Coiled Configuration for Flow Inversion and Its Effect on Residence Time Distribution

Flatter velocity profiles and more uniform thermal environments are extremely desirous factors for improved performance in flow reactors and heat exchangers. One means of achieving this in laminar flow systems is to use mixers and flow inverters. These improve performance but at higher initial and operating costs. This paper introduces a new and more effective device for flow inversion which is achieved by changing the direction of centrifugal force in helically-coiled tubes. Transient response experiments carried out under the conditions of both negligible and significant molecular diffusion reveal drastic narrowing of the residence time distribution (RTD). The effectiveness of the present device can be assessed by the fact that even at a Dean number of 3 the value of dispersion number as low as 0.0013 is obtained under the condition of significant diffusion, and in the case of negligible diffusion the value of dimensionless time at which the first element of tracer appears at the outlet is as high as 0.85.

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SCOPE

It is usually desired to achieve uniform reaction conditions or lower temperature gradients to improve the performance of flow reactors and heat exchangers. Narrower residence time and thermal time distributions can be obtained by increasing the mixing between the fluid elements of different age groups and temperatures. Commercial motionless mixers and flow inverters are employed in industrial practice to enhance heat transfer coefficients and to provide more uniform thermal and compositional environments (Nauman, 1979). Helical coils also find extensive use owing to the cross-sectional mixing induced by centrifugal force.

This paper proposes a very simple and extremely effective technique, "bending of helical coils," to cause multiple-flow inversions at low flow rates just sufficient for secondary flow to fully develop, i.e., $N_{De} > 1.5$ (Saxena and Nigam, 1979). A step response technique was used to measure the age distribution of fluid elements undemlaminar flow conditions in order to characterize the perforı ıance of these bent coils. The experiments revealed a signifi cant narrowing of the residence time distributions even for low values of Dean number. The parameters which are effective in narrowing the residence time distribution in bent coils are: number of bends, bend angle, and bend spacing. The optin al configuration consists of 90-degree bends equally spaced down the length of the tube.

CONCLUSIONS AND SIGNIFICANCE

This paper discusses how centrifugal force can be used to induce flow inversion in laminar flow systems. Experimental results show that the sudden shift in the direction of centrifugal force (in bent coils) is more effective than a gradual change (in coiled coils) in order to narrow the residence time distribution (RTD). For the case of a fully-developed secondary flow, a 90-degree bend induces a flow inversion which most effectively narrows the RTD for equal arm lengths before and after the bend. This concept holds good for any number of bends. The RTD is highly sensitive to the number of bends involved; increasing the number nar ows the RTD. Experiments with a unit having 57 bends showed the narrowest RTD known in a laminar flow device.

A design parameter, R_A, is suggested which takes care of the number of bends, bends pacing, and characterizes the performance of bent coils. Advantages offered by the proposed device over conventional metheds are: its performance substantially closer to plug flow; compactness and case of fabrication.

BACKGROUND

A motionless mixer is a no-moving-part, duct-like mixing device which, by redistributing the fluid across the flow channel, rearranges temperature and composition distributions and narrows the residence time distributions. Such devices are usually effective in eliminating severe temperature and composition gradients but have high capital costs and high pumping costs as compared to an open duct (Nauman, 1979). The experimental data show that the improvement caused by these mixers is not as significant as may expected intuitively (Nigam and Vasudeva, 1976). Nauman (1979) has introduced a comparatively economical alternate to motionless mixers, called flow inverters, which may be installed midway or at more locations and are separated by relatively long lengths of open pipe. His analysis shows about 25 to 30% improvement in Nusselt number even with a single inverter installed midway in a heat exchanger for Graetz parameter above about 10.

Secondary flow induced in helical flow also facilitates narrower residence time distributions and higher heat and mass transfer coefficients as compared to a straight tube. Dean (1927) was the first to analyze mathematically the phenomenon of secondary flow in helically-coiled tubes of circular cross-section. He obtained analytical expressions for the velocity profile valid for large radii of curvature ($\lambda_c \gg 1$) and low Dean numbers ($N_{RE}/\sqrt{\lambda_c} \ll 17$).

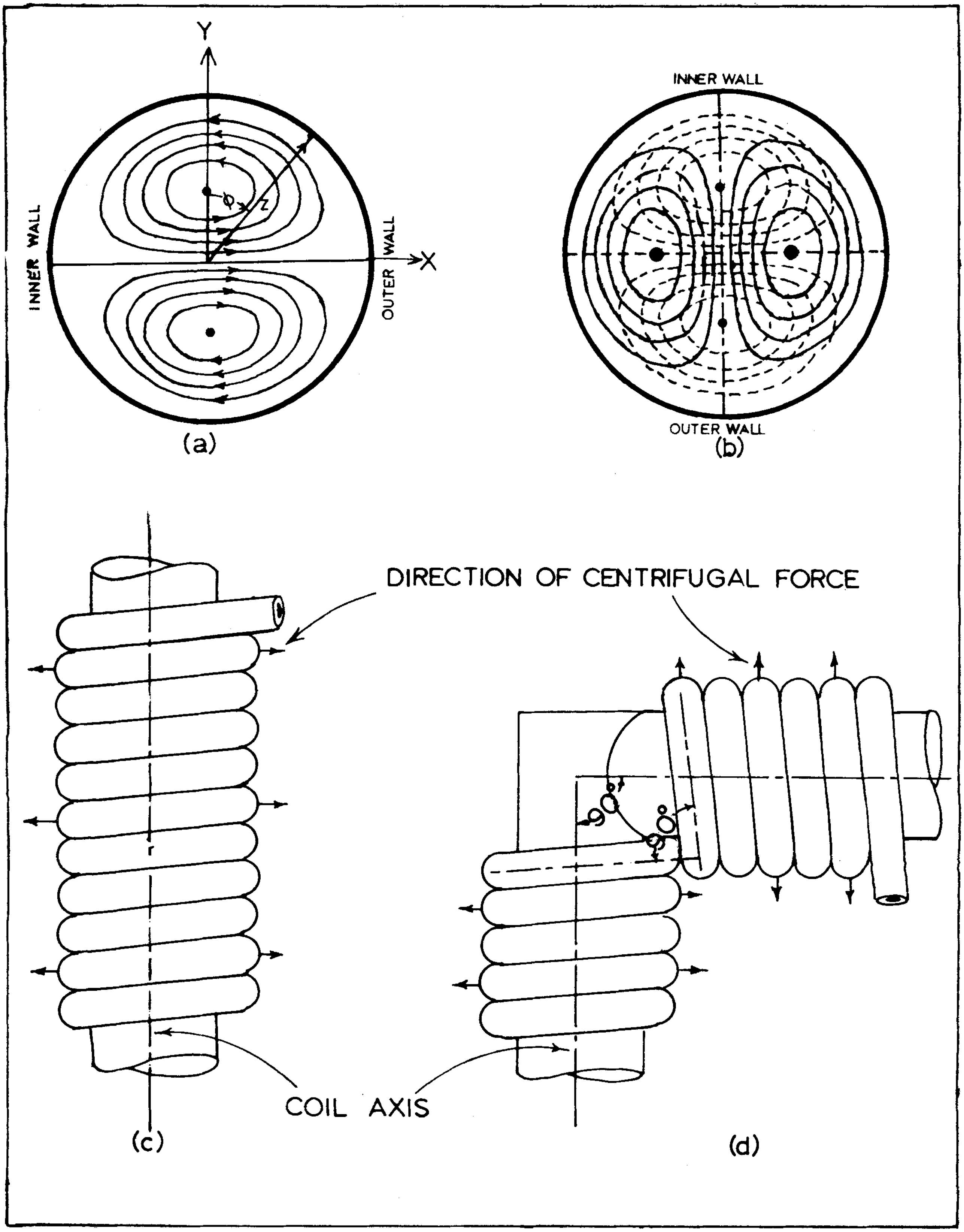

Figure 1. Inversion of flow due to bending of helical coil.

Ruthven (1971) using Dean's velocity profiles computed diffusion-free RTD for laminar flow in helical coils which was later improved by Nauman (1977). Apart from minor differences, both have obtained a unique RTD which is independent of curvature ratio and Reynolds number and is narrower than the RTD of a straight circular tube reported by Danckwerts (1953). Recently Saxena and Nigam (1979) have shown that this unique RTD is valid for $1.5 \leq N_{De} \leq 6$. McConalogue (1970) computed the RTD for diffusion-free helical flow using numerically obtained velocity profiles of McConalogue and Srivastava (1968) and showed a gradual narrowing of RTD with increases in Dean number over the range $16.6 \leq N_{De} \leq 77$. The experimental study of Trivedi and Vasudeva (1974) also revealed a noticeable narrowing of diffusion-free RTD for $N_{De} \approx 11$.

Theoretical studies of Erdogan and Chatwin (1967) and Nunge et al. (1972) on axial dispersion in curved tube reveal a drastic reduction in axial dispersion with increase in Reynolds number. Experimental results of Trivedi and Vasudeva (1975) show that the actual reduction in axial dispersion due to coiling of tubes is much less than predicted by these analyses. In case of motionless mixers, the experimental results of Nigam and Vasudeva (1980) also fail to reveal any significant reduction in axial dispersion.

The experimental studies reported so far reveal that very high Dean numbers are required in order to induce significant mixing in the cross-sectional plane. A simple and economical alternative, "Bending of Helical Coils," is very efficient in inverting the flow and improving cross-sectional mixing in a coiled tube. Figure 1 illustrates the concept for the case of a 90-degree bend. Figure 1a shows the D-shaped streamlines predicted from Dean's velocity profiles. If we change the direction of centrifugal force by any angle, the plane of vortex formation also rotates with the same angle. If this rotation is by an angle of 90 degree, the readjustment of streamlines will be as shown in Figure 1b. The points at which apparent axial velocity was maximum before changing the direction of centrifugal force are now lying on the streamline which corresponds to the smallest axial velocity, and the new points of maximum velocity are induced on the streamline which previously had the lowest axial velocity. Thus in helical flow a 90-degree shift in the direction of centrifugal force causes a flow inversion [though it is not exactly inversion in the sense of Nauman (1979)].

The direction of centrifugal force is always perpendicular to the axis of the coil, Figure 1c. Hence it can be changed by any angle just by bending the axis of the helical coil with the same angle. Figure 1d shows a 90-degree shift in the direction of centrifugal force.

It may be of some interest to see the effect on the RTD if, instead of a sudden shift in the direction of centrifugal force, the plane of vortex formation is gradually rotated. This can be achieved by simply coiling a helical coil over a cylindrical base. The effect of these two aspects on mixing in a cross-sectional plane was investigated by experimentally measuring residence time distribution in bent coils and coiled coils.

EXPERIMENTAL

The effect of flow inversion, caused by bending of coils, on the residence time distribution was studied in 21 bent coils. These coils were prepared by winding thick-walled PVC tubing over mild steel pipe pieces which were welded together to form a desired geometry. The effect of a gradual rotation in the direction of centrifugal force was studied in two coiled coils, prepared by coiling the PVC tubing over thick-walled rubber tube and winding the helix so formed over cylindrical bases of two different diameters. Diethylene glycol (DEG), 80% aqueous solution of DEG and distilled water were used as flowing media and congo red dye as a tracer. The experimental technique was reported in detail by Trivedi and Vasudeva (1974, 1975).

DISCUSSION AND RESULTS

In the present study an attempt was made to optimize the coiled configuration so as to narrow the RTD. One may expect the following parameters to effect the RTD in coiled flow inverters.

i) Number of bends
ii) Spacing between bends
iii) Angle between different arms of helix
iv) Dean number

This paper discusses the effect of these parameters on RTD in coiled flow inverters. RTD's in bent coils were numerically computed and compared with experimental results. The procedure for computing theoretical RTD's was parallel to that of Nauman (1977) and discussed in detail elsewhere (Saxena, 1982).

The step response experiments under the influence of negligible diffusion were carried out in coiled flow inverters using pure DEG and 80% aqueous solution of DEG as flowing media. A test for the absence of diffusional effect was made as reported by Trivedi and Vasudeva (1974). The number of bends were varied from 0 to 57 and the angle of bends was changed from 0 to 180 degree. The effect of spacing of bends on the performance of coiled flow inverters was also studied. The experiments were carried out in the range of $1.5 < N_{De} < 5$, for which the secondary flow in a straight helix is fully developed (Saxena and Nigam, 1979), so that the effect of bending of coil on the RTD could be studied.

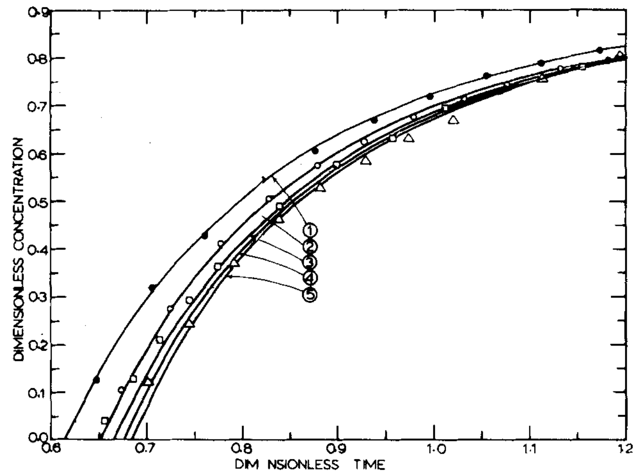

Figure 2. Diffusion-free RTD to helical coil having one 90-degree bend and different lengths of tube before and after the bend.

Length proportion before and after the bend	1:0 (St. Helix)	1:7	3:1	3:5	1:1
Theoretical	1	2	3	4	5
Experimental (N_{De} = 3.5)	●	○	□		△

Effect of Bend Location and Angle of Bend on RTD

Figure 2 shows the theoretical and experimentally-obtained RTD's for helical coils having one 90-degree bend and different spacings, before and after the bend. Good agreement between experimental and theoretical RTD's is evident from the figure. The narrowest RTD is obtained for equal lengths of coil before and after the 90-degree bend. In the case of flow inverters also Neuman (1979) has shown theoretically that a single-flow inverter is most effective when installed midway in the flow duct. Our experimental results, Figure 2, confirm his finding.

Numerically-computed RTD's in bent coils having one centrally located bend of 30, 45, 60 and 90 degree are shown in Figure 3 along with experimental RTD's. The agreement between theoretical and experimental results in this case is also good. It is evident from the figure that a maximum narrowing of the RTD is attained with a bend of 90 degrees.

Step response experiments were also carried out in bent coils having three bends of different angles at different locations. In these coils too, the narrowest RTD could be obtained when bends were of 90 degree and equispaced. This is due to the fact that a 90-degree bend induces a complete flow inversion, and an odd number of equispaced bends provide equal opportunity for centrifugal force to act in two perpendicular directions.

Effect of Number of Bends

Experiments were carried out to examine the effect of number of equispaced bends (n), 90 degree each, on RTD, Figure 4. For $n > 3$, an increase in the number of bends drastically narrows the RTD. It would be of interest to note that for the coil of 57 bends

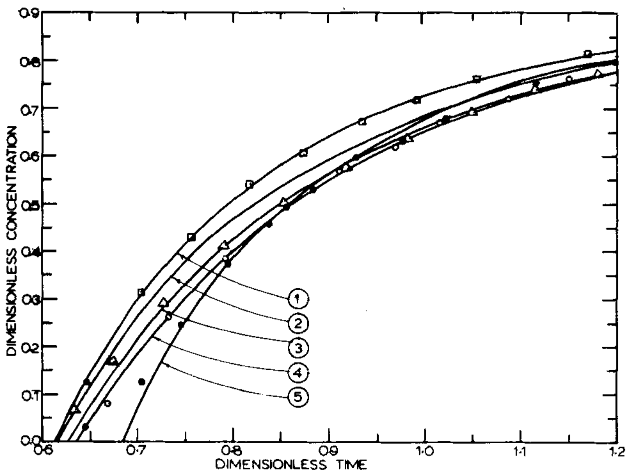

***Figure 3.* Diffusion-free RTD's in helical coil having one centrally-located bend of different angles.**

Bend Angle	**180 (St. Helix)**	**30**	**45**	**60**	**90**
Theoretical	**1**	**2**	**3**	**4**	**5**
Experimental (N_{De} = 3.5)	□		△	○	●

the dimensionless time at which the first element of the fluid appears at the outlet is as high as 0.85.

In view of this observation that the higher the value of n the narrower is the RTD, a parameter R_A is defined as:

$$R_A = \frac{\text{Volume of the largest arm of bent coil}}{\text{Total volume of the helix}} \tag{1}$$

This parameter characterizes the performance of coiled flow inverters. The lower the value of R_A, the narrower is the RTD. The volume of the largest arm used in defining R_A takes care of the number of bends as well as spacing among bends. For a given odd number of bends (n), the lowest value of R_A would occur when bends are equispaced for which R_A can be given as

$$R_A = \frac{1}{n + 1} \tag{2}$$

In practice the requirement of some minimum number of turns necessary for developing secondary flow in each arm imposes a restriction on the maximum number of bends in a coiled tube of fixed curvature ratio, volume and diameter. In practice about two turns are required for developing a secondary flow in the cross-sectional plane (Muzavar and Raja Rao, 1978). In the present study a maximum of 57 bends could be attained which corresponds to R_A = 0.0172 and five turns on each arm.

Effect of Dean Number on RTD in Bent Coils

Figure 5 shows the effect of Dean number on the diffusion-free RTD in a coiled flow inverter having 15 equispaced bends of 90 degrees each. Diffusion-free RTD's for a straight helix and straight tube are also shown in the figure. The gradual narrowing of RTD with increases in Dean number is evident from the figure. A similar trend was also observed for other bent coils which is in agreement with the experimental finding of Saxena and Nigam (1979) for a straight helix over the range of $0.007 < N_{De} < 1.5$. It is worth mentioning that, in the case of a bent coil, the unique RTD is obtained at $N_{De} = 3$ which is higher than the value of 1.5 reported for a straight helix. This may be because of the fact that in bent coils the narrowing of RTD is caused by two mechanisms.

1) Development of a secondary flow in each arm of the helix which is fully developed for $N_{De} \geqslant 1.5$.

2) Interchange of velocities among the fluid elements of different ages due to the shift in the direction of centrifugal force.

Therefore, for the increase in Dean number above 1.5, the first mechanism no longer affects the RTD but the second effect causes more efficient shifting at the bends to further narrow the RTD and is active up to $N_{De} \approx 3$. This argument is supported by the experimental results shown in Figure 5, which reveal that for the range of Dean number $0.1 < N_{De} < 1.2$ where both the mechanisms are likely to grow with increases in Dean number, the rate of narrowing is much faster as compared to that in the range $1.2 < N_{De} < 3$ where only second mechanism is active.

Another interesting point worth noticing in Figure 5 is that, unlike the straight helix, the narrowing of RTD with increases in Dean number ($N_{De} > 0.1$) starts from a point A which corresponds to $\theta = 1$, i.e., fluid element flowing with approximately average axial velocity. The probable reason for this is that the narrowing of the RTD is caused by mixing of fluid elements of different ages at each bend. At very low Dean number (~0.1) where the secondary flow is weakly developed, mixing will take place only among those fluid elements which have enough secondary momentum, before as well as after the bend, to induce mixing. For very weakly developed secondary flows, these streamlines can not be close to the tube wall or to the center of vortex. Naturally these will have $\theta \approx 1$.

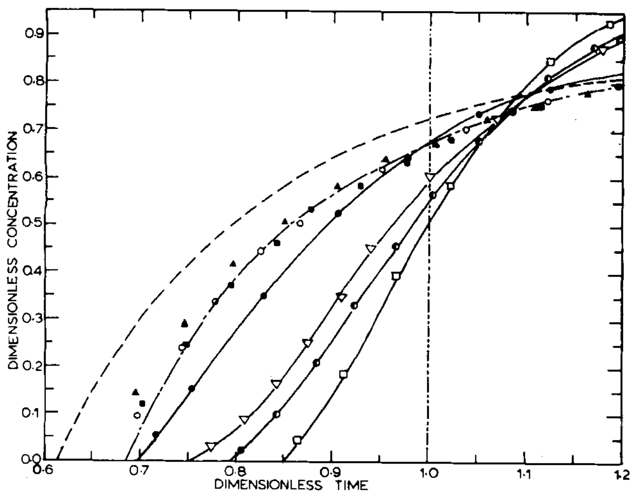

Figure 4. Effect of number of 90-degree equispaced bends on diffusion-free RTD. Number of bends-symbol: 1 - ■, 2 - ▲, 3 - ○, 7 - ●, 15 - ▽, 31 - ◐, 57 - □; theoretical RTD's; straight helix - - - - -, Bent coil having one centrally-located 90-degree bend — - — - —

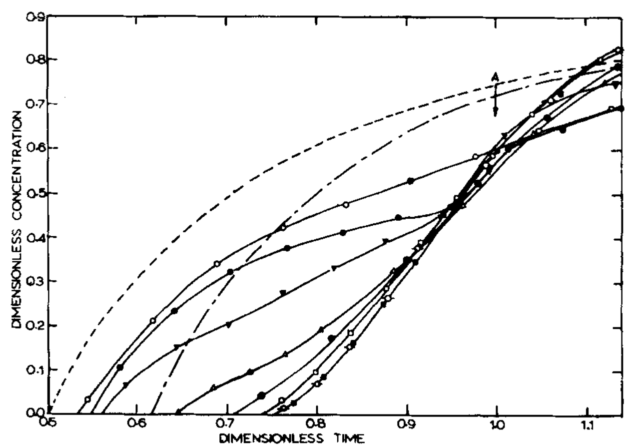

Figure 5. Effect of Dean number on diffusion-free RTD in bent coil having 15 equispaced 90-degree bends. Dean Number: Symbol: 0.1–0, 0.3 - ●, 0.43 - ▼, 0.59 - △; 1.2 - ⊙, 2.35 - □, 3.0 - ■, 4.5 - -O-; Theoretical RTD's for straight tube - - - - - - and for straight helix — — — — —

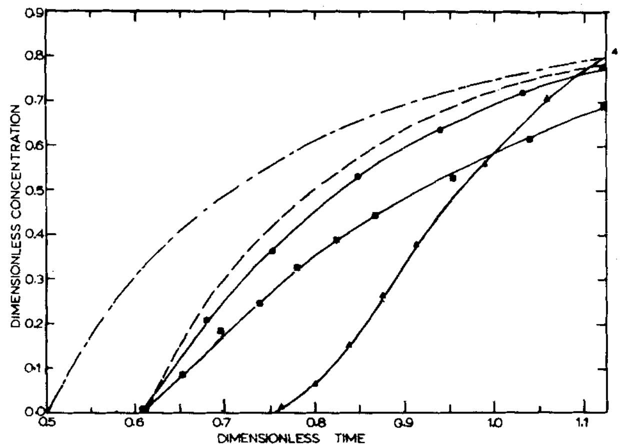

Figure 6. Effect of coiling of coil on diffusion-free RTD's (N_{De} = 3). Coil-symbol: coiled coil of λ_{cc} = 8.9 - ●, coiled coil of λ_{cc} - 4.3 - ■, bent coil having 15 equispaced 90° bends - ▲; theoretical RTD's for straight tube — — — — — — and straight helix - - - - - -.

Effect of Coiling a Coil

To study the effect of a gradual change in the direction of centrifugal force on the RTD in coiled tubes, experiments were carried out in two coiled coils of different $\lambda_{cc}(= d_{cc}/d_t)$ and identical $\lambda_c(= d_c/d_t)$. Figure 6 shows that the coiling of coils also narrows the RTD by reducing the fraction of fluid appearing at $\theta = 1$, though the value of $\theta_{\min}$ is not much affected. Figure 6 also includes RTD's for straight and coiled tubes along with the experimentally-obtained RTD in a bent coil of fifteen 90-degree equspaced bends. The criterion for comparing the experimental results for a coiled coil of λ_{cc} = 4.3 with the bent coil of 15 bends was chosen to be equal length and periphery of both the coils and identical Dean number. Bent coils are more effective than coiled coils in reducing the spread of residence time.

Axial Dispersion with Significant Molecular Diffusion

Under the condition of significant molecular diffusion, the effect of different parameters on axial dispersion in bent coils was studied using water as the flowing media and congo red dye as a tracer. The Reynolds number was varied from 10 to 200 which corresponds to Dean number of 3 to 60. Experimentally-obtained step response curves for different coiled flow inverters are shown in Figure 7. It is clear from the figure that as the value of R_A decreases (i.e., number of equispaced bends increases) the RTD approaches closer to that of plug flow.

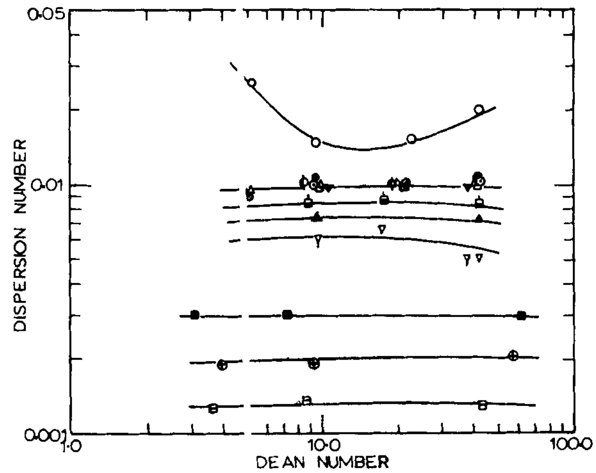

Figure 8. Dispersion number vs Dean number.

Cell	Symbol
Straight helix	○
One centrally-located 90° bend	⊙
One 90° bend located at 3:1 position	△
One 90° bend located at 1:3 position	◘
One 90° bend located at 1:7 position	●
One centrally-located 45° bend	◐
One centrally-located 60° bend	▼
Two 90° bends located at 1:2:1 position	□
Three equispaced 90° bends	▲
Seven equispaced 90° bends	▽
Fifteen equispaced 90° bends	■
Thirty one equispaced 90° bends	⊕
Fifty seven equispaced 90° bends	□

Taylor's dispersion mode (1953) was fitted to experimentally-obtained F curves using the criterion suggested by Trivedi and Vasudeva (1975). The best fit computed values of dispersion number are plotted against Dean number in Figure 8. It is evident from the figure that in coiled flow inverters the dispersion number is independent of Dean number. The experimentally-obtained values of dispersion number are correlated to the design parameter R_A as

$$\frac{D}{\bar{u}\,l} = 0.016\,R_A^{0.58} \text{ for } 3 \leq N_{De} \leq 60 \qquad (3)$$

$$\text{and } R_A < 0.5$$

It is interesting to mention that about a twentyfold reduction in dispersion number as compared to a straight helix can be obtained in a coil having 57 equispaced bends of 90 degrees each.

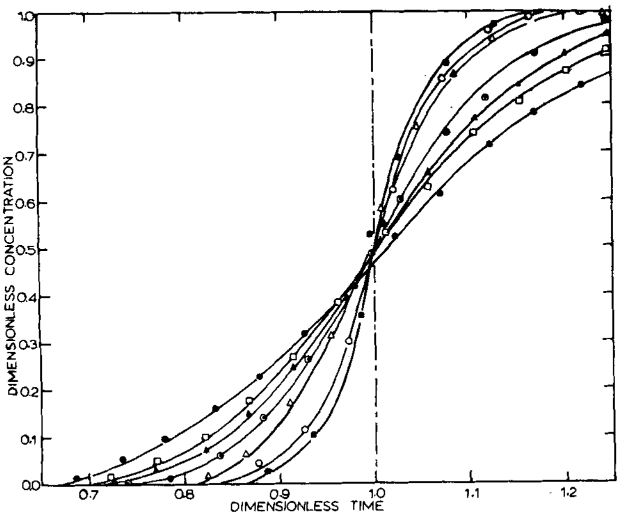

Figure 7. Step response curves with significant molecular diffusion (N_{Re} = 140). R_A - Symbol; 1 - ●, 0.5 - □, 0.33 - ▲, 0.125 - ⊙, 0.0625 - △, 0.0312 - ○, 0.0172 - ■, RTD for plug flow - - - - - -.

Pressure Drop in Coiled Flow Inverters

Pressure drop experiments were carried out in coiled flow inverters to assess the cost of the improvement in mixing in terms of pumping energy. A standard technique for the measurement of pressure drop was used, and the results for a straight helix were found to be in agreement with those reported by Mishra and Gupta (1979).

Experimental results on pressure drop surprisingly revealed a reduction in friction factor in coiled flow inverter with one bend and two bends as compared to a straight helix. Further increases in the number of bends resulted in increased pressure drop. The probable explanation for this unexpected behavior may be the influence of two factors which should affect the pressure drop in coiled flow inverters:

i) Dissipation of energy due to the mixing in fluid elements of different ages at the bends.

ii) Viscous forces which in turn depend upon the axial velocity gradient.

The first factor should increase the pressure drop with increases in number of bends while the second factor tends to reduce it owing to the weaker velocity gradients caused by interchange of velocities at the bends. For fewer bends ($n \leq 2$), the first factor is less effective but the second one shows its substantial effect (reflected by the shifting of θ_{min} from 0.613 to 0.68 even for a single bend, Figure 2) causing a reduction in pressure drop. As the number of bends is increased ($n > 2$), the first factor dominates which enhances pressure drop. The maximum enhancement in friction factor due to bending the coils (with 57 bends) was found to be about 1.7 fold at a Dean number of about 35.

The ease of fabrication, compactness and narrower RTD found with coiled flow inverters establish their superiority over other mechanical devices, known in literature, for inducing mixing in a cross-sectional plane and making flow closer to plug flow.

NOTATION

D = effective diffusion coefficient, cm^2/s
d_c = diameter of the helical coil, cm
d_{cc} = diameter of the coiled coil, cm
d_t = tube diameter, cm
F = residence time distribution function, dimensionless
l = length of the tube, cm
n = number of bends
N_{De} = Dean number ($= N_{Re}/\sqrt{\lambda}$), dimensions
N_{Re} = Reynolds number ($= d_t\bar{u}\rho/\mu$), dimensionless
R_A = parameter defined by Eq. 1
$\bar{t}$ = mean holding time, s
$\bar{u}$ = overall average axial velocity, cm/s
θ = dimensionless residence time
θ_{min} = residence time for the fastest moving fluid element, dimensionless
λ_c = coil to tube diameter ratio ($= d_c/d_t$), dimensionless
λ_{cc} = coiled coil to coil diameter ratio, dimensionless
ρ = fluid density, g/cc
μ = fluid viscosity, cp

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Dynamics and Control of an Activated Sludge Process As a Mixed Culture System

One of the difficulties encountered in the operation of an activated sludge process is the phenomenon of bulking sludge.

In an activated sludge process which is composed of a completely mixed aeration tank and a sedimentation vessel, the dynamic behavior of the system can be analyzed using a mathematical model. The model developed here is based on the kinetics and settleability of the combination of floc-forming sludge and bulking sludge. The operating conditions that cause the bulking phenomenon are clarified on the phase plane. It is also shown that a type of nonlinear state feedback regulator makes the system stable.

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SCOPE

An activated sludge process is used for the biological oxidation of sewage. In its conventional form it consists of an aerated reactor and a sludge sedimentation tank which provides recycled sludge. One of the difficulties encountered in the operation of the activated sludge process is connected with the phenomenon of bulking sludge. Bulking sludge settles poorly

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