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Proceeding Paper

Analysis of Local Shear Rate Distribution in a Double Coaxial Bioreactor Containing Biopolymer Solutions Using Computational Fluid Dynamics †

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Abstract: Uniform gas dispersion and shear distribution in highly viscous non-Newtonian fluids is challenging due to the complex rheological behavior exhibited by this type of media. In addition, most large-scale bioreactors in biochemical processes such as wastewater treatment and fermentation demand higher aspect ratios (i.e., fluid height to tank diameter ratio) than laboratory-scale bioreactors. This, in turn, underlines uneven gas and shear distribution throughout the bioreactor, especially those comprising yield-pseudoplastic fluids. For this type of fluid, there are two distinct zones within the bioreactor, a higher-shear zone with a lower apparent viscosity around the impeller and a lower-shear area with a higher apparent viscosity away from the impeller. Due to the viscosity gradient, homogeneous gas dispersion within a single impeller aerated bioreactor with an aspect ratio of more than one is hard to attain. It has been reported that a well-designed mixing configuration contributes to maintaining a consistent fluid viscosity, resulting in improved mixing performance and consistent final product quality. Recent studies have demonstrated the superior performance of double coaxial bioreactors furnished with two central impellers and one anchor for uniform shear distribution and gas dispersion in pseudoplastic fluids. Despite the widespread use of yield-pseudoplastic fluids in various industries, a knowledge gap was identified for analyzing the shear distribution within the double coaxial mixers containing pseudoplastic fluids possessing yield stress. This study examined the effect of four coaxial mixing configurations, including down-pumping and co-rotating, up-pumping and co-rotating mode, down-pumping and counter-rotating, and up-pumping and up-pumping and up-pumping and counter-rotating modes on the local shear rate distribution. In this regard, computational fluid dynamics (CFD) was employed for the evaluation of the local shear distribution within the coaxial bioreactor.

Keywords: double coaxial mixer; yield-pseudoplastic fluids; local shear distribution; computational fluid dynamics

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1. Introduction

Aerated mixing bioreactors have been extensively used in chemical and biochemical operations [1]. While mixing of Newtonian fluids has been commonly used in various industries, mixing processes including non-Newtonian fluids are gaining popularity because of their numerous applications in biofermentation processes [2]. However, comprehending the fluid hydrodynamics has become difficult because of the intricate rheological characteristics of highly viscous non-Newtonian fluids. The complicated rheological characteristics demonstrated by fermentation broth have a considerable impact on the mixing efficiency of bioreactors, encompassing gas dispersions, flow pattern, power consumption, and gas-liquid mass transfer [3].

Moreover, most of the bioreactors employed in large-scale biochemical operations, including wastewater treatment, fermentation, and pharmaceutical manufacturing, require greater aspect ratios (i.e., fluid height to tank diameter ratio) compared to laboratory-scale bioreactors [4]. Consequently, this highlights the issue of non-uniform gas and shear distribution throughout the bioreactor, particularly in those containing yield-pseudoplastic fluids [5]. As reported in the literature, enhancing the impeller rotational speed and aeration rate can partially offset the increase in broth viscosity during aerobic fermentations, leading to maintaining appropriate volumetric mass transfer coefficient values. However, a high shear environment owing to higher impeller rotational speeds can cause severe damage to the morphology of microorganisms [6].

The literature showed that a well-designed mixing bioreactor plays a crucial role in maintaining a more uniform apparent viscosity of the shear-thinning fluids, leading to improved mixing performance and consistent final product quality [7]. Coaxial mixers have been demonstrated to be a suitable design, particularly for systems containing shear-sensitive microorganisms since these systems minimize the maximum shear rate and promote a more uniform mixing process, resulting in reduced dead zones [8]. By combining the advantages of small and large-diameter impellers, coaxial mixers offer an effective solution for addressing the uneven gas dispersion and shear rate distribution that plagues conventional mixers containing highly viscous non-Newtonian fluids [9]. Recent studies revealed the superior performance of double coaxial bioreactors equipped with two central impellers and one anchor to achieve more uniform shear distribution and gas dispersion for pseudoplastic fluids [5]. Even though yield-pseudoplastic fluids are widely used in numerous industries, a knowledge gap was found in analyzing the shear distribution within double coaxial mixers containing pseudoplastic fluids with yield stress. Therefore, the main objective of this study was to evaluate the effect of different mixing configurations including the rotational mode (i.e., co-rotating and counter-rotating) and pumping direction of the central impeller (i.e., downward and upward) on the local shear rate distribution of an aerated double coaxial mixier containing yield-pseudoplastic fluids. In this regard, the computational fluid dynamics (CFD) technique was employed to analyze the local shear rate distribution within an aerated double coaxial mixier containing 1 wt% xanthan gum solution with an aspect ratio of 1.25.

2. Materials and Methods

The working fluid employed in this study was xanthan gum solution with a concentration of 1 wt%, a shear-thinning fluid possessing yield stress. The rheological characteristics of the Herschel-Bulkley model, including the yield stress (τ_y) consistency index (K) and flow index (n), were determined using a Kinexus Pro+ Rheometer (Malvern Instruments, USA) at a temperature of 22 °C, which was the operating temperature of the experiments. The resulting rheograms obtained from bob and cup geometry were used to plot the shear stress versus shear rate. Table 1 presents the rheological properties of the 1.0 wt% xanthan gum solution used in this research.

The experiments were carried out in a flat-bottom cylindrical stirred tank equipped with a double impeller coaxial mixer. The coaxial bioreactor had a working volume of 62.8 L and an aspect ratio of 1.25. The coaxial mixer used in the experiment consisted of two coaxial shafts, with two centrally mounted pitched blade impellers installed on the top shaft and a close clearance anchor installed on the bottom shaft. The top and bottom shafts were driven by two separate electrical motors and controlled by frequency inverters to test four different mixing configurations, including up-pumping and co-rotating, down-pumping, and co- rotating mode, up-pumping and counter-rotating, and down-pumping and counter-rotating were tested in the experiments. A circular sparger with 20 pores was located at a 0.1 m clearance from the tank bottom to disperse air within the mixing system. The airflow rate was measured and controlled using a rotameter and a control valve.

Table 1. The rheological properties of xanthan gum solution.

Density, ρ (kg/m^3)	978
Yield stress, τ_y (Pa)	2.047
Consistency index, k (Pa.s^n)	10.113
Power law index (n)	0.184

3. Numerical Approach

The present study utilized the commercial software ANSYS FLUENT V.2022, which operates on the finite volume method, to conduct simulations. The laminar flow model was employed for the numerical simulation of the shear-thinning fluid with yield stress [10]. The sliding mesh approach was adopted to model the impeller's rotation, which allowed for the reconstruction of transient information on the flow fields. The computational zone was discretized using non-uniform tetrahedron grid cells. Three distinct mesh configurations consisting of 774,330, 1,368,748, and 2,824,553 cells were implemented to ensure the grid's independence in the obtained results. By increasing the number of cells from 774,330 to 1,368,748, the error percentage for the volume-averaged liquid velocity and overall gas hold-up was reduced by 19.0% and 31.1%, respectively. Further increase in cell number from 1,368,748 to 2,824,553 resulted in minor deviations of 3.3% and 2.2% in volume-averaged liquid velocity and global gas hold-up, respectively. The mesh with 1,368,748 grid cells was the optimal choice since the results obtained with the second and third meshes did not differ significantly. The CFD modeling employed the SIMPLE algorithm to couple the pressure and velocity equations. The momentum equation was discretized using the second-order upwind scheme, and a second-order implicit scheme was adopted for time advancement. The simulations achieved a pseudo-steady state within 72 revolutions of the central impellers. To attain convergence within each time step, 20 iterations were executed to ensure that every normalized residual fell below the prescribed convergence tolerance of 10^{-7}. Additionally, dynamic gas hold-up profiles were monitored for four ERT planes, and it was observed that after almost 72 revolutions the local gas hold-up profiles reached the pseudo-steady-state condition, which shows the simulation has converged. Parallel computing on 12 CPUs was utilized to achieve convergence of each simulation, which took between 168 to 240 h.

3.1. Results and Discussion

As mentioned previously, investigating the effects of different operating conditions and design parameters on shear rate distribution is of great importance. Accordingly, this study examined the impact of various mixing configurations, such as down-pumping and co-rotating, up-pumping and co-rotating, down-pumping and counter-rotating, and up-pumping and counter-rotating on the local shear distribution. Figure 1 shows that the red regions near the central impeller's blades correspond to the highest values of the shear rate, which is due to the higher energy dissipation rate by the central impellers. A comparison between the downward pumping and upward pumping mode of the central impellers indicates that a higher shear rate was concentrated near the central impellers in the down-pumping mode. Furthermore, it was observed that the local shear rate was distributed more non-uniformly in the down-pumping and counter-rotating mode, with the lowest shear rate at the bottom of the coaxial mixer bioreactor and near the liquid surface. According to Figure 1, it can be concluded that among various mixing configurations, up-pumping and co-rotating modes led to a more homogenous local shear rate distribution in the double coaxial mixing system containing yield-pseudoplastic fluids.

Upon analyzing the apparent viscosity contours, a reduction in apparent viscosity was observed in proximity to the central impellers, where the shear rate was found to be high. As illustrated in Figure 2, an uneven apparent viscosity distribution was obtained in the down-pumping and counter-rotating mode, with the highest apparent viscosity at the top and bottom of the bioreactor. The apparent viscosity contours show a more uniform apparent viscosity distribution within the double coaxial mixing bioreactor in the up-pumping and co-rotating mode, which also confirms the results obtained by shear rate contours. It can be concluded that the synergistic impact of the central impellers and anchor in the up-pumping and co-rotational mode led to a more even shear distribution within the system, resulting in improved mixing performance.

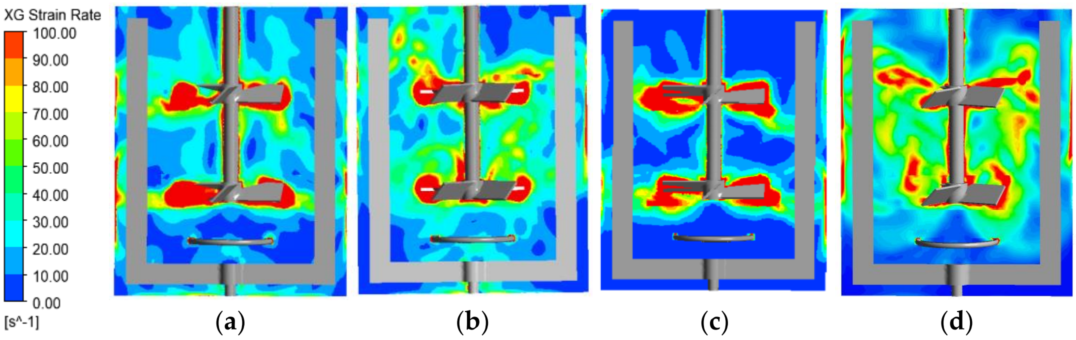

Figure 1. Shear rate contours for different mixing configurations at N_a = 10 rpm, N_c = 350 rpm, and an aeration rate of 0.16 vvm: (**a**) down-pumping and co-rotating, (**b**) up-pumping and co-rotating, (**c**) down-pumping and counter-rotating, and (**d**) up-pumping and counter-rotating.

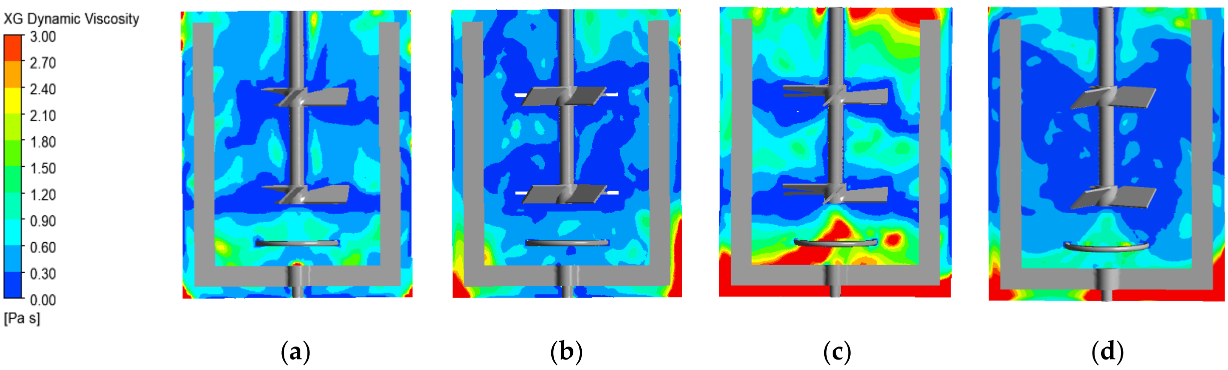

Figure 2. Apparent viscosity contours for different mixing configurations at N_a = 10 rpm, N_c = 350 rpm, and an aeration rate of 0.16 vvm: (**a**) down-pumping and co-rotating, (**b**) up-pumping and co-rotating, (**c**) down-pumping and counter-rotating, and (**d**) up-pumping and counter-rotating.

4. Conclusions

This study compared the impact of various configurations, including down-pumping and co-rotating, up-pumping and co-rotating, down-pumping and counter-rotating, and up-pumping and counter-rotating on the local shear distribution in a dual coaxial mixing system containing 1 wt% xanthan gum solution, a yield-pseudoplastic fluid possessing yield-stress. It was found that the down-pumping and counter-rotating mode led to a non-uniform local shear rate distribution. Additionally, the synergistic impact of the central impellers and anchor in the up-pumping and co-rotational mode favored a more even shear distribution, resulting in reduced apparent viscosity and improved mixing performance.

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