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INVESTIGATION OF FEEDPIPE BACKMIXING IN AN AGITATED VESSEL

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Abstract – Feedpipe backmixing in an agitated vessel was investigated using a newly developed conductivity technique. By this technique, the onset of feedpipe backmixing could be detected and the penetration depth of the vessel fluid into a feedpipe was determined. For a given feedpipe flowrate, critical agitator speeds to eliminate feedpipe backmixing were determined using Rushton six-bladed disk turbine impeller (6BD) and high efficiency, axial-flow type 3-bladed impeller (HE-3) of 8.89 and 12.70 cm diameters in 11.2 liter reactor. The ratio of the feedpipe velocity to the critical agitator speed (v_f/v_t) was determined as a function of feedpipe Reynolds number ($N_{Re,f}$). The conductivity technique was successful either in the laminar regime, the transitional regime, or in the turbulent regime in the feedpipe.

Key words: Conductivity Technique, Feedpipe Backmixing, Feedpipe Velocity, Critical Agitator Speed

INTRODUCTION

Many experimental studies [Belevi et al., 1981; Bourne et al., 1981b; Bourne et al., 1981c; Bourne and Rohani, 1983; Paul and Treybal, 1971; Rice and Baud, 1990] have demonstrated that the yield of desired products for fast competitive or competitive/consecutive reactions can be enhanced by increasing the homogeneity of the reagents at the molecular scale. The increase in the homogeneity can be achieved by feeding into the impeller discharge stream which is the most turbulent region of the vessel. However, high fluid velocity and turbulent intensity in the impeller discharge stream can also cause backmixing of the reactor contents into the feedpipe. The feedpipe backmixing results in side reactions within the feedpipe, where the level of turbulence is lower than that of turbulence within the agitated vessel and, consequently, decreases the yield of desired products.

The effect of feedpipe backmixing on a chemical reaction was first reported by Bourne et al. [1981a]. They investigated (in a 2.5 liter vessel with a 6BD impeller) the effect of feedpipe backmixing on the yield of desired product resulting from a fast competitive/consecutive reaction. For their largest feedpipe diameter and lowest feedpipe velocity the yield of secondary product (from the slowest reaction) was increased about 10 fold by feedpipe backmixing.

There has been no definitive study to determine the condition where feedpipe backmixing can be eliminated. Fasano and Penney [1991] have recommended that the ratio of the feedpipe velocity to the impeller tip speed (v_f/v_t) be above 0.5 to eliminate feedpipe backmixing with the feedpipe located in the impeller discharge stream. However, their recommendation was based not on experimental results, but on the knowledge of turbulent intensities in agitated vessels. Recently, Fasano et al. [1992] used a visual dye technique and determined the agitator speed at which feedpipe backmixing occurred in a vessel agitated with a 6BD impeller. They determined that for the feedpipe located in the impeller discharge stream, $v_f/v_t<0.2$ would eliminate feedpipe backmixing as evidenced by backward migration of dye within the end of the feedpipe. Unfortunately, the visual dye technique was limited to laminar feedpipe flow conditions, i.e., ($N_{Re,f}<1,300$). However, in industry, most fast reactions are conducted with turbulent feedpipe flow conditions. Therefore, a more quantitative technique is needed to determine the penetration of backmixing into a feedpipe.

The objectives of this study included: (1) development of a conductivity technique to detect feedpipe backmixing under laminar, transition, and turbulent feedpipe flow conditions, (2) determination of the critical agitator speeds to eliminate feedpipe backmixing for a given feedpipe flow rate and (3) investigation of penetration depth of the vessel fluid into feedpipe at feedpipe backmixing conditions as a function of feedpipe Reynolds number.

DEVELOPMENT OF THE CONDUCTIVITY TECHNIQUE

To detect backmixing of the vessel contents into the feedpipe, a conductivity technique was developed in the present study. This technique used the difference in the conductivity between tap water in the feedpipe and NaCl solution in an agitated vessel. To apply this concept conductivity electrodes were designed. Fig. 1 presents the schematic of the electrodes in the feedpipe. 0.5 mm diameter platinum wire was inserted through a stainless steel tube and the tube was installed on the centerline of the feedpipe. The stainless steel tube was used to hold the platinum wire and used as the counter electrode to the platinum electrode as well. Epoxy was filled into the gap between the platinum wire and the steel tube in order to fix the wire and to electrically isolate the wire from the steel tube. Both electrodes were connected to a Linear, Model 585, Dual Channel Pen-Chart Recorder. When feedpipe backmixing oc-

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curred, conductivity around the electrodes in the feedpipe was increased by backmixing of the NaCl solution in the vessel into the feedpipe. The change in the conductivity was sensed by the electrodes and the resultant output signal was recorded by the Pen-Chart Recorder.

To operate the Pen-Chart Recorder with the conductivity electrodes in the feedpipe, an electric circuit was designed as shown in Fig. 2. It was composed of a 6V battery as the eletromotive force (E.M.F.) and two resistance components. One resistance was the resistance of an external resistor, R_e, and another resistance was the resistance of tap water between the electrodes, R_p. The resistance of the tap water and the external resistor were both 16,000 Ω. The resistance, R_p, was hooked up across the Pen-Chart Recorder.

At high agitator speeds vessel turbulence will force the vessel fluid into the feedpipe, the NaCl solution will penetrate into the feedpipe to reach the electrodes and, thus, increase conductivity around the electrodes. Therefore, there is a resistance drop in the resistance, R_p and, subsequently, there is a resultant drop of V_b-V_a in the electric circuit. This voltage drop causes a change in the input signal to the Pen-Chart Recorder resulting in a peak on the strip-chart of the recorder.

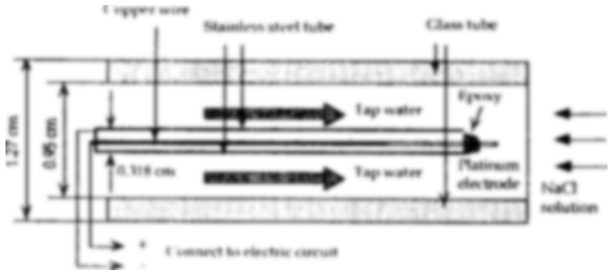

Fig. 1. Schematic of the conductivity electrode.

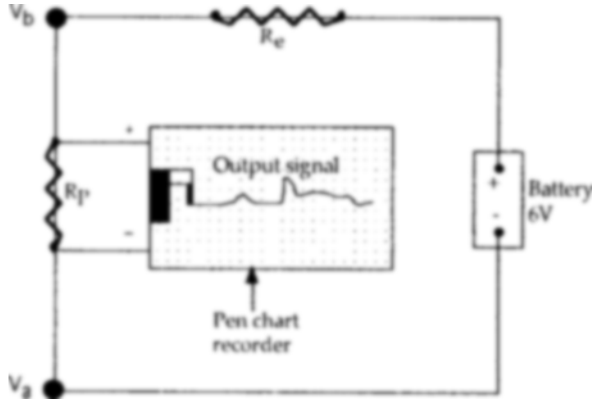

Fig. 2. Diagram of the electric circuit.

OTHER EXPERIMENTAL EQUIPMENT

A sketch of the vessel and experimental apparatus is shown in Fig. 3. The vessel was constructed of a Plexiglas® cylinder of 25.4 cm outside diameter and 0.64 cm wall thickness. The inside diameter and the height of the vessel is 24.12 cm. The top plate is 2.54 cm thick Plexiglas®. Initially, the compartment was full of tap water. Tap water was fed through the feedpipe and the overflow was routed to the drain through a pipe attached to the top plate of the vessel. A Graham Model E29VF variable speed drive was used to adjust the impeller speed. The agitator speed was measured with an Airpax Digital Tachometer. The feedpipe flow rate was measured using a Schute-Koering Lo-Flo Rotameter. The glass feedpipe was either positioned pointing towards the discharge of the impeller (at the impeller midplane) or above the impeller at a radial location of 3.8 cm from the vessel vertical centerline. The inside and outside diameters of the glass feedpipe were 0.95 cm and 1.27 cm, respectively. The conductivity electrodes were equipped inside the feedpipe. The distance between the tip of the platinum electrode and the end of the feedpipe (L) was varied from 0 to 0.95 cm into the feedpipe.

In this experiment, 6BD and Chemineer HE-3 impellers of two different diameters were used. The dimensions of the impellers are given in Table 1.

EXPERIMENTAL

At the start of an experiment the vessel was filled with tap water and water flowed into the vessel through the feedpipe.

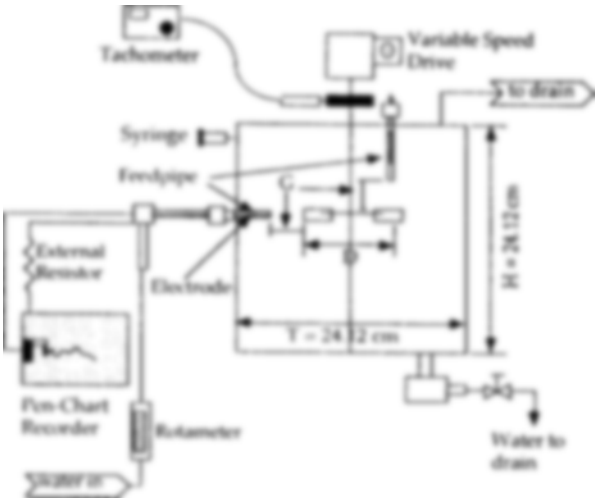

Fig. 3. Experimental apparatus for feedpipe backmixing experiment.

Table 1. Dimensions of impellers

	D (cm)	W_h (cm)	W (cm)	D_d (cm)	d_s (cm)	W_h/D	W/D	D_d/D
6BD	8.89	1.78	2.23	5.89	1.27	0.20	0.25	0.66
"	12.70	2.54	3.18	5.89	1.27	0.20	0.25	0.66
HE-3	8.89	N/S	N/A	N/A	1.27	N/A	N/A	N/A
"	12.70	"	"	"	1.27	"	"	"

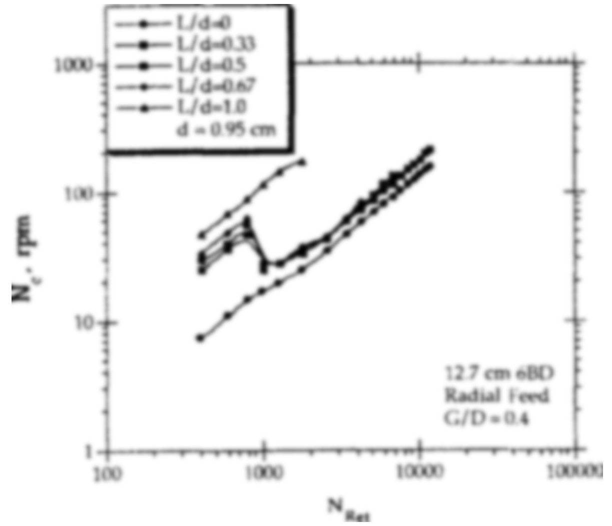

Fig. 4. N_c vs N_{Ret} for radial feedpipe location for 12.70 cm 6 BD impeller and for G=5.08 cm.

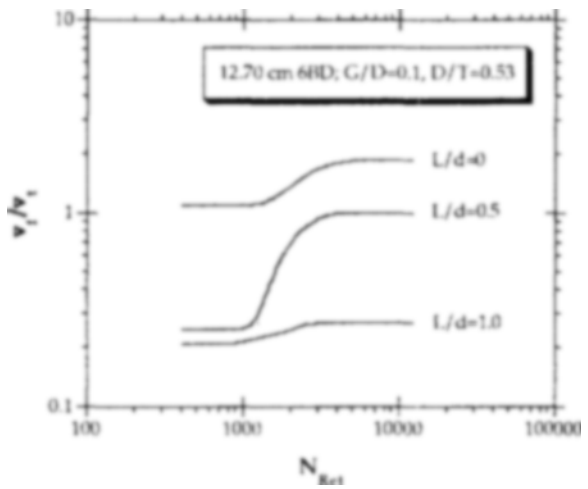

Fig. 5. Design plot for 6BD impeller, for radial feed and for G/D=0.1.

Then, 60 ml of 25 wt% NaCl solution was injected into the vessel. The agitator speed was incrementally increased until a detectable response was observed on the Strip Chart Recorder. The speed at which a detectable response was observed is the critical agitator speed, N_c, to give backmixing into the feedpipe to the vicinity of the conductivity probe. While running the experiment, 25 wt% NaCl solution was added to keep the bulk concentration at about 40 mmole/liter.

RESULTS AND DISCUSSION

A set of experiments were conducted using 6BD and Chemineer HE-3 impellers of 8.89 and 12.70 cm diameters. The feedpipe was located either (1) radially in the midplane of the impeller or (2) above the impeller. Two positions were tested for the radial orientation and only one for the above impeller location. The tip of the platinum electrode was positioned a distance, L, into the feedpipe and on its centerline. The minimum and maximum feedpipe velocities used were 3.32 and 124 cm/sec, respectively. The corresponding feedpipe Reynolds number ranged from 315 to 11,800.

1. Variation of Critical Agitator Speed (N_c) with Feedpipe Flow Rate (v_f)

Fig. 4 gives a plot of N_c vs N_{Ret} for the 12.70 cm 6BD impeller, for the radial feedpipe location, and for the ratio of the distance of the tip of the platinum electrode into the feedpipe to the feedpipe inside diameter (L/d). N_c increased with feedpipe Reynolds number, N_{Ret}, for $N_{Ret}<700$, for $0 \leq L/d \leq 1.0$. For $0.33 \leq L/d \leq 0.67$ N_c decreased as the feedpipe flow rate increased when N_{Ret} exceeded 700. This behavior indicated that the feedpipe flow probably started becoming turbulent at $N_{Ret} \simeq 700$. Actually, in this transitional regime, there existed triple values of N_{Ret} for a given agitator speed (N_c) for $0.33 \leq L/d \leq 0.67$. That is, three different values of feedpipe flow rate gave the same value of N_c as shown in Fig. 4. As the feedpipe velocity was further increased, N_c eventually increased as the flow became increasingly turbulent. These results indicate that it was more difficult for the vessel fluid to penetrate into the feedpipe counter to laminar flow than counter to turbulent flow.

2. Design Plots of v_f/v_t with N_{Ret} to Eliminate Feedpipe Backmixing

It was observed that the ratio of the feedpipe velocity to the impeller tip speed (v_f/v_t), at critical feedpipe backmixing conditions, was essentially constant for either laminar or fully turbulent flow in the feedpipe. Thus, v_f/v_t vs N_{Ret} was plotted for a given G/D and D/T as shown in Figs. 5 to 12. These plots are based on the experimental results obtained from the conductivity technique of this investigation. For a given geometrical condition and for a given feedpipe Reynolds number (N_{Ret}), equal or higher values of v_f/v_t than the values of v_f/v_t on the design plots are recommended to prevent backmixing from penetrating past the L/d indicated on the charts.

3. Effect of the Feedpipe Flow Regime on Feedpipe Backmixing

As shown in Figs. 5 to 12, the values of v_f/v_t in the laminar regime was lower than those of v_f/v_t in the turbulent regime. v_f/v_t started increasing at the start of the transitional regime where the feedpipe Reynolds number was about 700, and where turbulent flow probably started to occur in the feedpipe. v_f/v_t finally became constant at the start of fully turbulent flow in the feedpipe where the feedpipe Reynolds number was about 3,000. Thus, relatively higher agitator speeds were needed in the laminar regime than in the turbulent regime to cause backmixing of the vessel fluid into the feedpipe to a given location. This finding indicates that it is more difficult for the vessel fluid to penetrate into the feedpipe counter to laminar flow than counter to turbulent flow.

4. Effect of the Feedpipe Location and Impeller Type on Feedpipe Backmixing

For the 8.89 cm 6BD impeller, experiments were conducted with the same geometrical conditions of D/T=0.37 and G/D=0.8 both for the above impeller feedpipe location and for the radial feedpipe location. Therefore, the effect of the feedpipe location on feedpipe backmixing could be compared directly using data for the two locations.

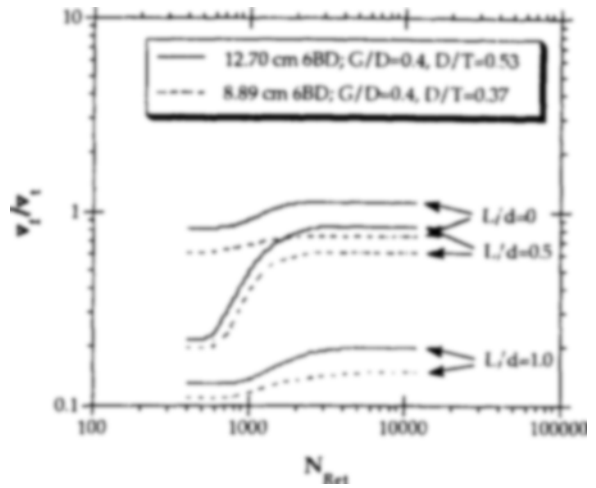

Fig. 6. Design plot for 6BD impeller, for radial feed and for G/D=0.4.

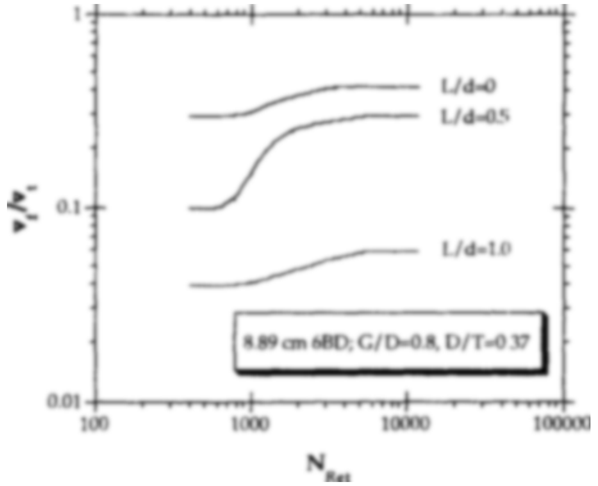

Fig. 7. Design plot for 6BD impeller, for radial feed and for G/D=0.8.

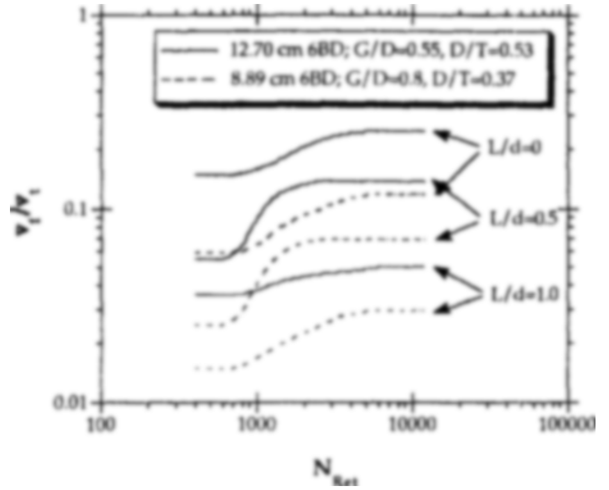

Fig. 8. Design plot for 6BD impeller and for above impeller feed.

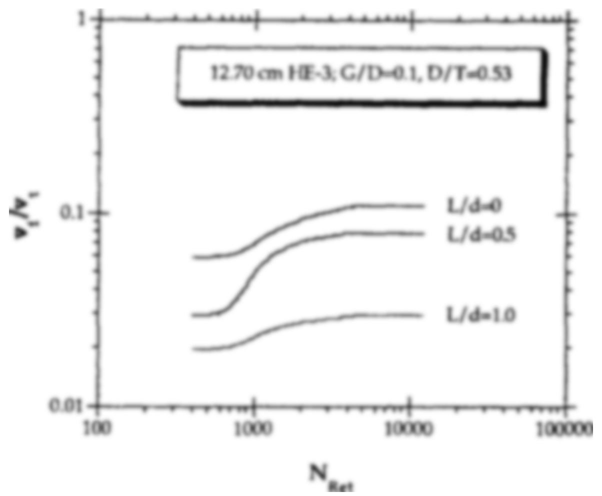

Fig. 9. Design plot for HE-3 impeller, for radial feed and for G/D=0.1.

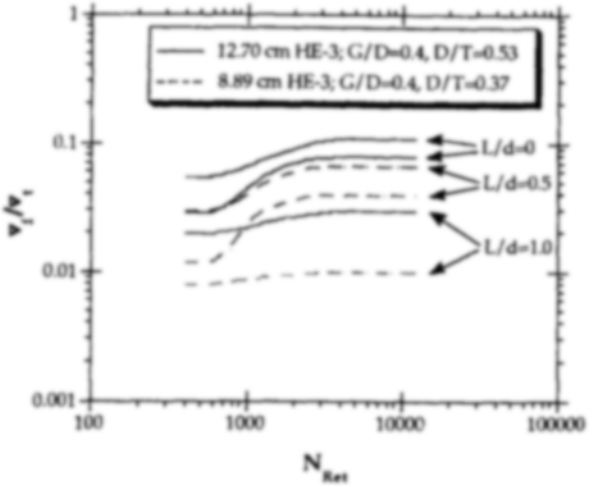

Fig. 10. Design plot for HE-3 impeller, for radial feed and for G/D=0.4.

As shown in Figs. 7 and 8, v_f/v_t for the above impeller feedpipe location was significantly lower (about 4 times) than v_f/v_t for the radial feedpipe location. This result was attributed to the fact that the disk turbine impeller is a radial flow impeller and has a principal direction of discharge normal to the axis of rotation. Therefore, velocities and turbulent energy dissipation are much higher in the impeller discharge stream than for above (or below) impeller locations. Consequently, for a given feedpipe velocity (v_f), higher agitator speeds (v_t) were needed to cause feedpipe backmixing for the above feedpipe location than for the radial feedpipe location.

On the contrary, for the 8.89 cm HE-3 impeller with the same D/T=0.37 and G/D=0.8, overall v_f/v_t for the above impeller feedpipe location was higher than v_f/v_t for the radial feedpipe location as shown in Figs. 11 and 12. This is because the HE-3 impeller is an axial impeller and has a principal direction of discharge in the axial direction. Consequently, for a given feedpipe velocity, relatively lower agitator speeds were needed to cause feedpipe backmixing for the above feedpipe location than for the radial feedpipe location.

5. Comparison of Results with the Results of Other In-

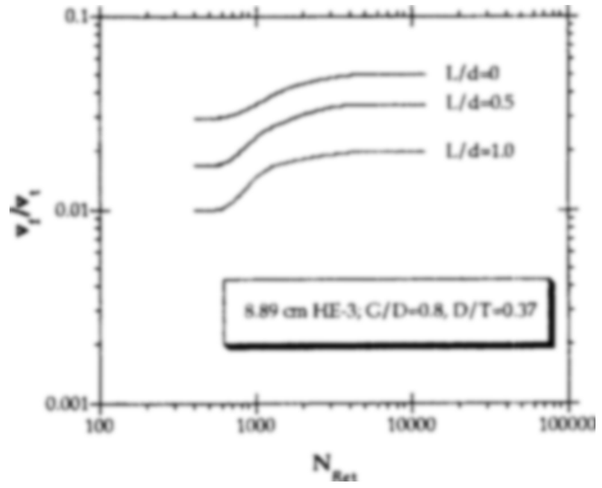

Fig. 11. Design plot for HE-3 impeller, for radial feed and for G/D=0.8.

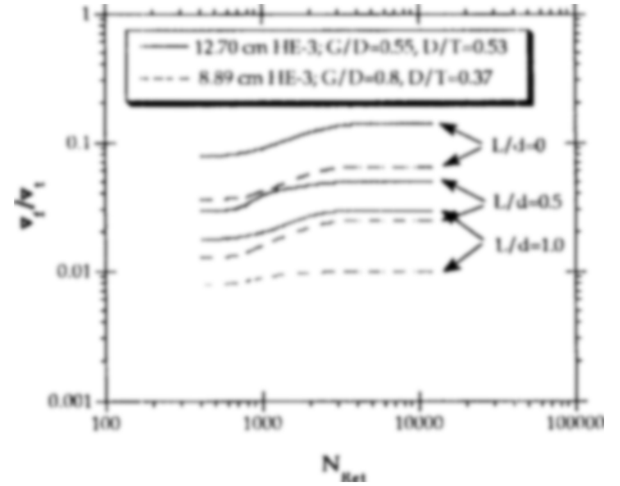

Fig. 12. Design plot for HE-3 impeller and for above impeller feed.

vestigators

The current results were compared with the previous results of Fasano et al. [1992] for backmixing determination using a dye detection technique and with the results of Bourne et al. [1981] for backmixing determination using a pair of consecutive/competitive reactions (Bourne's first reaction).

For the 12.70 cm 6BD impeller, v_f/v_t of the dye technique was consistent with v_f/v_t for L/d=1.0 of this investigation for all feedpipe locations (radial feed or above impeller feed) . For the 8.89 cm 6BD impeller, v_f/v_t of the dye technique was consistent with v_f/v_t for $0.33 \leq L/d \leq 0.67$ of this investigation. This comparison indicates that the dye technique is only capable of detecting backmixing which penetrates 1/3 to 1.0 feedpipe diameter into the feedpipe.

Bourne et al. [1981] used a 6BD impeller with below impeller feed injection. Their yield of primary reaction was lowered by feedpipe backmixing. The smallest value of v_f/v_t, to provide feedpipe backmixing which lowered the yield of the primary product (from the faster reaction), was consistent with v_f/v_t for $0.33 \leq L/d \leq 0.67$ from the conductivity technique. From the comparison, it appears that feedpipe backmixing must penetrate at least to L/d=1/3 to produce a significant effect of backmixing on Bourne's first reaction.

CONCLUSIONS

A sensitive conductivity technique was successfully developed to determine the depth of penetration of bulk vessel turbulence into a feedpipe. The ratio of feedpipe velocity to impeller tip speed (v_f/v_t) versus feedpipe Reynolds number (N_{Ret}), for a given impeller and vessel geometry, was used to characterize and correlate feedpipe backmixing.

It was observed that it was more difficult for the vessel fluid to penetrate into the feedpipe counter to laminar flow than counter to turbulent flow.

For the radial feedpipe location, v_f/v_t decreased as G/D increased for both 6BD and HE-3 impellers. However, for 6BD impellers, v_f/v_t for the above feedpipe location was significantly lower than v_f/v_t for the radial feedpipe location and, for HE-3 impellers, v_f/v_t for the radial feedpipe location was lower than v_f/v_t for the above feedpipe location.

NOMENCLATURE

6BD : Rushton 6 bladed disk turbine impeller
D : impeller diameter [cm]
D_d : impeller disk diameter [cm]
d : feedpipe diameter [cm]
d_s : shaft diameter [cm]
G : spacing between feedpipe end and impeller blade tip [cm]
H : batch height in stirred tank reactor [cm]
HE-3: high efficiency, axial-flow type 3 bladed impeller
L : distance of the platinum electrode tip from the feedpipe end [cm]
N : impeller rotational speed [rpm]
N_c : critical impeller rotational speed [rpm]
N_{Ret} : feedpipe Reynolds number=$v_f d\rho/\mu$
R_e : resistance of the external resistor [Ω]
R_p : resistance of tap water between the electrodes [Ω]
T : diameter of stirred tank reactor [cm]
V_b-V_a : voltage drop across R_p [volt]
v_f : feedpipe velocity [cm/s]
v_t : impeller tip speed [cm/s]=πND
W : impeller blade width [cm]
W_h : impeller blade height [cm]

Greek Letters

μ : viscosity [g/cm s]
ρ : density [g/cm^3]

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