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Using tomography to visualize the continuous-flow mixing of biopolymer solutions inside a stirred tank reactor

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HIGHLIGHTS

- Continuous-flow mixing of the biopolymer solutions was studied using 2D and 3D tomograms.
- Effects of six various operating conditions and design parameters were investigated.
- An efficient flow visualization method for the opaque fluids was demonstrated.
- Non-ideal flows such as channeling and dead zones inside the reactor were identified.
- The rheology of the biopolymer solution had a significant effect on the mixing quality.

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ABSTRACT

The vast majority of non-Newtonian fluids are naturally opaque; therefore, visualizing the flow field of such fluids inside a reactor is a challenging task. To identify non-ideal flows, such as dead volumes and channeling, in a continuous-flow mixing system, the flow field inside a stirred tank reactor was visualized using electrical resistance tomography (ERT), an efficient non-intrusive measurement technique. The key objective of this study was to employ the ERT technique in order to explore the effects of the inlet and outlet locations (four configurations: top inlet–bottom outlet, bottom inlet–top outlet, bottom inlet–bottom outlet, and top inlet–top outlet), fluid rheology (0.5–1.5% xanthan gum concentration), jet velocity (0.317–1.660 m s^{-1}), feed flow rate (5.3×10^{-5}–2.36×10^{-4} m^3 s^{-1}), impeller type (the Rushton turbine and Maxblend impellers), and impeller speed (54–250 rpm) on the flow patterns generated in the continuous-flow mixing of the xanthan gum solution, which is a pseudoplastic fluid exhibiting yield stress. Using 2D and 3D tomography images, this article effectively presents a competent method to visualize the flow of opaque fluids in laminar and transitional regions inside a reactor. In this study, the existence of non-ideal flows in a stirred tank reactor for opaque fluids was identified using ERT. The quantitative results showed that the tracer distribution (or mixing quality) inside stirred vessel was enhanced by decreasing the fluid yield stress, increasing the impeller speed, increasing the jet velocity, and using the close clearance impeller. The results also showed that the location of the inlet and outlet streams has a significant effect on the mixing quality. To improve the design of the continuous-flow mixing of non-Newtonian fluids, the findings of this study can be integrated into the design criteria to achieve optimal mixing results.

1. Introduction

To enhance the degree of homogeneity in a system, mixing operations are commonly used in the chemical and related process industries such as polymer processing, drinking water and wastewater treatment, pulp and paper, cosmetic and pharmaceutical, and food processing. Non-Newtonian fluids exhibiting yield stress such as wastewater sludge, certain polymer and biopolymer solutions, and pulp suspension are often encountered in the aforementioned industries. Mixing is normally carried out in a continuous or batch mode in stirred tanks. Compared to batch mixing, continuous-flow mixing is more advantageous as it improves process control, provides high production rate, and saves operation time and labor cost. The design of continuous-flow mixing systems for the non-Newtonian fluids is more challenging than that for the Newtonian fluids because of the complex rheology of non-Newtonian fluids. Non-Newtonian fluids form a stagnant zone in a stirred vessel away from the impeller, where the impeller-imparted shear stress fails to exceed fluid yield stress. The studies on the yield stress fluids have shown that non-ideal flows such as channeling, recirculation, and dead volumes significantly influence

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Nomenclature

A	cross section area of the inlet pipe (m^2)
A_i	swept area by the impeller (m^2)
D	impeller diameter (m)
D_c	cavern diameter (m)
f	percentage of channeling (fraction)
H	fluid height in the vessel (m)
H_c	cavern height (m)
K	consistency index (Pa s^n)
K_s	Metzner–Otto constant (–)
M	torque (N m)
n	power-law index (–)
n_e	number of electrodes (–)
N	impeller rotational speed (s^{-1})
N_Q	dimensionless impeller flow number (–)
P	power (W)
P_o	power number (–)
$P1$–$P6$	plane number (–)
Q	volumetric flow rate ($m^3\ s^{-1}$)
$Q_{impeller}$	impeller pumping rate ($m^3\ s^{-1}$)
Re	Reynolds number (–)
r	cylindrical coordinates (m)
T	tank diameter (m)
v	velocity of the fluid passing through the inlet (m s^{-1})
V_c	cavern volume (m^3)
$V_{fully\ mixed}$	fully mixed volume (m^3)
V_j	jet velocity (m s^{-1})
υ_{tip}	impeller tip velocity (m s^{-1})
V or V_{total}	fluid volume inside the mixing tank (m^3)
z	cylindrical coordinates (m)

Greek letters

Φ	cylindrical coordinates (°)
$\dot{\gamma}$	shear rate (s^{-1})
$\dot{\gamma}_{avg}$	average shear rate (s^{-1})
η	apparent viscosity (Pa s)
ρ	fluid density (kg m^{-3})
τ_s	shear stress (Pa)
τ_y	fluid yield stress (Pa)

Abbreviations

2D	two-dimensions
3D	three-dimensions
BI	bottom inlet
BO	bottom outlet
DAS	data acquisition system
ERT	electrical resistance tomography
LDV	laser Doppler velocimetry
rpm	revolution per minute
RT	Rushton turbine
RTD	residence time distribution
TI	top inlet
TO	top outlet

the performance of the continuous-flow mixing systems [1]. The existence of non-ideal flows within a mixing vessel leads to an ineffective heat and mass transfer, which results in end products with poor quality, production loss, and product degradation. The stagnant zone also leads to inefficient use of vessel volume. To improve the efficiency of continuous-flow mixing systems, these non-ideal flows should be eliminated or minimized in stirred vessels.

Some studies have been carried out to investigate the continuous-flow mixing of Newtonian fluids in stirred vessels. Roussinova and Kresta [2] studied the continuous-flow mixing of Newtonian fluids using a spectrophotometer and found that for the design of an ideal mixer, the ratio of the residence time to the batch mixing time should be less than 10 and a line from the inlet to the outlet should pass through the impeller. The fluid flow of the continuous-flow mixing of Newtonian fluids was simulated by Khopkar et al. [3] using computational fluid dynamics (CFD). They observed that the locations of the inlet and outlet affect the performance of continuous-flow mixing systems. The effect of the pumping direction of an axial flow impeller in the continuous-flow mixing of Newtonian fluids was investigated by Aubin et al. [4] using CFD. They concluded that channeling through the bottom outlet may be reduced when the impeller was employed in the up-pumping mode instead of the down-pumping mode. Samaras et al. [5] studied the continuous-flow mixing of Newtonian fluids using the residence time distribution (RTD) and CFD. They observed that the mixing of Newtonian fluids with the axial-flow impellers was prone to channeling when the location of the outlet was directly below the impeller discharge; however, this problem was not observed when a radial-flow impeller was used. Mavros et al. [6–8] studied the continuous-flow mixing of Newtonian fluids using the laser Doppler velocimetry (LDV) and found that non-ideal flows such as channeling are likely to occur in a mixer if the ratio of the residence time to the batch mixing time is less than 10. The aforementioned studies are about the Newtonian fluids.

Some researchers have also studied the continuous-flow mixing of non-Newtonian fluids in stirred vessels. Using ERT and dynamic tests, Patel et al. [9] characterized the continuous-flow mixing of non-Newtonian fluids with yield stress using the ratio of residence time to the batch mixing time. They found that this ratio should be at least 8.2 to achieve ideal mixing; otherwise non-ideal flows are likely to occur in the continuous-flow mixing system. Ein-Mozaffari et al. [10] and Patel et al. [11] explored the effect of impeller size on the performance of the continuous-flow mixing of non-Newtonian fluids with yield stress using dynamic tests. They found that the efficiency of the continuous-flow mixer improved as the impeller diameter was increased. The performance of a continuous-flow mixing system also depends on the fluid rheology [12] and fluid feed flow rate [13,14]. The dynamic test results showed that the extent of non-ideal flows, such as channeling and dead volume, increased when the fluid yield stress as well as the fluid flow rate were increased in the mixing of non-Newtonian fluids exhibiting yield stress [15,16]. Ford et al. [17] studied the fluid flow of pulp suspensions (a non-Newtonian fluid) in an agitated pulp stock chest equipped with a side-entering impeller using CFD. They found that with the inlet at the top of the vessel, the extent of non-ideal flows was reduced using the bottom outlet compared to the side outlet. The effect of the fluid height in the vessel, types of impeller (axial-flow, radial-flow, and close clearance), impeller off-bottom clearance, residence time, and jet velocity on the dynamic performance of the continuous-flow mixing of non-Newtonian fluids were explored by Patel et al. [11] using dynamic tests. They found that the extent of non-ideal flows decreased when the clearance of the impeller was increased from $H/3.4$ to $H/2.1$ and the jet velocity was increased from 0.317 to 1.66 m s^{-1}. Furthermore, as the fluid height in the vessel was increased, the extent of non-ideal flows also increased. In addition, increasing the residence time of the fluid in the vessel decreased non-ideal flows. Jones et al. [18] evaluated the performance of the continuous-flow mixing using the momentum ratio (the ratio