EXPERIMENTAL FLUID DISPERSION MEASUREMENTS IN PERIODIC BAFFLED TUBE ARRAYS

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Abstract—We report experimental flow pattern and associated residence time distribution measurements for multipass and multitube arrays where periodic baffles and fluid oscillation may be present. The observations show that controlled mixing and well-defined residence time distributions can be obtained for both the engineering configurations tested. In addition, a single parameter axial dispersion coefficient is determined and it is shown that dispersion using oscillatory flow in baffled tubes can be less than axial dispersion for a turbulent net flow.

INTRODUCTION

Efficient fluid mixing within chemical engineering devices is an important ingredient required for process engineering units, and dominates considerations in relation to heat, mass transfer and product uniformity. In the 1960s pioneering work within the nuclear industry showed that fluid oscillation in sieve plate columns could produce effective two-phase mixing of immiscible liquids and the columns were successfully used for enhanced solvent extraction (see, for example, Longsdail and Thornton, 1957; Long, 1967; Lo and Baird, 1987). In the 1970s Bellhouse *et al.* (1973) demonstrated the utility of fluid oscillation in furrowed channels for enhanced membrane transfer and Sobey *et al.* (1980) successfully numerically predicated flow patterns in this geometry. It has been demonstrated that, by combining oscillation with periodically spaced baffles in a tube, vigorous eddy mixing can be achieved between baffles, leading to excellent mixing (Brunold *et al.*, 1989) where events at the wall are similar to events at the centre of the tube. As a consequence of this, a sharp (or near plug flow) residence time distribution (RTD) can be achieved at moderately low Reynolds numbers in a single-tube device operated either horizontally (Dickens *et al.*, 1989) or vertically (Mackley and Ni, 1991). The implication from these results suggests that the fluid mechanics generated by this means could be extended to different tube array arrangements, and in this paper we present our experimental findings on flow patterns, RTD and fluid dispersion measurements in a multipass apparatus and flow patterns and RTD measurements in a multitube configuration. These configurations are of potential importance in terms of design for continuous reactors and other process units.

Modelling of the fluid mechanics associated with oscillatory flow in baffled tubes has been carried out by Sobey (1980), Howes (1988) and Howes *et al.* (1991). The oscillatory Reynolds number, Re_o, that these simulations can be reliably taken to is of order 300–400. This paper is concerned with fluid mixing and RTDs where the values of Re_o is well above this limit and consequently comparison with numerical predications would be dubious. However, the experimental conditions described in this paper are in the range of potential commercial operation of the device where very effective mixing and RTD characteristics are obtained.

This paper investigates a range of fluid mechanical regimes. Firstly, as a basis for comparison with usual configurations, data are obtained for both laminar and turbulent flows when no baffles and oscillations are present. Secondly, the introduction of baffles with a net flow only covers the static mixer regime and these again are examined at modest and high Reynolds number. Finally, the regime where both baffles and fully reversing flows are present is examined, and in this case the net flow Reynolds number is generally kept below that of the oscillatory flow Reynolds number.

THE FLUID MECHANICS

The fluid mechanics within a baffled tube is controlled by the geometrical configuration of the baffles and two dimensionless groups, the oscillatory Reynolds number, Re_o, and the Strouhal number, St, defined as below, respectively:

$$Re_o = \frac{D\omega X_o}{\nu} \tag{1}$$

$$St = \frac{D}{4\pi X_o} \tag{2}$$

where ω is the angular frequency of oscillation (rad/s) and X_o the centre to peak amplitude of oscillation (m), D the tube diameter (m) and v the kinematic viscosity (m^2/s). If there is an additional net flow along the tube, a net flow Reynolds number, Re_n, is also relevant, given as

$$Re_n = \frac{DU}{v} \qquad (3)$$

where U is the superficial net flow velocity through the tube (m/s).

EXPERIMENTAL FACILITIES AND PROCEDURE

The multipass apparatus is shown schematically in Fig. 1. The device consists of five 25 mm I.D., 1.0 m long Perspex tubes. These tubes are operated vertically and connected by four commercially available plastic bends having a central radius of curvature 160 mm. The straight sections and bends form a single-flow path of about 6.3 m in total length. The objective of using this configuration was to simulate a long RTD process unit and explore the effect of bends. When present, there are 27 baffles in each straight section of the tube and eight baffles in each 180° bend. The baffles are spaced three tube radii apart within each straight section and are also approximately in these positions around the bends. This baffle spacing

was optimized by Brunold et al. (1989) from interpretation of flow visualisation photographs to be the optimal baffle spacing for effective mixing over a broad range of amplitudes. The baffles were made from copper and supported by two 2 mm diameter longitudinal rods. The baffles were designed to give a "push fit" seal when positioned in the tubes. They occupied 34% of the tube cross-sectional area. The process fluid entered at the bottom of the far right tube shown in Fig. 1 and the exit port was taken from the top of the far left tube. The net flow was provided by an adjustable liquid pump from LOWARA. The flow rates were monitored by a digital flow meter and recorded simultaneously by a IBM computer. Fluid oscillation was achieved by means of a pneumatic cylinder from BOSCH at the flow entry. A non-return valve was also incorporated in the flow inlet in order to minimize propagation of fluid oscillation upstream of the inlet fluid. A frequency range of 0.5–9 Hz could be obtained by an oscillation drive-control unit. Different amplitudes of the oscillation were controlled by using different lengths of stoppers placed on the shaft of the pneumatic piston. The motion of the piston oscillation is essentially a square wave pulse and the displacements of the movement were measured by a Sangamo linear transducer and recorded by a computer.
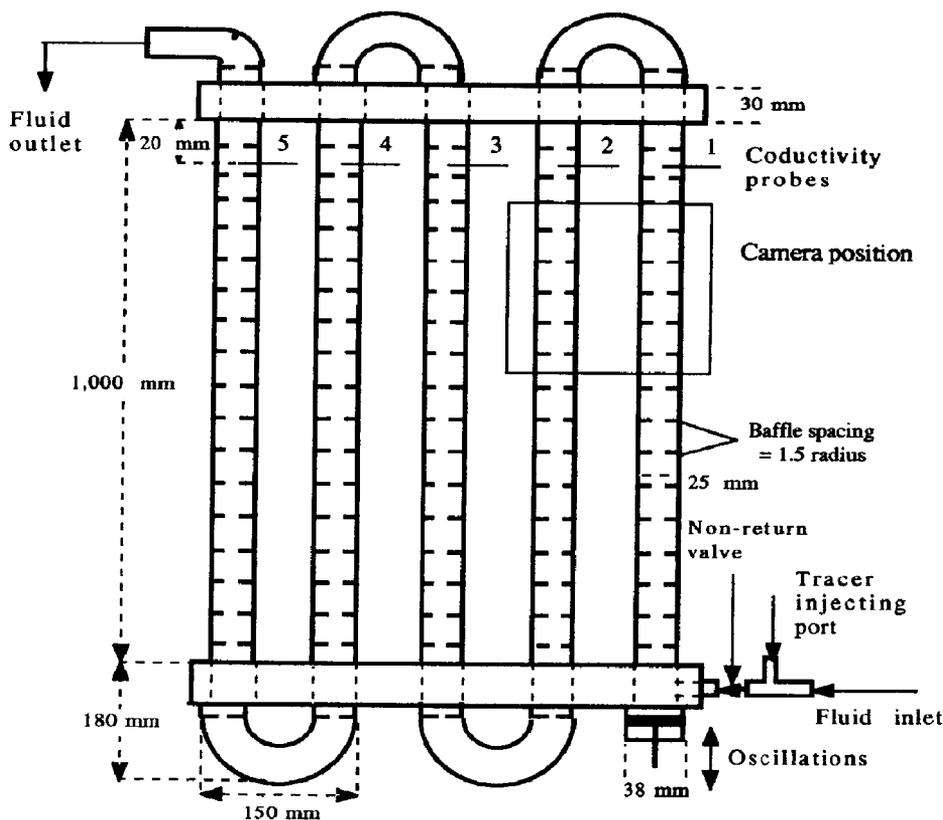

Fig. 1. The multipass apparatus.

Point conductivity probes manufactured by the Cambridge Environment Research Consultants were positioned at five locations, as shown in Fig. 1. Tracer experiments could be carried out by injecting a known amount of NaCl at the entry port and then following the time evolution of the trace at the respective probe positions. The signals from these probes are fed into a conductivity meter unit, where the data are converted into voltage signals. Those voltage signals together with the signals from the displacement transducer and from the flow meter are connected to a CED1401 module, which is a peripheral, capable of generating and receiving wave forms, digital and timing signals, under control of a computer. Data from the CED1401 module can be then filed onto a disc or plotted.

Experimental procedure

Flow visualisations and tracer measurements studies were carried out in a similar way to that described in Mackley and Ni (1991). When baffles were not present, the tracer profiles particularly in the multi-tube experiments were found to be very sensitive to the injection conditions. When baffles and oscillations were present tracer profiles were not very sensitive to injection conditions and reproducible results could be readily achieved. Typically 20 ml of 60 g/l NaCl was injected over a period of 3 s. In all cases the process fluid was water at room temperature.

RESULTS

Experiments in multipass rig

We present flow visualization photographs for the multipass apparatus. The solution containing polyethylene particles (20 ml) was injected into the entry port and after a time delay visualisation of the particles was made at certain positions within the apparatus.

Visualizations, no baffles. The position of the camera is shown in Fig. 1 for the multipass rig. The photographs were taken when the tracer particles could be seen in both the first riser tube (right-hand side) and the first downcomer tube (left-hand side). In the case shown in Fig. 2 this occurred 3 min after injection. The photograph shows that as expected for the laminar fluid motion the streak lines are dominantly axial. However, from the length of the particle streaks it would appear that the velocities in the downcomer were higher than the riser. This effect is due to the radial velocity profile within the tube and the photograph was taken when the nose of the particle front was in the downcomer. The particles on the left-hand tube were the faster moving central ones whilst the particles on the right-hand side were the slower moving ones that were initially positioned near the outer radii of the tube. The photograph clearly illustrates the difficulties in dispersion associated with the laminar flow.

Figure 3 shows the situation where a laminar net flow of $Re_n = 212$ is applied together with fluid oscil-
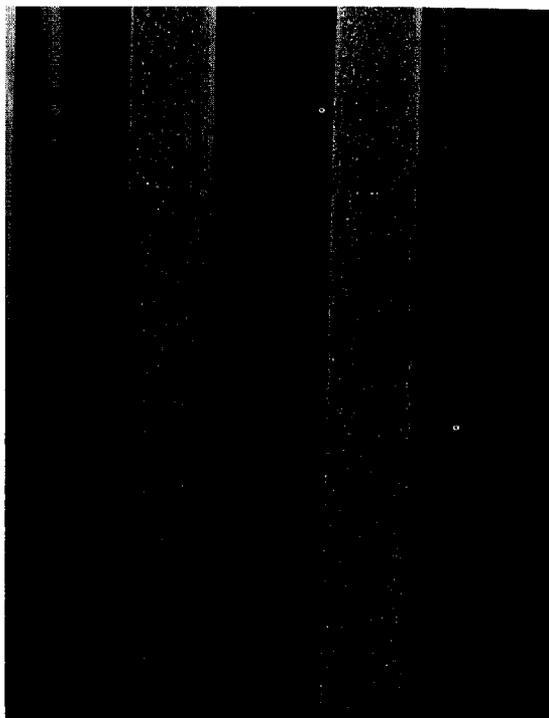

Fig. 2. Flow profile for laminar flow in a multipass rig. Tracer = polyethylene mixed in 60 g/l NaCl, bulk fluid = water. No baffles. $Re_n = 212$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm, net flow: up in the right tube, then down in the left tube.

lation without the presence of baffles and $Re_o = 2324$ and $St = 0.5$. The situation is similar to that shown in Fig. 2 and the axial motion dominates. Again low velocity particles are seen near the wall on the right-hand tube and high-velocity particles on the left-hand side.

Figure 4 shows the situation for a net flow of $Re_n = 2121$ where we believe the flow to be turbulent. This Reynolds number was the highest we could achieve with our experimental equipment, and the entry and bends in the system appear to ensure that we have passed the laminar turbulent transition. In this picture the delay time of about 15 s for photographing after injection was considerably reduced to the previous case. The photograph shows the high concentration of central particles passing down the left tube and the lower concentration of particles that are left near the walls on the right-hand side. The flow trajectories appear to be dominantly axial although some radial motion can be seen in the photographs. The photograph again shows that even with a turbulent flow, the slow-moving particles reside near the wall of the tube after the bulk of the particle have passed through.

Visualizations, with baffles. Figure 5 shows the initial effect of the introduction of baffles with a low net
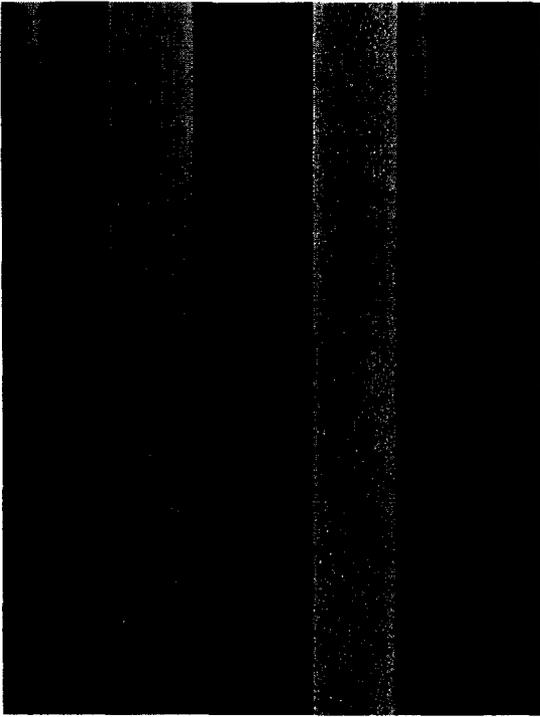
Fig. 3. Flow profile for oscillatory flow in a multipass rig. Tracer = polyethylene mixed in 60 g/l NaCl, bulk fluid = water. No baffles. $Re_n = 212$, $Re_o = 2324$, $St = 0.5$. Tube diameter = 25 mm, net flow: up in the right tube, then down in the left tube.
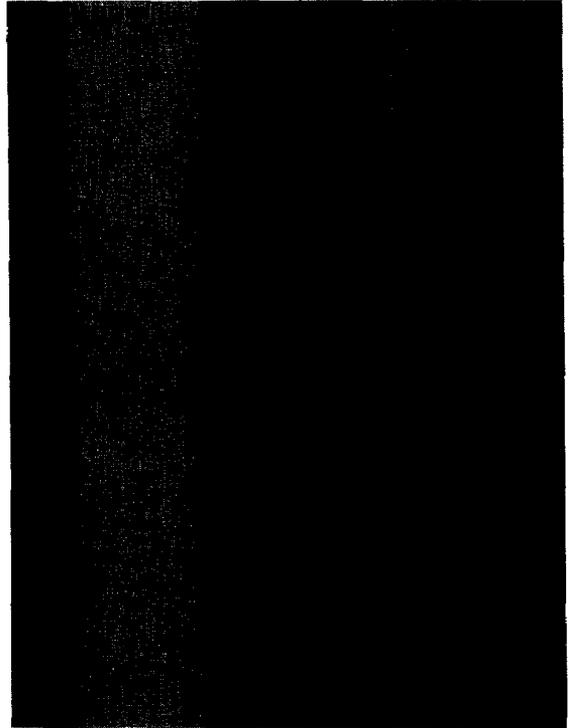

Fig. 4. Flow profile for turbulent flow in a multipass rig. Tracer = polyethylene mixed in 60 g/l NaCl, bulk fluid = water. No baffles. $Re_n = 2121$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm, net flow: up in the right tube, then down in the left tube.

flow $Re_n = 212$. Recirculating trapped vortices (Howes, 1988; Howes et al., 1991; Rowley and Patanker, 1984) behind each baffle are present, but difficult to see in the photograph. The overall impression is that of an axial flow.

Figure 6 contrasts significantly with those shown previously and this photograph corresponds to a situation where both baffles and oscillation are present. Here the chaotic advected flow generates good global mixing in both tubes and the particles uniformity throughout the tubes is clearly seen.

Finally in this series of photographs Fig. 7 shows the flow pattern where a high Reynolds number is applied in the presence of baffles but no oscillations. This picture shows apparent similarities to Fig. 6 and the unsteady eddy shedding behind each baffle (Howes et al., 1991) again generates good global mixing.

Concentration profiles, no baffles. The observed concentration profiles for the flow regimes described above, reflects the global response of the fluid mechanics that has been seen. In the multipass apparatus probes 1 and 2 indicated in Fig. 1 were positioned at the centre of the tube and the probes 3–5 near the walls. Figures 8–12 show plots of tracer concentration

measurements as a function of time for each five probe positions.

Figure 8 shows the case for no baffles at a laminar flow of $Re_n = 212$ in the absence of fluid oscillations. The tracers were found to be very sensitive to the injection conditions and all tracers were broad and generally not well defined.

The application of fluid oscillation in the absence of baffles made some difference to the tracers particularly for probes downstream of bends and there is the strong suggestion that the bends had some effect on the fluid mechanics (Fig. 9). The observation appears to be consistent with the published works on fluid mixing due to the introduction of right angle bends (Nigam and Nauman, 1985; Morris and Dutton, 1991). If the net flow was increased to yield a Re_n of 2121, the mean residence time correspondingly decreased and the profile shapes sharpened as shown in Fig. 10. In this flow regime we believe the flow to be turbulent. The RTD in this situation is well defined, reproducible and relatively independent of injection conditions. The mean residence time is inevitably greatly reduced because of the increase in Re_n.

Concentration profiles, with baffles. If baffles were introduced with a low net flow $Re_n = 212$ in the absence of oscillations, the concentration profiles re-
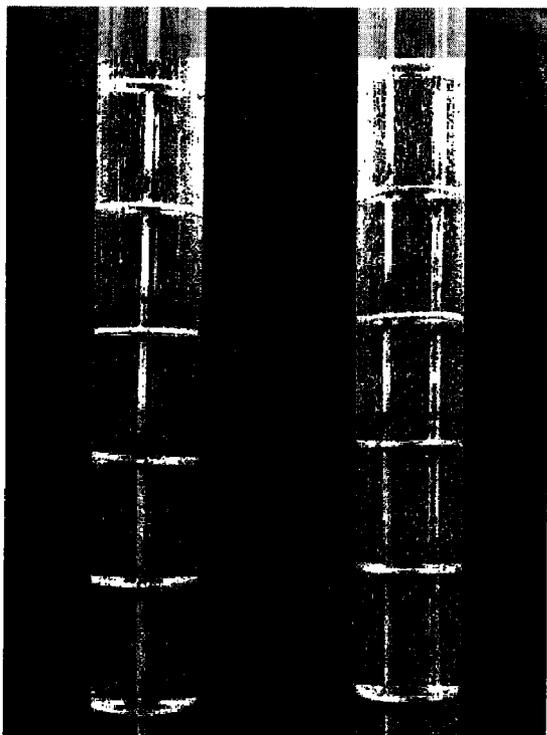
Fig. 5. Flow profile for laminar flow in a multipass rig. Tracer = polyethylene mixed in 60 g/l NaCl, bulk fluid = water. With baffles. $Re_n = 212$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm, net flow: up in the right tube, then down in the left tube.
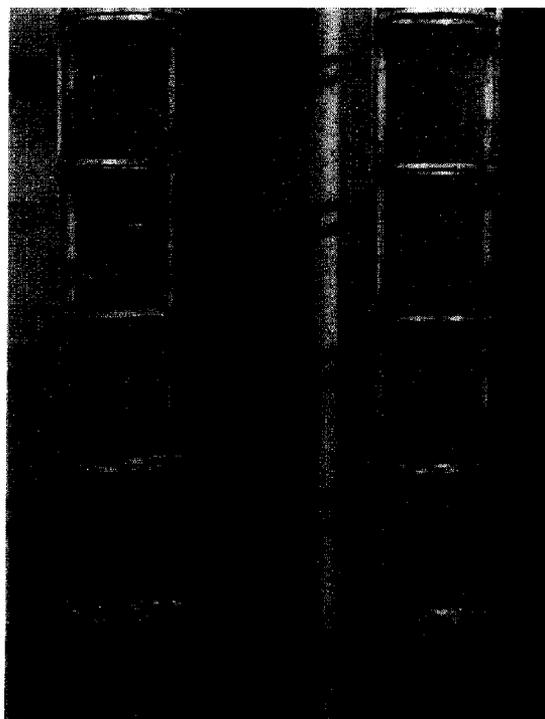

Fig. 6. Flow profile for oscillatory flow in a multipass rig. Tracer = polyethylene mixed in 60 g/l NaCl, bulk fluid = water. With baffles. $Re_n = 212$, $Re_o = 378$, $St = 1.66$. Tube diameter = 25 mm, net flow: up in the right tube, then down in the left tube.

mained irregular and broad, and sensitive to injection, similar to those shown in Fig. 8.

Figure 11 shows the situation when both baffles and oscillations are present and $Re_n = 212$, $Re_o = 378$ and $St = 1.66$. In this case because of the low Reynolds number the mean residence time is high, and the baffles and fluid oscillation provide good mixing resulting in well defined near symmetrical concentration profiles which to a first approximation are of a Gaussian form.

Figure 12 shows the concentration profiles obtained at a high flow rate but without fluid oscillation in the baffled tube array. The measured profiles display a sharp profile which is also of a Gaussian form and similar to those shown in Fig. 11. The mean residence time of the fluid is greatly reduced from the oscillatory flow case. At the high net flow Reynolds number 2121, with no fluid oscillation, the residence time distributions for the unbaffled tube (Fig. 10) and the baffled tube (Fig. 12) appear to a first approximation to be similar. Closer inspection shows that the unbaffled tube data have a longer tail to the distributions associated with low velocities near the wall.

In summary, good fluid mixing can be achieved in the multipass unit either by oscillatory flow or by a high net flow in the baffled tube array. Control of

mean residence time can be achieved in the oscillatory flow case.

Dispersion modelling using multipass data

In order to quantify some of the dispersion data described for the multipass rig we choose to model the flow in terms of plug flow with axial dispersion. This model is particularly appropriate to flows where oscillation and baffles are both present. The nature of the fluid mechanics ensures good radial mixing within the tube and the level of axial dispersion depends in particular on both Re_o and St (i.e. amplitude of oscillation). We also compare the oscillatory-flow axial dispersion coefficients with axial dispersion coefficients derived from the turbulent flow data with no oscillation and/or baffles present. The model of axial dispersion in plug flow is not appropriate for the laminar flow regimes with no oscillation and/or baffles.

The equation governing the axial dispersion for the oscillatory flow is

$$\frac{\delta C}{\delta t} = D \frac{\delta^2 C}{\delta^2 x} - U \frac{\delta C}{\delta x} \qquad (4)$$

where C is the concentration of species (g/l), U the mean axial velocity of flow (m/s) and D the absolute
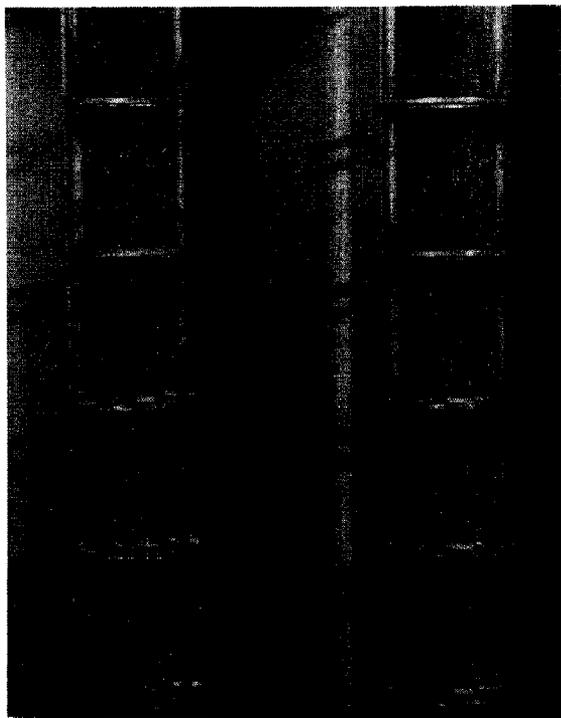
Fig. 7. Flow profile for turbulent flow in a multipass rig. Tracer = polyethylene mixed in 60 g/l NaCl, bulk fluid = water. With baffles. $Re_n = 2121$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm, net flow: up in the right tube, then down in the left tube.
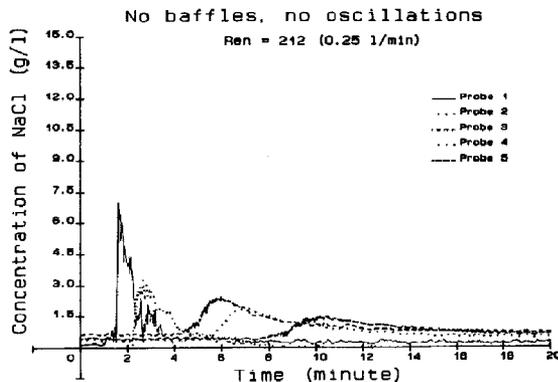

Fig. 8. Concentration measurement for laminar flow in a multipass rig. Tracer = 60 g/l NaCl, bulk fluid = water. No baffles. $Re_n = 212$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm.

Fig. 9. Concentration measurement for oscillatory flow in a multipass rig. Tracer = 60 g/l NaCl, bulk fluid = water. No baffles. $Re_n = 212$, $Re_o = 2324$, $St = 0.5$. Tube diameter = 25 mm.

Fig. 10. Concentration measurement for turbulent flow in a multipass rig. Tracer = 60 g/l NaCl, bulk fluid = water. No baffles. $Re_n = 2121$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm.

Fig. 11. Concentration measurement for oscillatory flow in a multipass rig. Tracer = 60 g/l NaCl, bulk fluid = water. With baffles. $Re_n = 212$, $Re_o = 378$, $St = 1.66$. Tube diameter = 25 mm.

axial dispersion coefficient (m²/s). This equation can be solved for the appropriate boundary conditions of our problems and the details are given elsewhere (Mackley and Ni, 1991). By using an imperfect pulse technique (see, for example, Goebel et al., 1986) eq. (4) can be numerically solved between the two probe positions. The upstream experimental profiles and the
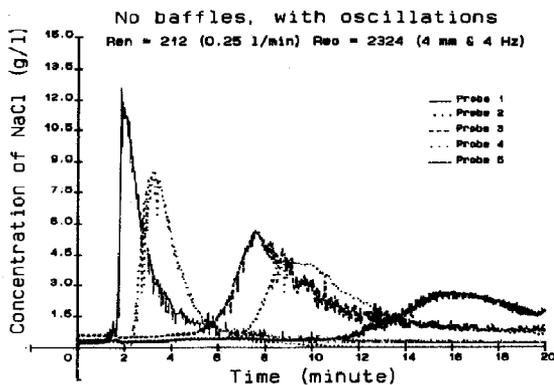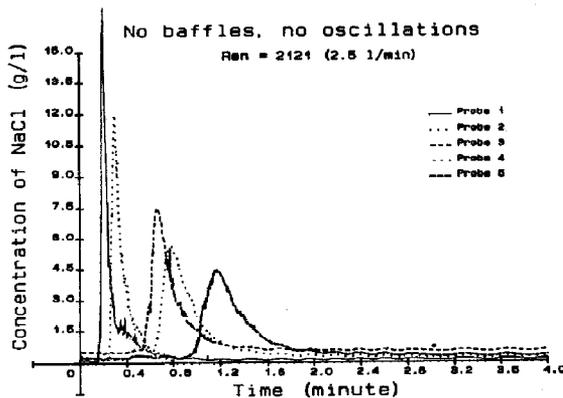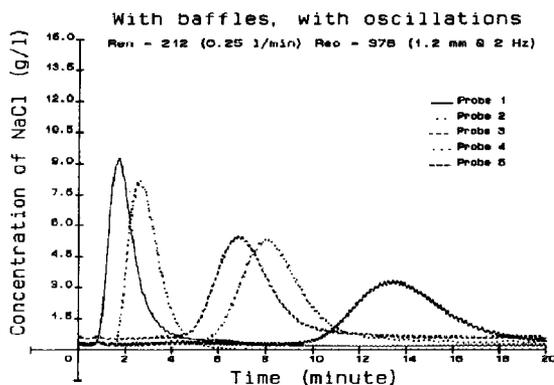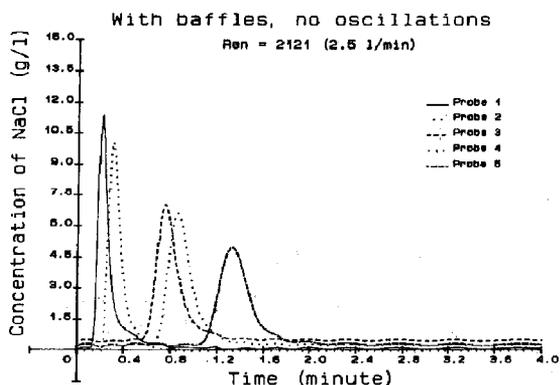
Fig. 12. Concentration measurement for turbulent flow in a multipass rig. Tracer = 60 g/l NaCl, bulk fluid = water. With baffles. $Re_n = 2121$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm.

Dispersion results

From the concentration profiles that we have already reported it would appear that realistic modelling using the axial dispersion model can only be systematically applied to the cases where baffles are present in the tubes and either when the fluid oscillation is applied or where Re_n is above of order 400. In both these situations the tracer profiles are of a near Gaussian form.

When fluid oscillation and baffles are present, axial eddy dispersion develops above an oscillatory Reynolds number of order 100. For a given amplitude of oscillation the dispersion coefficient then appears to be relatively independent of the oscillation frequency, i.e. Re_o. Figure 13 shows the axial dispersion coefficient that was calculated using data from probes 2 and 3. The results show that the absolute magnitude of the dispersion coefficient is relatively independent of Re_o and Re_n for the Strouhal number tested. Further, experiments were carried out at a fixed frequency of $\omega = 12.6$ rad/s and a plot of the absolute axial dispersion coefficient as a function of $1/St$ is given in Fig. 14. These data show a trend for low values of Re_n reported initially by Dickens et al. (1989), namely that as the amplitude of the oscillation is increased (i.e. $1/St$ increased) the dispersion appears to go through a minimum at an amplitude of order 0.5–1.0 mm centre to peak oscillation. At higher amplitude the dispersion increases. At higher values of Re_n the dispersion is less sensitive to the amplitude of oscillation, i.e. $1/St$, which reflects the fact that the fluid mixing in this case is influenced by the net flow. For low values of Re_n the data also appear to indicate that the pipe bend has, under the conditions tested, no significant effect on the observed dispersion.

Table 1 shows the calculated dispersion coefficients for two particular cases giving the values of the dimensionless group, D/uL, and the absolute value of the dispersion coefficient D, for different probe positions. In each case the absolute dispersion around the bends alone between probes 1 and 2, 3 and 4 are similar and within our experimental resolution.

The values of D/uL and D obtained for the multipass system are compared with data reported previously for single pass systems (see, for example,

model are used together to predict the downstream probe profile and the numerical program iterates to determine a best fit value for both the mean axial velocity U and the dispersion coefficient D.

Dispersion between the probe positions 2 and 3 were generally considered for the multipass rig. This involved the flow along two full straight sections and one bend with a total path length of $L = 2270$ mm. Additional dispersion measurements were also made between the probe positions 1 and 2, and 3 and 4. Each of these involved one bend only ($L = 350$ mm). It was found that the calculated dispersion between the probe position 1 and 2, 3 and 4 were in close agreement.
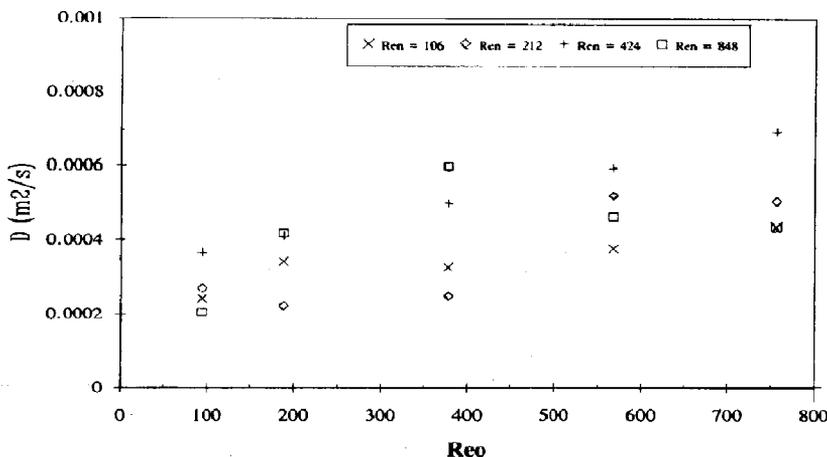

Fig. 13. Axial dispersion coefficient D as a function of the oscillatory Reynolds numbers for the multipass rig containing baffles. Measurements taken between probes 2–3, $St = 1.66$.
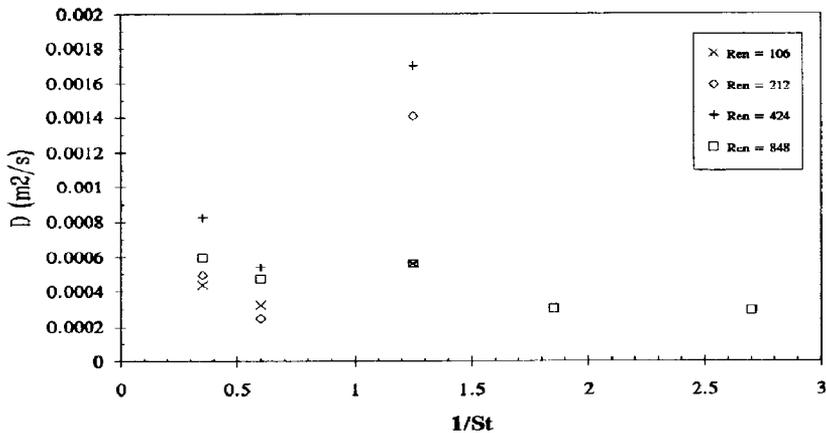
Fig. 14. Axial dispersion coefficient D as a function of the reciprocal Strouhal numbers for the multipass rig with baffles. Measurements taken between probes 2–3, $\omega = 12.6$ radians/s.

Table 1. The calculated D/uL and D for different probe locations (tube contains baffles)

Cases	I	II
Re_o	378	1696
Re_n	848	848
St	1.66	0.37
D/uL ($L = 0.35$ m) probes 1–2	0.012	0.014
D/uL ($L = 0.35$ m) probes 3–4	0.019	0.028
D/uL ($L = 2.27$ m) probes 2–3	0.0033	0.0067
D (m^2/s) ($L = 0.35$ m) probes 1–2	0.00021	0.00025
D (m^2/s) ($L = 0.35$ m) probes 3–4	0.00033	0.00049
D (m^2/s) ($L = 2.27$ m) probes 2–3	0.00029	0.00059

Table 2. Comparison of D/uL and D for single pass and multipass units

	Multipass rig	Mackley and Ni (1991)	Dickens et al. (1989)
Re_n	106	128	120
St	1.66	1.66	1.81
Re_o	378	377	622
u_{mean} (m/s)	0.0042	0.0051	0.0048
L (m)	2.27	0.37	0.67
D/uL	0.02915	0.0513	0.054
D (m^2/s)	2.81×10^{-4}	9.68×10^{-5}	1.74×10^{-4}

Dickens et al., 1989; Mackley and Ni, 1991) and the consistence of the data for the units are shown in Table 2.

The low net flow Reynolds numbers employed in the oscillatory flow work means that the mean residence times in the device ranged from 4 to 10 min between the stations 2 and 3. If the fluid mixing is generated by the net flow alone the net flow Reynolds number must in general be higher and in consequence the mean residence time will be significantly reduced. The relation between the mean residence time and the net Reynolds numbers is shown in Fig. 15. Obviously, long mean residence times are achieved with low values of Re_n. Fluid oscillation in the presence of

baffles enables these low values of Re_n to be used whilst still maintaining good levels of mixing.

Figure 16 shows the calculated values of the absolute axial dispersion coefficients plotted as a function of the net flow Reynolds numbers for flows in the multipass baffled tube array with no fluid oscillation. Comparison of the absolute values of the dispersion coefficients shows that the minimum D obtained under oscillatory flow conditions (Fig. 14) is 2×10^{-4} m^2/s, which is significantly less than that obtained for net flow alone, of order $1–5 \times 10^{-3}$ m^2/s (Fig. 16).

From the data presented it is apparent that dispersion for the system studied can, with reasonable pre-
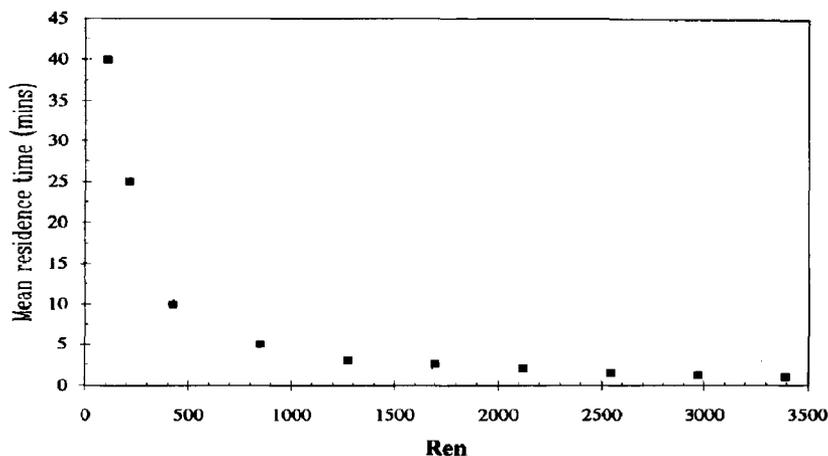
Fig. 15. Mean residence time versus Re_n for the multipass rig based on a path length of 2.63 m.
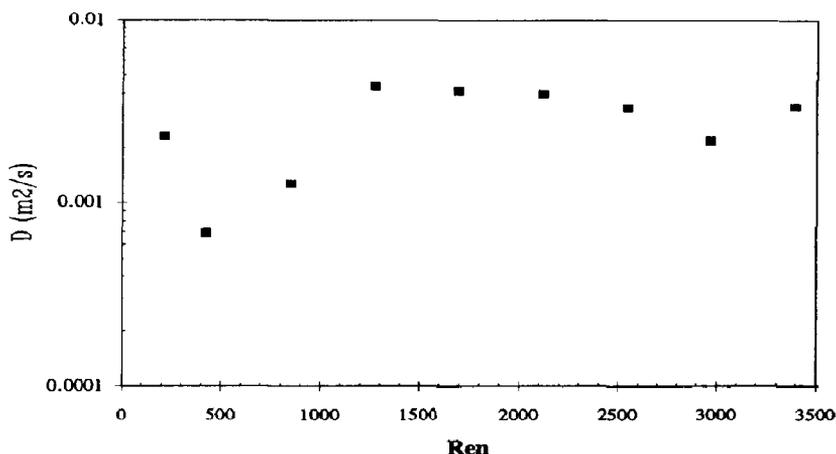

Fig. 16. D vs Re_n for the multipass rig with baffles and no fluid oscillation.

cision, be modelled using the axial dispersion model. The results show that when oscillations and baffles are present, the absolute dispersion coefficient, D, is relatively insensitive to Re_o but is influenced by the amplitude of oscillation. This is consistent with expectations that the amplitude of oscillation will control the length of eddy generated along the tube. The absolute dispersion data show quantitatively that flow behaviour around the bends of the apparatus is similar to that in the straight sections for the situations tested. The absolute magnitude of the dispersion coefficient determined for the oscillatory flow case is less than that for turbulent flow with no fluid oscillation, which again indicates that the oscillatory flow system offers advantages both in level of mean RT control and RTD control.

Experiments in multitube rig

We now present data related to a multitube array as shown in Fig. 17. The objective here is to demon-

strate that fluid oscillation can have a beneficial effect in a system where there are a number of baffled tubes assembled in parallel. Examples of this situation might be a heat exchanger or a reactor. In particular, this configuration could be used for situations where both high heat transfer and continuous reaction with a controlled residence time and RTD were required. The configuration of tubes in parallel would enable the reactor to be easily scaled in relation to volume throughput.

In Fig. 17 the five tubes are joined by two manifolds at the top and bottom, respectively. These tubes are designed so that four tubes are 90° apart on the radii of 48 mm of the centre tube. Fluid entered the system via a side port at the bottom manifold, then was distributed over five tubes and finally converged into the manifold at the top.

Experimental flow visualizations were carried out and shown to be similar in any tube to the results described in the multipass rig. In general, where
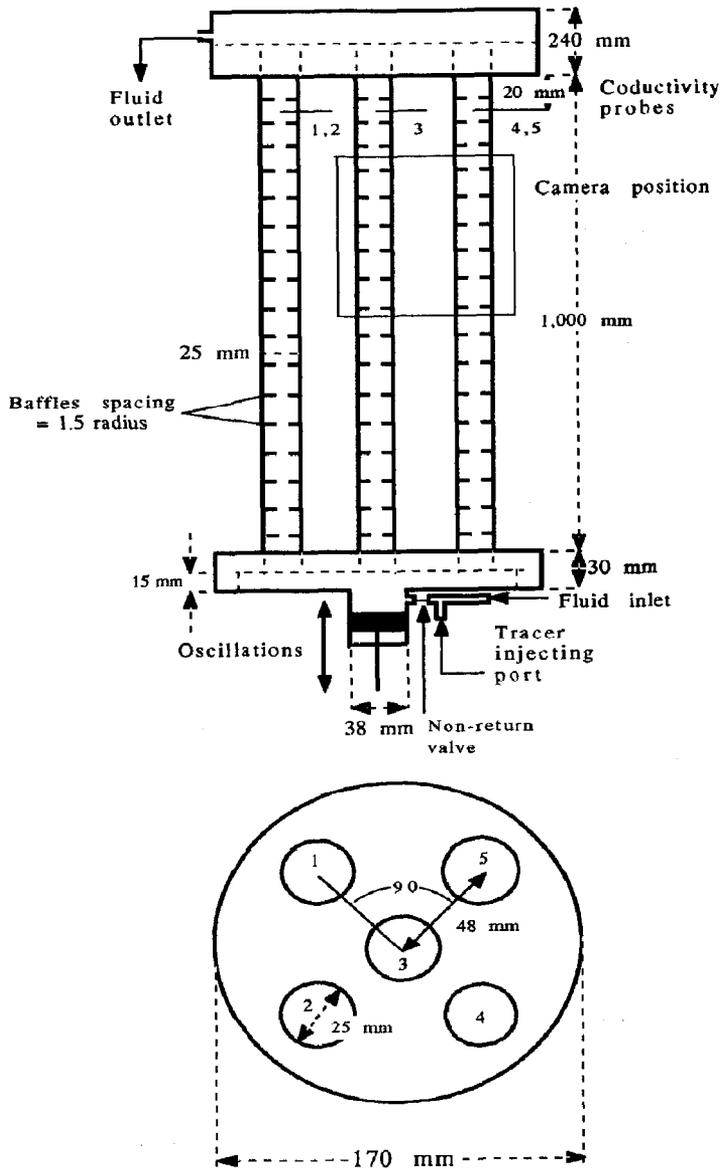
Fig. 17. The Multitube apparatus.

baffles and oscillation were present the flow was seen to be chaotic and well mixed. In other situations axial streamline predominated with evidence of variability between different tubes. These observations were consistent with the concentration profiles that were observed for each tube.

We show two concentration profiles for the multitube rig. Figure 18 shows the concentration profiles for the laminar flow ($Re_n = 42$) in the unbaffled tube array without oscillations. If there was perfect distribution of flow, the form of the profiles when present should be similar at each probe position with no time delay for all probes. The actual profiles have displayed different forms of concentration measurements with time delays, indicating that the non-uniformity of tracer distribution existed in the system. This is consistent with our flow visualisations. The measured concentration profiles demonstrate once again the typical laminar flow behaviour with a long tail after the breakthrough.

When both oscillations and baffles are superimposed in the system with the same tubeside Reynolds number as shown in Fig. 18, each of the tube profiles has the form of a Gaussian curve with the same mean residence time. The eddy mixing has ensured that there is uniform distribution of tracer in each tube and also that the flow within the tube is effectively plug flow with axial dispersion (Fig. 19).
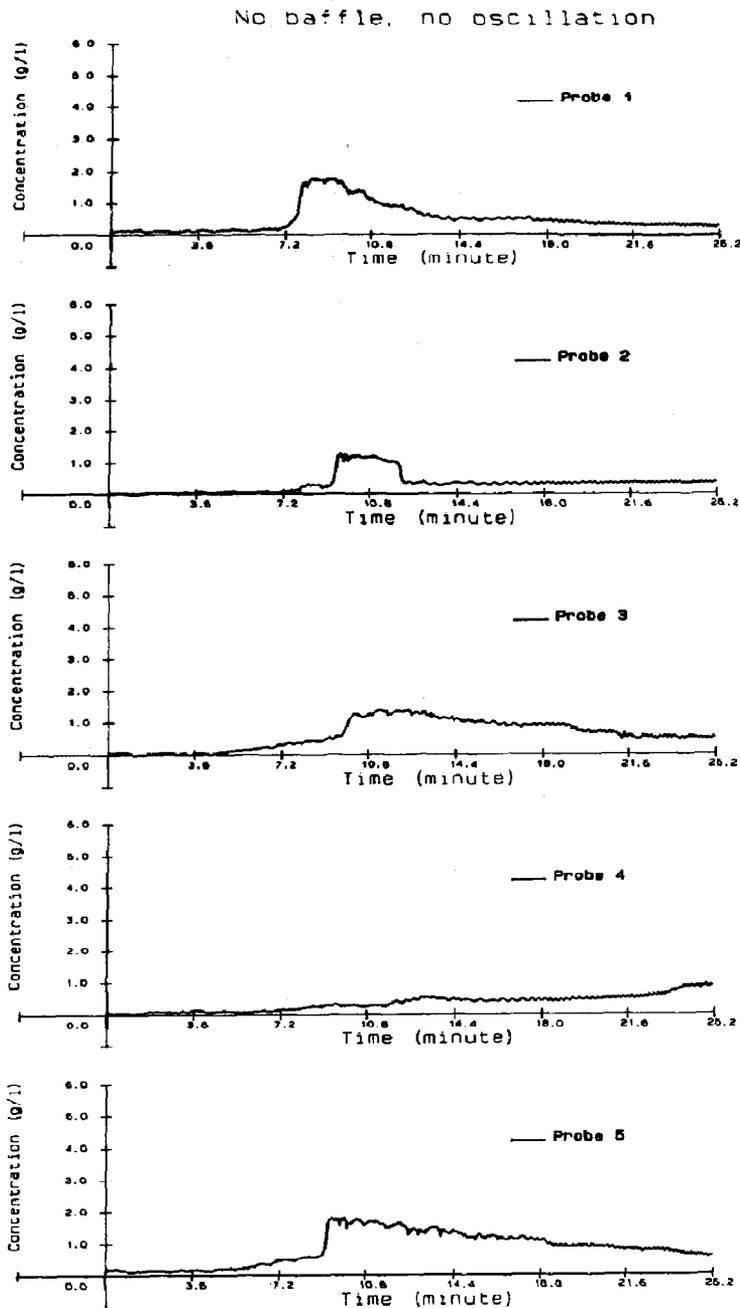
Fig. 18. Concentration measurement for laminar flow in a multitube rig. Tracer = 60 g/l NaCl, bulk fluid = water. No baffles. Tubeside $Re_n = 42$, $Re_o = 0$, $St = 0$. Tube diameter = 25 mm.

In summary, good fluid mixing can be obtained in both the multitube and multipass rigs provided periodic baffles and oscillations are present. If there is no fluid oscillation, the value of Re_n must exceed of order 400 and for our system where $Re_n \sim 2000$ this leads to a mean residence time of about 1 min in the multipass rig. If fluid oscillation is applied a value of Re_o greater than of order 100 is needed. In this case

Re_n can be significantly lower and for example in the case described the mean residence time was increased to 10 min.

CONCLUSIONS

In this paper we have shown that reproducible and controlled RTDs can be obtained for both multipass
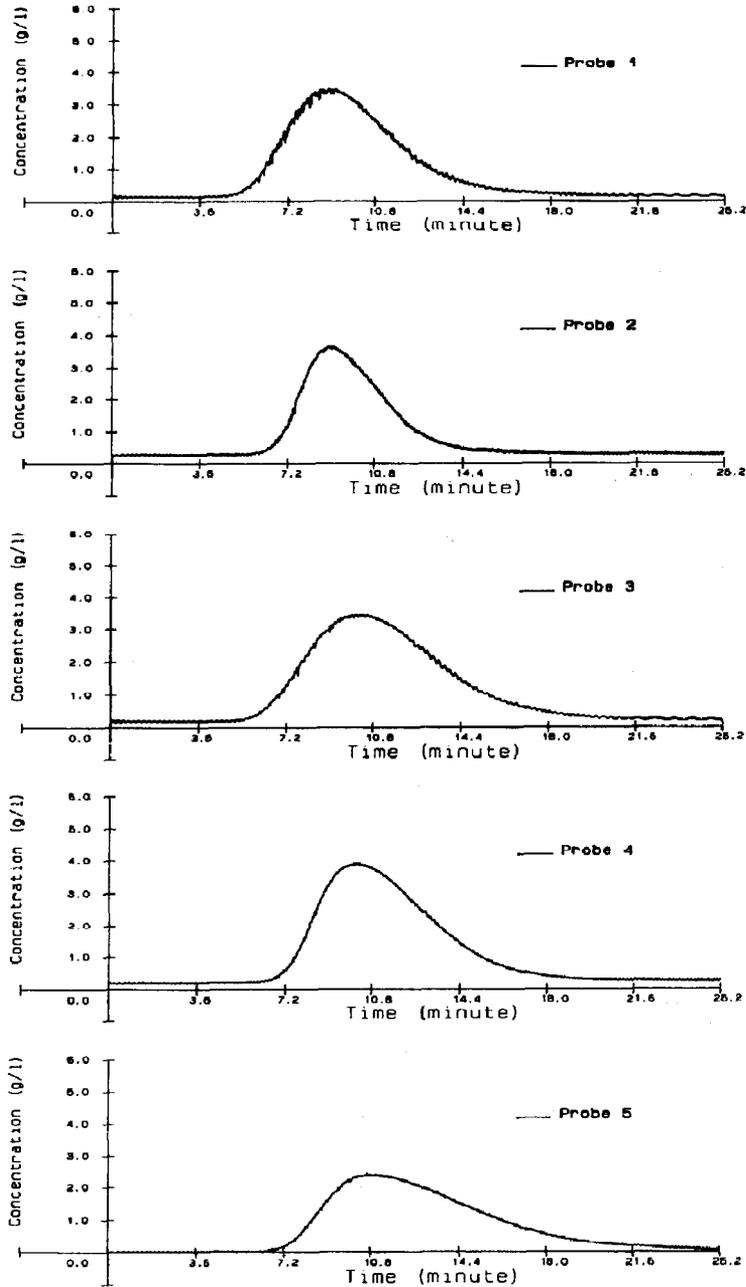
Fig. 19. Concentration measurement for oscillatory flow in a multitube rig. Tracer = 60 g/l NaCl, bulk fluid = water. With baffles. Tubeside $Re_n = 42$, $Re_o = 435$, $St = 2.15$. Tube diameter = 25 mm.

and multitube configurations provided fluid oscillations and baffles are present. These observations extend our previous results and also show the viability of the system, for example in use as a reactor or heat exchanger where both multipass or multitube configurations might be required.

The multipass RTD data expressed as a single-parameter axial dispersion coefficient are consistent with previous results (Dickens et al., 1989) and shows that the dispersion coefficient is sensitive to oscillation amplitude but not very sensitive to oscillation frequency. In the multipass system the presence of bends

Table 3. Absolute dispersion in turbulent flow

	No oscillation, with baffles	No oscillation, no baffles
Re_n	2121	2121
D (m²/s)	0.00395	0.00355

in the tube does not have a great effect when oscillations and baffles are present. The multitube RTD data shows the important result that the RTDs in each tube are very similar and there is no phase shift between each tube.

We also compared dispersion, using oscillation flow and baffles, with that obtained by running the tube with a turbulent net flow. Table 3 shows that when the net flow Reynolds number is high the presence of baffles makes little difference to the dispersion. However, the absolute value of dispersion in a turbulent net flow can be considerably higher than that using oscillatory flow with baffles at a lower net flow Reynolds number. These results show that, for a given residence time requirement, a narrower RTD can be achieved using oscillatory flow and baffles over a turbulent net flow.

From the results reported here we have confidence that scale-up in terms of mean residence time can be achieved by using a multipass system of pipes. Mean residence times of between 30 s and several hours could be envisaged. In addition if scale-up in terms of volumetric flow is required the multitube configuration is equally viable; here both residence time and heat transfer control may well offer genuine strategic advantage over other tubular configurations.

The flow visualization experiments in particular also show that fluid oscillation in baffled tubes is an effective way of keeping particles in suspension and well mixed. The particles used for the visualization were 100–150 μm polyethylene reactor powder. These particles are nearly neutrally buoyant having a density of 960 kg/m³. In both the multitube and multipass configurations we observed that when baffles and oscillation were present the particles chaotically mixed and did not accumulate in any particular section of either rigs. Experiments with particles of greater densities and settling velocities of order 10 mm/s could also be kept in suspension and these results clearly show that the configuration described here could be used for example as continuous liquid/solid reactors, where efficient mixing, heat transfer and residence time control are required.

NOTATION

C concentration of species, g/l
D axial dispersion coefficient, m²/s
L distance between probes, m
D tube diameter, m
Re_n the net Reynolds number
Re_o the oscillatory Reynolds number
St the Strouhal number
t time variable, s
U superficial net flow velocity through a tube, m/s
X_o centre to peak amplitude of oscillation, m

Greek letters
v kinematic viscosity, m²/s
ω angular frequency of oscillation, radians/s

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