6}$ Nm/s^2 for water).

A further dimensionless group, the stroke ratio can be used to classify the flow,

$$\text{Stroke Ratio} = \frac{2x_0}{H} \tag{2}$$

with H the distance between baffles, as well as a velocity ratio

$$\text{Velocity Ratio} = \frac{V_{\text{oscillatory}}}{V_{\text{terminal}}} \tag{3}$$

where V_{terminal} is the terminal velocity of a single particle under quiescent conditions and $V_{\text{oscillatory}}$ is defined by the oscillatory conditions of the apparatus:

$$V_{\text{oscillatory}} = 2\pi\omega x_0 \tag{4}$$

Initial findings related to the effect of fluid oscillation on the suspension of particles contained within a vertical baffled tube are explored with the system described operated in a batch mode. The primary variables examined are amplitude and frequency. Further observations on baffle geometry and concentration of particles will also be made. In the modelling analysis it is assumed that the particle beads under test are small compared to the tube and baffle dimensions, and for most experiments, the concentration of beads at any point in the tube is low (less than 10% beads/water, by mass).

0263-8762/93/$05.00+0.00

EXPERIMENTAL APPARATUS AND PARTICLE CONCENTRATION MEASUREMENTS

Experiments were performed in an apparatus that is shown schematically in Figure 1. A vertical glass tube of internal diameter 23 mm was welded to a set of Pallatine stainless steel bellows which could be oscillated by an electromagnetic oscillator in the range $x_0 = 0$ to 4 m and $\omega = 0$ to 125 rad/s. Baffles of a configuration shown in Figure 1b were inserted into the tube. There is considerable choice in relation to the choosen configuration of the baffles. We have used a baffle spacing of 1.5 times the tube diameter as recommended by Brunold *et al.*, 1988. Quantitative results reported in this paper are restricted to an orifice diameter of 7 mm giving a constriction ratio of 0.09 where the constriction ratio is defined as the ratio of the obstructed area to the total area. The tube was filled with water with a surface height approximately 140 mm above the top baffle and particles of various size, mass and density were added via the top of the tube. Typically 3 g of resin beads and 0.162 litres of water were added to the column (not including the volume of water below the base baffle). A fine stainless steel mesh was positioned below the lowest baffle in order to clearly define the volume contained by the particle beads.

Particle concentrations were measured using small optical densitometers clipped onto the side of the tubes, shown schematically in Figure 1a. The densitometers consist of light emitting diodes which transmit a collimated light beam through the tube to a small aperture solid state light detector measuring the light transmitted through the tube. Calibration of the densitometers was carried out by uniformly suspending known concentrations of particles in the oscillatory flow rig and then measuring optical transmission. A calibration curve shown in Figure 2 was established. The figure shows the calibration data points for each concentration and a correlated fit to the data which was used for subsequent concentration measurements. The fit is reasonable between 0 and 10% beads by mass which encompasses most of the range of results presented here. Using this calibration curve it was then possible to establish particle concentration at any vertical station for a given set of flow conditions by moving the detectors up and down the tube (normally positioned midway between baffles). The spatial resolution of the detectors was of order one baffle spacing and consequently these detectors were not capable of measuring, if present, any concentration profiles within each baffle.

The particles used were ion exchange resin beads approximately 0.5 mm in diameter with a sedimentation velocity in water of 45 mm/s.

EXPERIMENTAL OBSERVATIONS AND RESULTS

Experiments were carried out by placing a charge of beads into the top of the tube which had previously been filled with water. The frequency and amplitude of the applied oscillation could then be chosen by adjustment of the waveform supplied to the electromagnetic oscillator. The starting conditions for the experiment were found not to be critical. When the beads were initially poured into the tube they would either sediment directly down the tube and collect on the bottom metal mesh or would deposit on the top face of the baffles. For

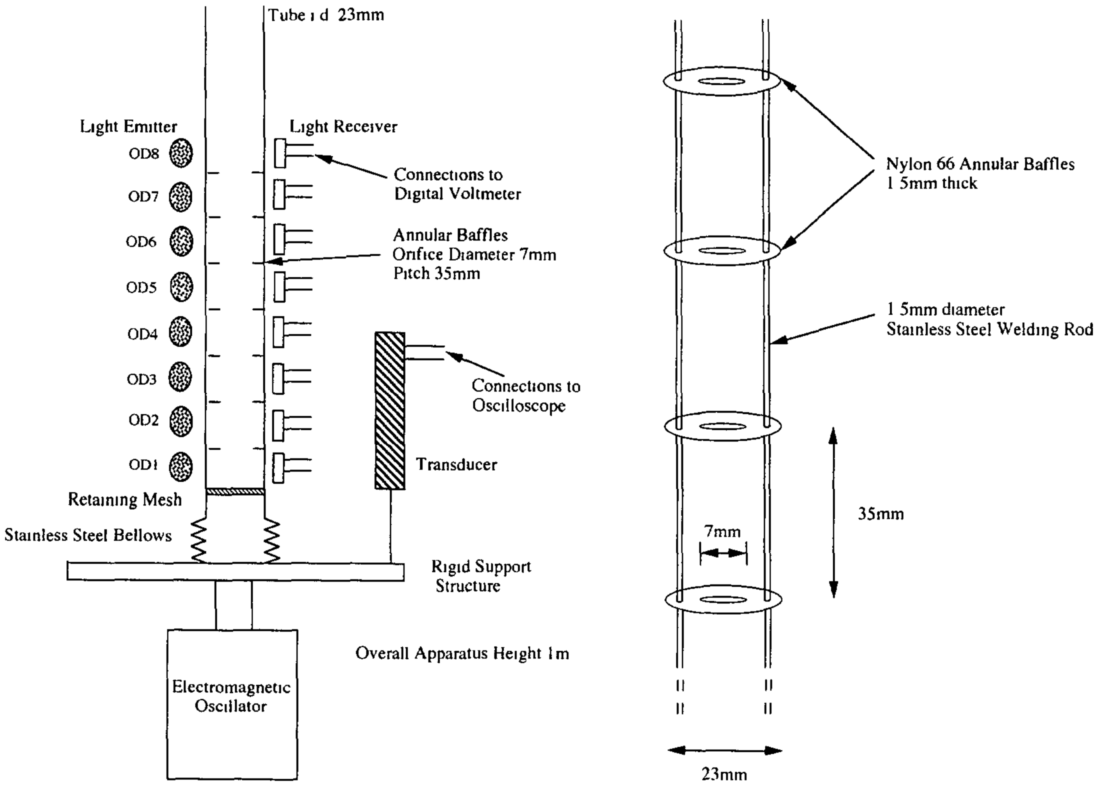

Figure 1 Schematic diagram of apparatus. (a) overall unit; (b) baffle inserts.

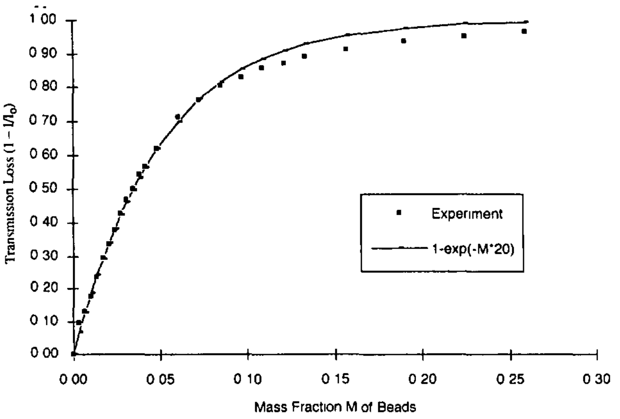

Figure 2 Calibration curve for optical detectors showing the relationship between optical transmission loss and mass fraction of beads.

all conditions reported in this paper, as soon as fluid oscillation was started the beads would become suspended within the fluid.

Small oscillations were found to keep sedimenting resin beads in suspension. For example 4 Hz and 1.5 mm amplitude ($Re_0 \approx 150$) was sufficient to prevent the beads from settling on any of the baffle surfaces or on the base of the tube for more than a fraction of a second. The flow patterns in the tube appear chaotic, with the rapid formation and disruption of vortices resulting from the oscillatory flow across the baffles. These oscillatory conditions correspond to an oscillatory pulse velocity of 38 mm/s, compared to the particle terminal velocity of 45 mm/s. Similar flow has been observed for neutrally buoyant particles suspended in pulsed baffled tubes (Dickens *et al.*, 1989). A photograph in Figure 3 gives an impression of this random particle motion in and between the baffled cells. The observed contrast within the liquid is from light scattering from the moving beads.

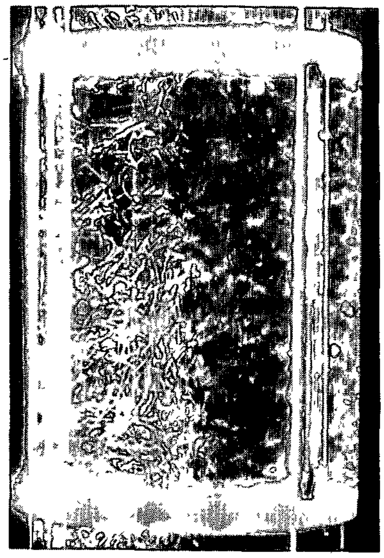

Figure 3 Photograph showing chaotic motion of particles in a baffled section of tube, tube internal diameter = 23 mm, oscillation frequency = 5 Hz, oscillation amplitude = 1 5 mm centre to peak Exposure time $\frac{1}{8}$ of a second.

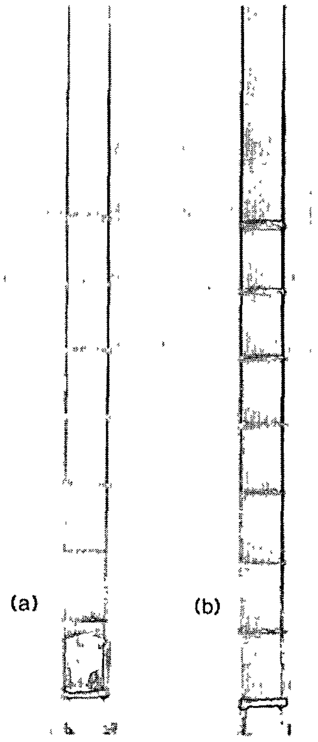

Figure 4 Photograph showing concentration profiles of particles up tube (a) 7 Hz, 1.5 mm centre-peak oscillation shows most particles concentrated at bottom of tube (b) 7 Hz, 2 5 mm centre-peak oscillation shows near uniform particle concentration The disengagement zone at the top of the tube can be seen

At 4 Hz and 1.5 mm amplitude, most of the particles were found towards the base end of the baffled tube (Figure 4a), and measurement of local bead concentration showed that the ratio of concentrations in adjacent cells was approximately constant throughout the tube. This surprising result held true for frequencies and amplitudes ranging from 4 to 20 Hz and 1.5 to 4 mm, although the value of the ratio of bead concentration in adjacent cells was found to vary with the degree of oscillation, such that at higher oscillatory velocities the bead population would tend to a more uniform distribution vertically up the tube as shown in Figure 4b. Experimental concentration profiles obtained using the optical detectors are shown in Figure 5 and the data demonstrates two conditions. At high oscillatory velocities, equivalent to several times the terminal

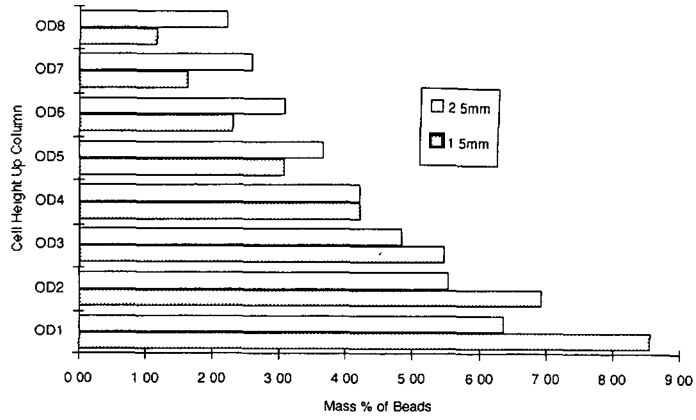

Figure 5 Plot showing concentration of ion exchange beads under two sets of oscillatory conditions Total mass %, based on mass of beds to mass of water in tube.

velocity of particles, the bead distribution appeared nearly uniform within the baffled section of the tube.

An additional phenomenon was observed at the top end of the baffled section where there appears to be a limiting height to which beads are suspended above the topmost baffle (Figure 4b). This disengagement height is relatively insensitive to the oscillatory condition and in this zone the beads are agitated to a lesser extent compared to the rest of the tube. The exact position of the disengagement zone is quite sharp and above this zone no particles were detected in the liquid. This observation is important in that it shows clearly that if no baffles are present the liquid oscillation alone in the tube is not capable of maintaining the particles in suspension. It is only when the combined effect of oscillation and vortex shedding from baffles is present the chaotic motion generated is capable of particle suspension.

If the concentration ratio between adjacent cells γ is defined as

$$\gamma = \frac{c_{n+1}}{c_n}, \tag{5}$$

then,

$$\frac{c_n}{c_1} = \gamma^{n-1} \tag{6}$$

and

$$\ln\left\{\frac{c_n}{c_1}\right\} = (n-1)\ln(\gamma) \tag{7}$$

Figure 6 shows a logarithmic plot of the concentration ratio as a function of cell number for the two conditions already presented in Figure 5. Approximately linear plots for the two logarithmic experimental concentration profiles are obtained, suggesting that to a first approximation, γ is indeed constant for specific pulsing conditions.

It was found that the particle concentration distribution (which could now be defined by γ alone) was dependent only upon the velocity of oscillation, i.e. the same particle distribution would be measured for a 4 Hz and 2 mm as for a 2 Hz and 4 mm oscillation. This dependence is shown in Figure 7 in which γ has been plotted against the ratio of oscillatory velocity to terminal velocity for a range of amplitudes and frequencies of oscillation. Also shown in Figure 7 is a correlation of the form

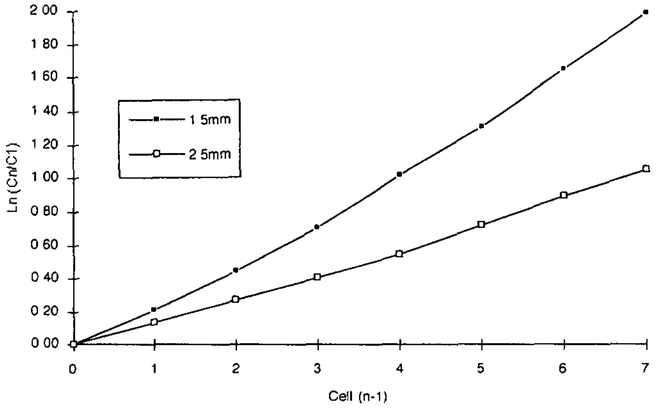

Figure 6 Logarithmic plots of cell concentration ratios plotted for two different amplitudes of oscillation.

$$\gamma = 1 - \exp\left\{-R\frac{V_{\text{oscillatory}}}{V_{\text{terminal}}}\right\} \tag{8}$$

with R a constant.

A series of experiments designed to test the sensitivity of the above correlation to various parameters found no dependence for a range of baffle spacings, orifice diameters, or particle type (similar sized sand particles with a terminal velocity of 78 mm/s). Thus, provided the fluid mechanics generated by the presence of the baffles and the oscillatory flow could generate a chaotic flow, the correlation give by equation (8) was quite generally able to predict the observed concentration profiles of particles. For the resin beads under test a best fit value for the R constant gave $R = 0.8$.

Observations were made at very high solids particle fractions. Fractions up to 30% solids by mass, which is close to the maximum packing density of the beads, could be kept in suspension. Optical measurements of concentration were not possible, but the movement of the beads appeared slower and more ordered than at the

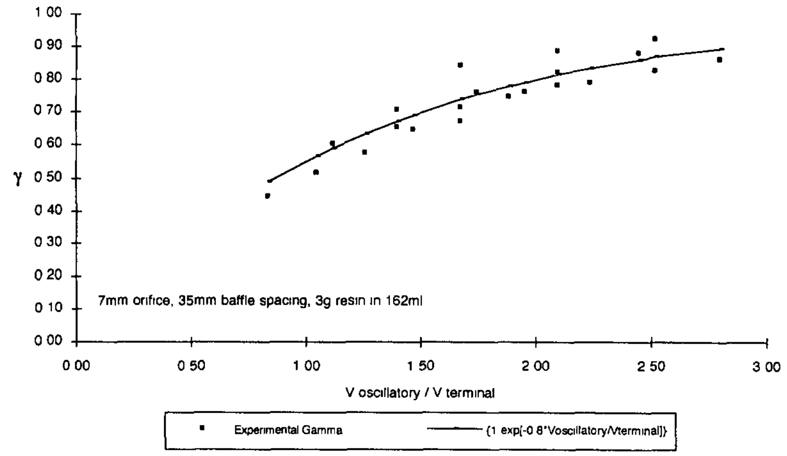

Figure 7 Graph of experimentally determined γ factor plotted as a function of $V_{\text{oscillatory}}/V_{\text{terminal}}$

lower concentration, but nevertheless remained chaotic. Under these conditions the effect of high particle concentration will affect the sedimentation velocity of the particles (Kay and Nedderman, 1985).

From the results reported here, it is clear that particles can be maintained within a confined volume in a well mixed state. If the intensity of oscillation is mild, a mixed state is achieved but with a concentration profile of particles up the tube. If the intensity of oscillation is increased, a situation can be achieved where a near uniform concentration of particles is observed within all the baffled sections of the tube. At this point γ approaches unity. A further increase in either frequency and or amplitude will result in γ remaining close to unity, but the particles will be subjected to an increasing intensity of mixing caused by an increase in the velocity fluctuations within each cell.

NUMERICAL SIMULATION OF PROFILES

Based upon the experimental results that have been described, the ratio γ of average particle concentration at steady state in adjacent cells is a constant. A model has been derived to explain this result and also propose kinetics for the progress to steady state condition.

Mechanism of Particle Suspension

The ability of baffled tubes to suspend particles under oscillating flow conditions may be put down to the particular type of fluid mechanics that is generated within each cavity. In particular, for each oscillation a vortex ring is formed at the throat of each baffle and this vortex appears to be the primary way in which sedimenting particles are held in suspension. This behaviour can, to a first approximation, be modelled as a symmetrical upward and downward flux of the particles between each baffled cavity with the number of particles being advected from one cell to the other depending on the concentration of the particles in the cell being considered. In addition to this diffusion flux, between cells there is the tendency of the particle, being of greater density than water, to sediment down to the base of the tube. Looking at the column as a whole, the diffusion flux produced by the oscillatory flow is advecting particles both up and down the tube causing a particle exchange between each baffled cavity. In addition to this there is a sedimentation flux that is driving particles downwards. A steady state situation can, however, be achieved if a particle concentration profile develops up the tube. In this situation the sedimenting contribution is balanced by the concentration inbalance in adjacent cells.

Numerical Model

The model is based upon the concept that set fractions of particles are advected up or down from each baffled cell per stroke, and that these fractions are constant for all cells in the column. In physical reality, these fractions are a combination of the fraction of liquid volume pumped from one cell to the next, and a value allowing for sedimentation effects which will be less than unity for fluid being pumped upwards (in which case the particle concentration in the fluid being pumped is less that the cell average) and vice-versa. The basis of the model is shown schematically in Figure 8.

Making the simplifying assumption that advection up and down occur simultaneously, it is possible to create a series of 1st order ordinary differential equations (ODEs) of the cell concentrations as a function of time, being analogous to a chain of stirred tanks with mass transfer in both directions.

Let V = volume of each baffled cell

c_n = concentration of beads in the nth cell (counting upwards from base to Nth baffled cell at top)

α_u = fraction of particles advected up into the cell above per s

α_d = fraction of particles advected down into the cell below per s

1st cell:

$$\begin{array}{ccc} \text{In} - \text{Out} & = & \text{Accumulation} \\ \{\alpha_d V c_2\} - \{\alpha_u V c_1\} & = & V\dfrac{dc_n}{dt} \end{array} \qquad (9)$$

n^{th} cell:

$$\begin{array}{ccc} \text{In} - \text{Out} & = & \text{Accumulation} \\ \{\alpha_u V c_{n-1} + \alpha_d V c_{n+1}\} - \{\alpha_d V c_n + \alpha_u V c_n\} & = & V\dfrac{dc_n}{dt} \end{array} \qquad (10)$$

For a system at steady state $dc_n/dt = 0$ for all cells, and the mass balances simplify to give the general result

$$\frac{c_n}{c_1} = \left\{\frac{\alpha_u}{\alpha_d}\right\}^{n-1} = \gamma^{n-1} \qquad (11)$$

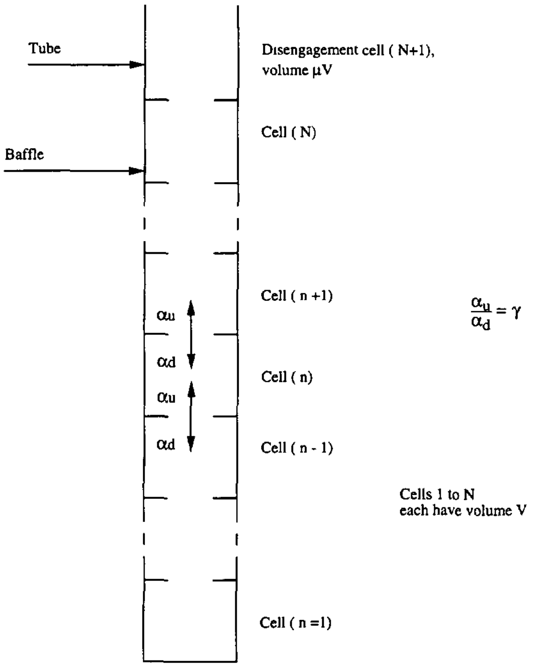

Figure 8. Schematic diagram of baffled tube model.

where γ is defined as the ratio α_u/α_d and is found to be the ratio of concentrations in adjacent cells as measured in the experimental section of this paper. α_u and α_d cannot be explicitly derived from steady state experimental results, although it is possible to derive values for known pulsing conditions and sedimentation properties by crude physical reasoning.

Unsteady State Analytical Solutions

To achieve conservation of particles in the system and allow solution of the ODEs, it is first necessary to add the disengagement zone to the model. As the presence of the zone is due to eddy mixing, it seems reasonable to model the zone in a similar manner to a baffled cell, albeit with a different volume μV where

$$\mu = \frac{\text{volume of disengagement zone}}{\text{volume of regular baffled cell}}$$

Allowing for no mass transfer of particles in or out of the top of the disengagement zone, and the fact that the volumes of suspension (and thus the 'fraction of particles') pumped are related to the baffled cell volume, we have

$$\begin{array}{ccc} \text{In} \quad - \quad \text{Out} & = & \text{Accumulation} \\ [\alpha_u V c_N\} - \{\alpha_d V c_{N+1}\} & = & \mu V \dfrac{dc_N}{dt} \end{array} \qquad (12)$$

giving the steady state result

$$\frac{c_{N+1}}{c_N} = \gamma \qquad (13)$$

which is observed experimentally where c_{N+1} corresponds to the concentration of particles between the top baffle and the disengagement zone.

Analytical solution using Laplace Transforms for system with more than 1 baffled cell and a disengagement zone ('2 cell' model) is found to be increasingly complex, and a general solution does not appear to exist. A numerical scheme was thus derived to enable solutions to be obtained for a range of α values and numbers of cells. The programme in FORTRAN 77 uses a 4th order Runge Kutta method to solve a set of coupled differential equations as described by Coulson *et al.*, 1979, with simple checks to ensure no negative cell concentrations and conservation of particles. Sample results are shown in Figures 9 and 10 for a column with 11 baffled cells and a disengagement zone, the latter having twice the volume of a regular baffled cell ('12 cell system'), with all the particles starting in the lowest cell. Concentrations are made dimensionless by dividing by the starting concentration in the base. Time is made dimensionless by multiplying by α_d (α_d is defined as a fraction per unit time). Results obtained as time tends to infinity are found to be in excellent agreement with the steady state results observed experimentally for a range of cases; agreement is also good with the analytical solution to the ODEs for the '2 cell' case.

Figures 9 and 10 show the numerically generated concentration profiles for the time evolution of the particle concentration for the initial condition that all the particles start in cell 1. In Figure 9 the γ factor chosen is $\gamma = 1$ and in this case the particle concentrations in each cell are tending towards a near uniform value. The concentration of particles in cell 1 progressively decreases and the concentration in the other cells increase as the exchange of particles proceeds between cells. A value of $\gamma = 1$ corresponds to equal flow of particles up and down the tube and consequently it is entirely reasonable to expect the profile to approach a uniform concentration.

In Figure 10 the results of the simulation are shown for $\gamma = 0.5$. In this case the downward inter-cell flux of particles is twice that of the upward flux. Thus the limiting concentrations are not uniform up the tube. The bottom cell has a higher concentration than the one above it and the steady state concentration profile is given by equation (11). The simulation shows that this steady state is approached relatively quickly. Experimentally, we found that for $\gamma = 0.5$ conditions, an equilibrium concentration profile appeared to be reached within about 10 seconds.

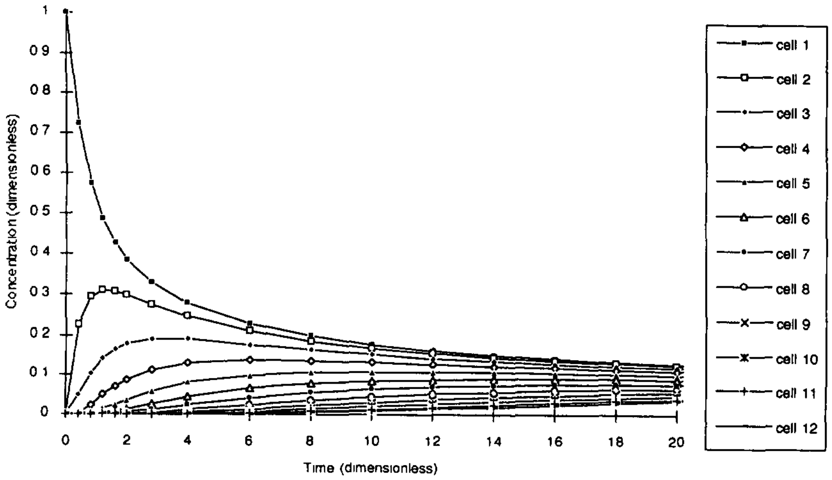

Figure 9 Plot of numerically generated concentration profile against time for a column with 12 cells and a disengagement zone twice the cell volume. $\gamma = \alpha_u/\alpha_d = 1$

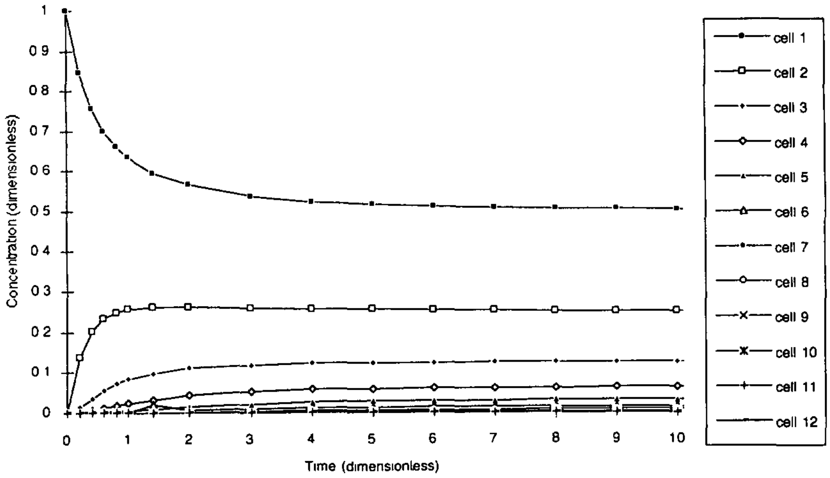

Figure 10 Plot of numerically generated concentration profile against time for a column with 12 cells and a disengagement zone twice the cell volume $\gamma = \alpha_u/\alpha_d = 0.5$

Depending on the chosen value of γ, the simulation is therefore capable to a first order approximation of predicting both the steady state concentration profile and the kinetic response to that steady state for an arbitrary starting condition.

DISCUSSION AND CONCLUSIONS

The key observation reported in this paper is the ability of oscillatory flow in baffled tubes to maintain sedimenting particles in suspension. We have demonstrated that the effect works for a 23 mm internal diameter baffled tube with particles of order 0.5 mm in diameter. It is our belief that there is a considerable range of particle size that could be suspended in this way and initial estimates range from a few microns to several centimetres. In addition, the device should scale up, where large diameter tubes with multiple baffle arrays could be envisaged. There also remains considerable scope for baffle design and optimization.

In one mode of operation, we have shown that it is possible to suspend particles such that a population profile up the tube is quickly obtained. If the particles naturally sediment, the largest concentration of particles will be at the bottom of the tube. If the particles naturally rise, the highest concentration will be in the top cells. When a greater state of agitation is applied by either increasing the frequency and/or increasing the amplitude of oscillation, it is possible to obtain a near uniform population of particles up the tube. Both the amplitude of oscillation and the frequency of oscillation have been found to be very sensitive controls on the extent of mixing achieved and these two variables can be ‘fine tuned’ to give the exact state of mixing required within the vessel.

To a first approximation, we have shown that the system can be modelled as a series of stirred tanks corresponding to each cavity between adjacent baffles. Superimposed on these well mixed cells is an asymmetric upward and downward flux brought about by sedimentation and flotation and the chaotic motion. This asymmetry is reflected in the γ factor introduced in this paper. When $\gamma = 1$ no asymmetry exists and when say $\gamma = 0.5$, there is a considerable migration of particles due to sedimentation. In Figure 7 we have generated an experimental correlation that shows that the γ factor largely depends on the ratio of the particles sedimentation velocity to the fluid oscillation velocity. From a knowledge of the particle sedimentation characteristics (Perry, 1984) and a suitable choice of oscillation conditions, it is therefore possible in principle to predict the type of population profile that can be expected.

For the effect to work it is essential that both fluid oscillations and baffles are present. In addition, the oscillatory Reynolds Number Re_0 should be greater than of order 150 and from the results reported here it would appear that a γ factor greater than about $\gamma = 0.5$ should also exist. It is not obvious to us why this chaotic flow can keep the particles in suspension because, for example, if oscillation of equal or greater intensity alone exists in the tube and the baffles are not present, the particles will sediment in nearly the same way as in a quiescent tube. This is clearly demonstrated by the sharp disengagement zone observed above the top baffle in the tube. When the eddy interaction from the top baffle disappears, no particles can be seen in the axial oscillatory flow. This disengagement effect thus ensures that particles are constrained to exist within the baffled region of the flow and this result offers considerable potential benefit for liquid solid separation both in batch and continuous mode of operation.

The effect works not only for solids concentrations of order 0–10% by mass reported in this paper, but also at concentrations as high as 30% where strong particle interaction must be taking place. The underlying feature of the particle mixing is the chaotic liquid flow; particle collisions happen, but do not appear to be a necessary part of generating the overall observed chaotic motion of the particles.

We have made preliminary tests on a system containing two types of particles with different sedimenting characteristics namely 45 mm/s and 78 mm/s. In this situation it is possible to tune the device to have a near uniform concentration of the lower sedimenting velocity particles and a profiled concentration gradient for the higher sedimenting particles. It is then possible to separate the particles because at the top of the tube there is dominantly the particle type with the lower sedimenting velocity. The device could in principle be used for size separation of an initially mixed set of particles.

An important aspect in the use of oscillatory flow in baffled tubes is the control possible for the extent of mixing achieved. For the system used the practical frequency range of operation was 1 to 20 Hz and the amplitude could be varied between about 0–6 mm. This gives effectively a factor of 100 variation in mixing intensity. At the low end, the mixing is chaotic but gentle and at the other end the flow is still chaotic but the level of mixing very intense. As the intensity of mixing increases then the energy input into the device increases but it is our belief that at all frequencies and amplitudes tested the device will prove to be energy efficient and we hope to establish this part quantitatively in future work

A wide scope for potential applications of the device is apparent. The obvious application is to use the device as a mixing vessel; enhanced heat transfer previously reported for single phase fluids (Mackley *et al.*, 1990) should mean that the device has interesting possibilities as a reactor and possibly a catalytic reactor Other possible application areas include size separation, dissolution and crystallization. All these operations could be envisaged in batch or continuous mode of operation which should mean that oscillatory flow fluid mechanics could have a significant effect on a number of future process engineering applications. Of course, the added complication of having to oscillate the flow needs to be considered as this can be a non trivial factor, particularly at large scale and at high frequencies.

NOMENCLATURE

α_u	fraction of particles advected up into the cell above per s
α_d	fraction of particles advected down into the cell below per s
ω	angular frequency of oscillation, rad/s
x_0	centre to peak amplitude of oscillation
μ	constant volume multiplier for the disengagement zone
v	kinematic viscosity Nm/s^2
c_n	concentration of particles in the nth cell
D	internal tube diameter mm
H	periodic spacing between baffles
I	intensity of light transmission through water and particle mixture
I_0	intensity of light transmisson through water only
M	mass fraction of solids in suspension
OD	optical densitometer
R	constant
Re_0	oscillatory Reynolds Number
U_{mf}	minimum fluidization superficial velocity for a fluidizing bed
V	volume between two adjacent periodically spaced baffles
$V_{oscillatory}$	oscillatory velocity of fluid in tube
$V_{terminal}$	constant velocity of particle in fluid in quiescent conditions

$$Re_0 = \frac{\omega x_0 D}{v} \qquad \text{Stoke Ratio} = \frac{2x_0}{H}$$

$$\text{Velocity Ratio} = \frac{V_{oscillatory}}{V_{terminal}} \qquad V_{oscillatory} = 2\pi\omega x_0$$

$$\mu = \frac{\text{volume of disengagement zone}}{\text{volume of regular baffled cell}}$$

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ACKNOWLEDGMENTS

We would like to thank Professor John Davidson for providing every encouragement to conduct novel Final Year Part II Chemical Engineering research projects and this paper reporting an alternative means of particle fluidization is dedicated to him on his retirement as Shell Professor in Chemical Engineering We would also like to thank the British Technology Group for their interest in this work

ADDRESS

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The manuscript was received 13 September 1993 and accepted for publication after revision 29 October 1993