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Hydrodynamics and Gas Hold-Up of a Gas-Liquid Coaxial Mixing System at Different Scales Containing a Non-Newtonian Fluid †

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Abstract: The gas-liquid mixing phenomenon in a mixing tank containing a non-Newtonian fluid is an important process in many industrial applications, such as chemical and biochemical processing. The design and optimization of the aerated mixing tank with such characteristics is a challenging task. Most of these challenges are due to the non-Newtonian behavior of the fluid, which can lead to compartmentalization of the mixing tank, and formation of oxygen segregated zones. These issues become more pronounced at larger scales. Therefore, the primary objective of this study was to identify the mixing dead zones and determine their impact on the overall mixing process for the coaxial mixing system at two different scales. This research focused on the evaluation of the hydrodynamics attained by a coaxial gas-liquid mixing tank through numerical and experimental methods. The study was conducted using computational fluid dynamics (CFD) and the electrical resistance tomography (ERT) method. The effects of the aeration rate, inner impeller speed, and rotating mode on the creation of dead zones were investigated.

Keywords: multiphase flow; coaxial mixing system; computational fluid dynamics; gas hold-up; non-newtonian fluid

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1. Introduction

Gas-liquid mixing systems play a crucial role in chemical and biochemical industries specifically at a large scale. Due to the high operational costs, it is essential to achieve an optimal mixing and better productivity in the gas-liquid mixing systems [1]. The occurrence of mixing segregation zones inside a mixing vessel can have detrimental effects on the mass transfer efficiency, energy dissipation rate distribution, and apparent viscosity of the fluid. This is particularly significant for a mixing tank containing fluids that exhibit shear-thinning behavior. As a result, the presence of such zones must be minimized to ensure optimal performance of the mixing vessel [2,3].

Recent studies have been demonstrated that the gas dispersion in coaxial mixing tanks provides a desirable performance for achieving uniform hydrodynamics in non-Newtonian fluids [4–6]. A coaxial mixing system comprises a vessel furnished with a central impeller and an anchor impeller. According to the comprehensive literature review, the effect of the mixing segregation zones on efficacy of the coaxial system has not been reported. Hence, the primary objective of this study was to explore the gas hold-up and hydrodynamics obtained by the coaxial mixer at various aeration rates, impeller speeds, rotating mode, and the vessel sizes.

2. Material and Methods

2.1. Experimental Method

In our research laboratory, two cylindrical coaxial mixing vessels with flat bottoms were fabricated. The diameters of the vessels were 0.4 and 0.6 m. The aspect ratio, which is the ratio of the fluid height inside the vessel to the diameter of the vessel, was maintained at one for both aerated mixing vessels. Both large-scale and small-scale vessels were fitted with an anchor impeller and a central impeller. The Scaba impeller was used as a central impeller in this study. The central impeller diameters for the small-scale and large-scale mixer were 18 and 27 cm, respectively. Additionally, a ring sparger was employed to supply air into the mixing vessel. Operating conditions of the experiments are listed in Table 1.

Table 1. Operating conditions.

Vessel	Aeration Rate (vvm)	Central Impeller Speed (rpm)	Anchor Impeller Speed (rpm)
Small-scale	0.12	350	10
Large-scale	0.12–0.20	230–450	10

The research utilized a non-Newtonian fluid consisting of a 0.5 wt% concentration of carboxymethyl cellulose (CMC) solution. The rheological behavior of the prepared solutions was examined using a Bohlin C-VOR Rheometer 150, manufactured by Malvern Instruments, UK. The rheological properties of the CMC solution at an ambient temperature of 22 ± 1 °C followed the power-law model. The consistency index and power law index were found to be 0.387 Pa.s^n and 0.8591, respectively.

The study utilized a non-invasive electrical resistance tomography (ERT) technique to measure the gas hold-up profile within the coaxial mixer. The adjacent measurement protocol was employed, with a predetermined frequency of 38.4 kHz and a current of 75 mA. This involved applying a current to electrodes attached to the mixing tank wall, and acquiring voltage measurements that were translated into quantitative data of the conductivity profile inside the coaxial mixer. The simplified Maxwell equation was then used to calculate the gas hold-up inside the mixer based on the conductivity data. Four sensor planes were installed in the mixing vessels at specific heights, with the small-scale mixing tank having planes at heights of 330 mm, 275 mm, 220 mm, and 165 mm, and the large-scale mixing vessel having planes at heights of 460 mm, 350 mm, 230 mm, and 120 mm, from the bottom of mixing tank. Each plane was equipped with 16 rectangular stainless steel electrodes.

2.2. Numerical Method

To simulate the gas-liquid hydrodynamics inside the coaxial mixer, the Eulerian-Eulerian multiphase model was utilized. The k-ε turbulence model was employed to account for the turbulence nature of the liquid phase. The Sato and Sekoguchi [7] model was used to describe the effect of bubble-induced turbulence on the hydrodynamics of the gas phase. The momentum balances for the gas and liquid phases were coupled by considering the modified Brucato et al. [8] drag force. The other forces had a negligible effect on the simulation results.

The momentum and volume fraction were discretized using second-order upwind and QUICK techniques. Unstructured tetrahedral meshes were used to create the solution domain grid. The sparger area was designated as stationary while the area close to the central impeller was treated as a moving zone. The remaining areas were classified as a moving zone influenced by the anchor impeller. The degassing boundary condition was applied to the surface of the working liquid, while no-slip boundary conditions were used for the other walls. To add air to the mixing tank, a mass flow rate boundary condition was applied to the upper surface of the sparger. The governing equations were solved using ANSYS FLUENT software (2020 R1). After conducting a grid independence test, it was determined that the CFD model with 1,673,962 grids and 4,673,692 grids could be used with reasonable accuracy for the small-scale and large-scale models, respectively.

3. Results and Discussion

The gas hold-up profile obtained from the ERT method for the coaxial mixer equipped with 50 L vessel is shown in Figure 1. This coaxial mixer was furnished with a Scaba and an anchor impeller. It was found that the flow regime obtained by the co-rotating coaxial mixer at a central impeller speed of 350 rpm, anchor impeller speed of 10 rpm, and an aeration rate of 0.12 vvm was under the complete gas dispersion condition. In fact, as can be seen in Figure 1, under these operating conditions the gas hold-up was uniformly distributed inside the mixing vessel.

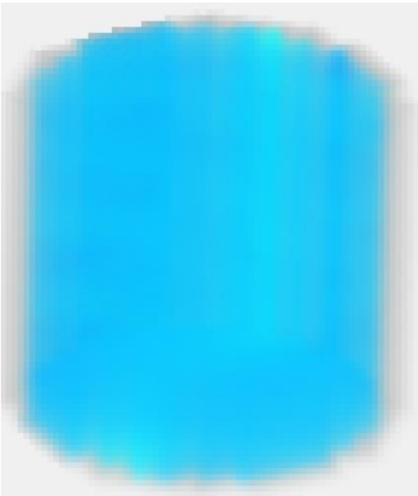
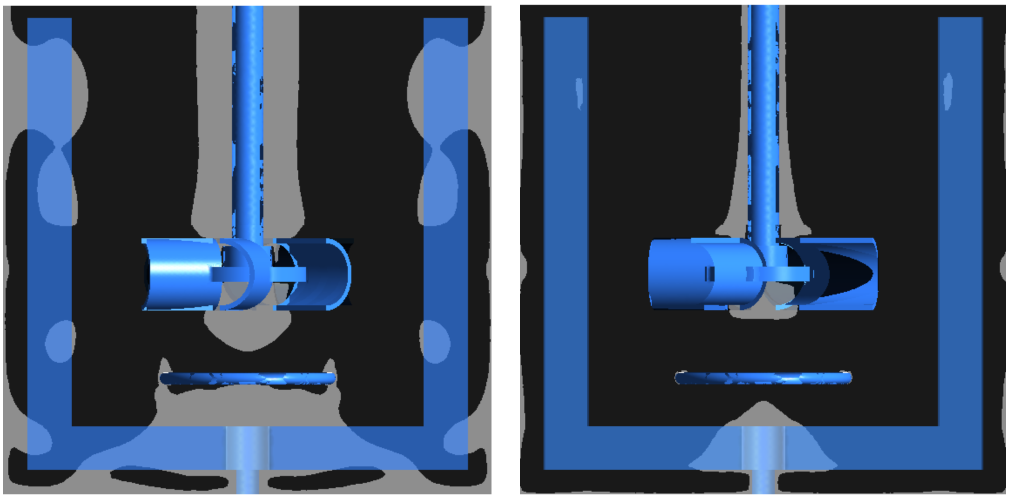


Figure 1. 3D tomogram obtained from the ERT method for gas dispersion inside the small-scale coaxial mixer equipped with the Scaba impeller at the co-rotating mode (central impeller speed = 350 rpm, anchor impeller speed = 10 rpm, and aeration rate = 0.12 vvm).

To evaluate the performance of the large-scale coaxial mixer, the gas hold-up and hydrodynamics inside the 170-L coaxial mixing vessel were investigated. It was discovered that the gas hold-up obtained in the co-rotating mode was higher than that attained in the counter-rotating mode. In addition, it was observed that by increasing the aeration rate the gas phase retention inside the mixing vessel increased.

In addition, the present study aimed to maintain similar performance between the small-scale and large-scale coaxial mixers. Therefore, the gas dispersion in the large-scale mixer was examined using the same aeration rate per working fluid volume and central impeller tip speed as those used in the small-scale mixer. It was discovered that under this condition the gas hold-up profile was not uniform. In fact, under this condition the mixing was not efficient and stagnant zones were observed as per result shown in Figure 2a. In this figure, the areas in which the fluid velocity is less than 10 percent of the maximum fluid velocity are depicted in gray color. The gray regions represent areas of low mixing intensity, indicating the creation of dead zones inside the coaxial mixer. However, a further increase in the central impeller speed reduced the dead zones inside the mixing tank significantly (Figure 2b). Therefore, more uniform gas hold-up obtained under this circumstance.



(**a**) (**b**)

Figure 2. Fluid velocity distribution obtained by the large-scale coaxial mixer containing a 0.5 wt% CMC solution: (**a**) central impeller speed = 235 rpm, anchor impeller speed = 10 rpm, and aeration rate = 0.12 vvm, and (**b**) central impeller speed = 330 rpm, anchor impeller speed = 10 rpm, and aeration rate = 0.12 vvm.

4. Conclusions

This research focused on the evaluation of hydrodynamics generated by an aerated coaxial mixing system through the numerical and experimental methods. The effect of the aeration rate, inner impeller speed, and rotating mode on the creation of dead zones were investigated. The location and the size of the dead zones were greatly dependent on the rotating mode and the size of the mixing vessel. Furthermore, the research outlined the relationship between the gas phase retention and the flow hydrodynamics inside the coaxial mixing tank. This study highlighted the importance of considering the flow hydrodynamics and gas hold-up when designing the coaxial mixers containing a non-Newtonian fluid.

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