presence of SO_4^{2-} ions leads to the increasing acid concentration within the resin at the particle surface. The sorption rate will thus be higher and the decrease of breakthrough capacity with increasing specific loading less sharp.

In case of converting some of the functional groups into HCO_3^- form, the sorption rate substantially increases (Richter, 1962). This may be realized either by the presence of carbon dioxide in the influent or by the regeneration with Na_2CO_3 or $NaHCO_3$ (Figure 2). The resin is now more ionized and may now behave partly like strong base anion exchanger. The sorption rate will thus be higher. The effect of variable solution composition has not been sufficiently tested, so it is difficult to prove the validity of the presented theory for other acid composition than hydrochloric acid.

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NOTATION

c_H = concentration of acid in the solution, meq/cm³ solution
$\bar{c}_H{}^0$ = concentration of acid within the resin at the resin particle surface, meq/cm³ solution
C_o = total volume capacity of the bed, meq/cm³ resin bed
C_s = breakthrough capacity of the bed at specific loading s, meq/cm³ resin bed
C_W = weight capacity of ion exchanger, meq/g dry ion exchanger
D_i = diffusion coefficient of species i in the solution, cm²/s
$\overline{D}_i$ = diffusion coefficient of species i in the resin, cm²/s
F = degree of exhaustion
k = constant of proportionality
m = molality of functional groups in the ion exchanger, meq/g solution
q = internal cross section of column, cm²
r_o = particle radius of resin beads, cm
s = specific loading of the bed, bed volumes/hr
t = time, s
v = linear flow rate, cm/s
v_B = rate of motion of the boundary in the column, cm/s
W = total water content of the ion exchanger, wt %
$\overline{X}$ = concentration of functional groups in the ion exchanger, meq/cm³ resin bead
$\overline{X}_s$ = concentration of exhausted functional groups in the ion exchanger at specific loading s, meq/cm³ resin bead
z = axial space coordinate in columns
z_G = Glueckauf's parameter
Z = bed height in column operations, cm
β = fractional void volume
ϵ = fractional pore volume in the ion exchanger

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Characterizing the Effect of Feed Rate in Continuous Flow Vessels Having Turbine Agitators

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Continuous flow agitated vessels are often used for processing non-Newtonian fluids, particularly for fermentation and polymerization processes. For process control applications and for scale-up purposes, the effect of feed rate on the operation of the system should be understood. The mixing in such systems is one aspect of the operation which can be studied in the laboratory by measuring residence time distributions. The effect of

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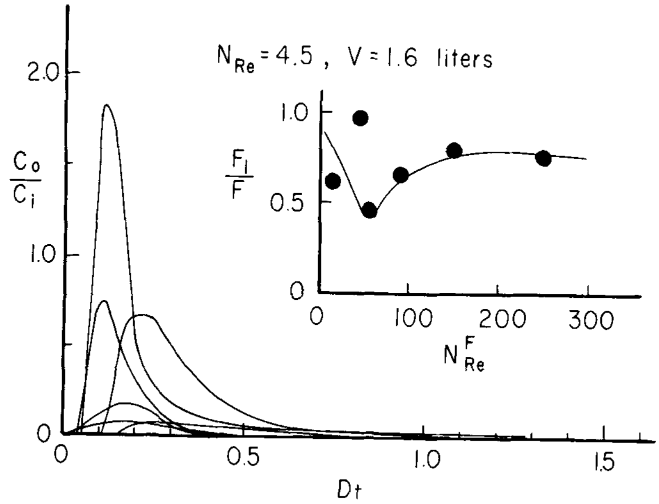

Fig. 1. Effect of throughput rate on residence time distribution.

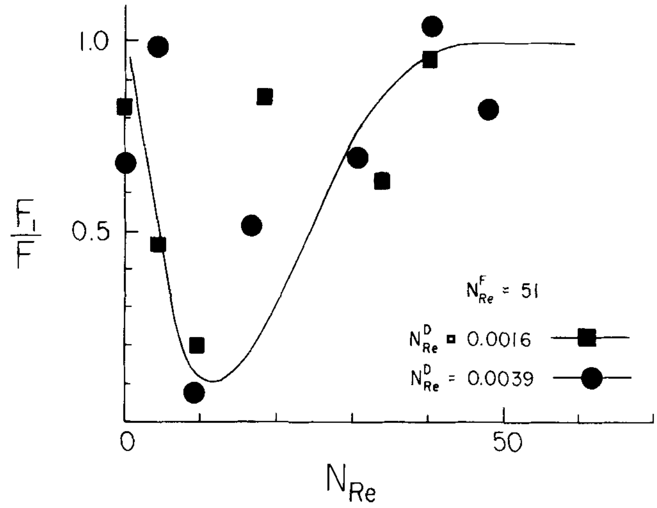

Fig. 2. Effect of $N_{Re}{}^D$ on mixing.

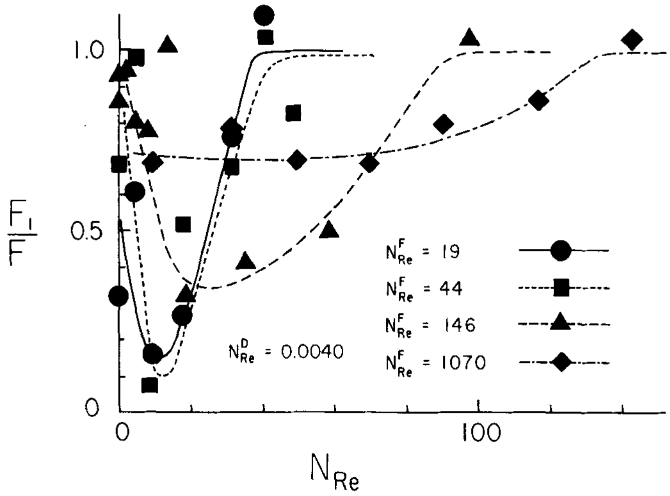

Fig. 3. Effect of $N_{Re}{}^F$ on mixing.

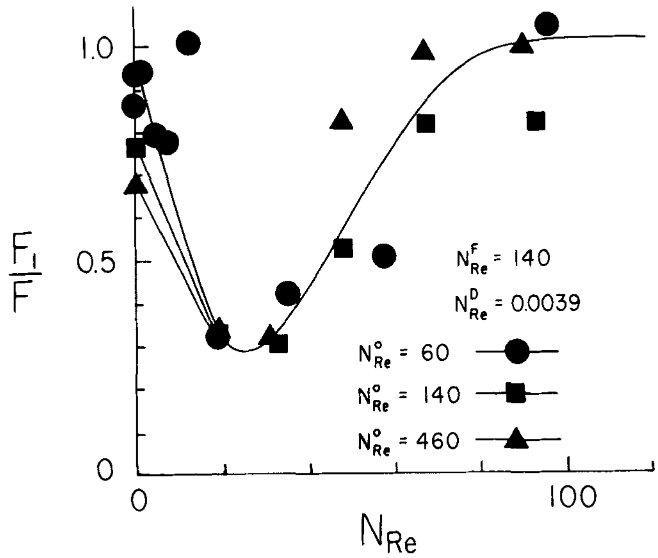

Fig. 4. Effect of $N_{Re}{}^0$ on mixing.

feed rate on residence time distribution was studied in order to find the best way to represent the effect in terms of dimensionless variables suitable for equipment design and scale-up.

Residence time distributions are usually determined by stimulus-response experiments as described by Levenspiel (1972). Residence time distributions have been measured by Taguchi et al. (1964) and by Moo-Young and Chan (1971) for continuous flow systems containing aqueous carboxymethyl cellulose solution. These solutions are non-Newtonian. Residence time distributions for continuous flow systems containing polysaccharide solutions have been reported by Hubbard and Calvetti (1972), by Johnson and Hubbard (1974), and by Williams (1974).

The effect of feed rate on the operation of continuous flow vessels has been studied by Clegg and Coates (1967) for nonagitated vessels and by Hubbard and Patel (1971) and Paquet and Cholette (1972) for agitated vessels using water as the fluid. Other authors discussing residence time distributions include the effect of feed rate implicitly, since the mean residence time includes the feed rate as one factor. The mean residence time is used in calculating the dimensionless time Dt used for plotting residence time distributions.

EXPERIMENTAL TECHNIQUES

Experiments were performed in a 1.6 l cylindrical, flat bottomed vessel having four radial baffles equally spaced around the vessel wall. A six-blade turbine impeller was used for agitation. The square geometry was used, liquid depth equal to D_T and $D_T = 2.5D_i$. The impeller speed used for the experiments ranged from 0 to 626 min^{-1}. Aqueous polysaccharide solutions containing 0.2 mass % polymer were pumped in at the top of the vessel and out at the bottom at volumetric flow rates ranging from 0.9 l to 4.8 l min^{-1}. Details of the experimental techniques are given by Williams (1974). The rheological properties of the solutions used were described by the power law model, $\tau = 10\sigma^{0.35}$. The units of the quantities in the equation are in centimeters, grams, and seconds.

The residence time distributions were measured using an impulse stimulus with iodide as the tracer material. At the start of an experiment, polymer solution containing enough potassium iodide to give $C_i = 10^{-2}$ molar was injected into the feed near the point where the feed entered the tank. The iodide concentration in the outlet stream was monitored using a specific ion electrode sensitive to iodide. Bulk fluid motion was assumed to be the dominant mechanism for solute transport.

RESULTS

Residence time distributions can be represented by mixing models as described by Levenspiel (1972). The data were represented by a model consisting of a plug flow region in series with a complete mixing region and a parallel bypass stream. A dead space region was also included. The model parameters V_p, V_d, V_b, and F_1 were evaluated from the data. F_1/F, the fraction of the feed not bypassed, has been used to characterize each residence time distribution. This enables representing the data from each experiment by a single number. For the purpose of this work, it was not necessary to characterize the residence time distributions completely.

Residence time distributions for different feed Reynolds numbers show that there is a strong dependence on throughput rate, a dependence in addition to the normal dependence for the perfect mixing situation where $C_o/C_i = \exp(-Dt)$. This is shown in Figure 1, where each residence time distribution curve was obtained for a different value of $N_{Re}{}^F$. The parameter F_1/F is also plotted as a function of $N_{Re}{}^F$ to show the effect of throughput rate on one mixing model parameter.

This is similar to results reported by Paquet and Cholette (1972). They plotted F_1/F as a function of N for marine propellers rotating in water in a system for which $D_T = 24D_i$. Their feed was directed vertically upward immediately beneath the impeller, and the outlet was through an annular space around the impeller shaft. Quite a strong effect of throughput was noted. F_1/F decreases as the throughput rate increases. The data for polysaccharide solutions shown in Figure 1 seem to exhibit a minimum at a feed Reynolds number of approximately 60. Such a minimum is not evident in the data reported by Paquet and Cholette.

To select the dimensionless parameter which best characterizes the effect of throughput rate, F_1/F was plotted as a function of N_{Re} with various other Reynolds numbers being used as parameters. Figure 2 shows one case. $N_{Re}{}^D$ is used to characterize the effect of throughput rate, and $N_{Re}{}^F$ is held constant. Within experimental error, the value of $N_{Re}{}^D$ seems to have little effect on the curves, and it is concluded that $N_{Re}{}^D$ does not provide a very sensitive measure of the effect of throughput rate. In Figure 3, $N_{Re}{}^F$ is used to characterize the effect of throughput rate, and $N_{Re}{}^D$ is held constant. Changes in $N_{Re}{}^F$ have a significant effect on $F_1/F(N_{Re})$. In Figure 4, the outlet Reynolds number $N_{Re}{}^O$ is used to characterize the effect of throughput rate. For N_{Re} less than 25, there is a small effect on the curves. For higher N_{Re}, the effect disappears.

The effects of impeller speed on F_1/F were noted by Paquet and Cholette in the paper cited above. They found a minimum similar to the minimum which appears when F_1/F is plotted as a function of N_{Re} as in Figures 2, 3, and 4 for polysaccharide solutions. Paquet and Cholette offer an explanation for the existence of this minimum based on the interaction of the impeller blades and the jet of liquid from the feed pipe. Their data showing the effect of the inlet jet velocity indicate that the jet velocity has an important effect upon the dependence of F_1/F on N.

CONCLUSIONS

Residence time distributions, as represented by mixing model parameters, seem to be most sensitive to changes in $N_{Re}{}^F$. This means $N_{Re}{}^F$ is the most useful parameter for characterizing the effect of throughput rate. The jet formed by the feed stream entering the tank apparently has a strong effect on the velocity distribution within the tank, an effect best described by the jet velocity not by the jet flow rate. $N_{Re}{}^F$ is related to the jet velocity, while $N_{Re}{}^D$ is related only to the jet flow rate. The interaction of the rotating impeller blades and the feed jet seems to occur regardless of the system geometry.

NOTATION

C_o = outlet tracer concentration
C_i = reference tracer concentration
D = dilution ratio = F/V
D_i = impeller diameter
D_o = outlet diameter
D_p = inlet diameter
D_T = tank diameter
F = volumetric feed flow rate
F_1 = main flow rate
F_2 = bypass flow rate
k = consistency index
N = impeller speed
N_{Re} = $D_i^2 N^{2-\gamma}\rho/k$
$N_{Re}{}^F$ = $D_p{}^\gamma \langle v_p \rangle^{2-\gamma}\rho/k$
$N_{Re}{}^O$ = $D_o \langle v_o \rangle^{2-\gamma}\rho/k$
t = time from start of an experiment
V = vessel volume
V_b = volume of complete mixing region
V_d = volume of dead space region
V_p = volume of plug flow region
$\langle v_p \rangle$ = inlet velocity = $4F/\pi D_p{}^2$
$\langle v_o \rangle$ = outlet velocity = $4F/\pi D_o{}^2$
γ = flow behavior index
ρ = density
σ = shear rate
τ = shear stress

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