Study of the mixing of solids in non-Newtonian media with PIV

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Abstract

The laminar mixing of solid–liquid suspensions in non-Newtonian liquid was studied with Particle Image Velocimetry (PIV) and digital image analysis combined with a refractive index matching technique. A specific fluid has been developed to ensure laminar flow conditions and match the refractive index of the solid PMMA spheres. Different volumetric concentrations of the spheres were used up to 5%. The experimental investigations have shown that 1.5 mm particles tend to accumulate at the core of the vortices in the flow for a non-Newtonian background fluid. The results were compared with those obtained with Newtonian liquids.

Introduction

The suspension of solid particles in stirred vessels is a ubiquitous unit operation in industry. Its applications range from the manufacture of fine chemicals, pharmaceuticals, polymers and personal care products, as well as food. Solid–liquid processing poses a formidable challenge to industry, especially in those applications involving complex, highly-viscous non-Newtonian liquids (Paul et al., 2004). In some cases, the nature of the fluid limits the regime of mixing to laminar or transitional flow, rendering the homogenization task even more difficult. The methods generally used for designing stirred vessels for solid–liquid mixing are largely based on global empirical data. A localized hydrodynamic approach provides a better basis for design since it enables a detailed description of the multiphase flow structure and the identification of poor mixing zones. Particle image velocimetry (PIV) is a technique widely used to investigate the flow field in stirred tanks (Virdung and Rasmunson, 2007; Gabriele et al., 2011; Montante et al., 2012), even though most of the available studies are limited to very dilute conditions and Newtonian fluids.

This study uses a refractive index matching technique to track the suspension of solid particles in both Newtonian and non-Newtonian shear-thinning liquids. The aim is to understand the influence of the fluid rheology and the solid volume fraction on the mixing performance.

Experimental Facility

The fluid employed was accurately developed in order to fit different criteria. First, it needs to have a tunable refractive index to match the optical properties of the solid phase. In this study, we used 1.43 ± 0.15 mm PMMA spheres provided by Cospheric® with a refractive index of 1.4937 at 532 nm. Then, a moderately high viscosity is required to avoid the onset of turbulence for a wide range of impeller speeds. Finally, it should be easy to become shear-thinning with the addition of a polymer while maintaining its transparency. We selected a mixture of glycerol, water and zinc chloride (GWZ), whose properties are shown in Table 1. Since the mixture is water-based, it was possible to dissolve Xanthan gum in it to obtain a non-Newtonian shear-thinning fluid (GWZ_X). In figure 1, we report the rheological behavior of the two mixtures.

Table 1. Fluids properties

	ρ [Kg m^{-3}]	R. I.
GWZ	1636	1.4915
GWZ_X	1636	1.4905

The mixing studies were carried out in a cylindrical acrylic tank with an internal diameter of 50 mm, equipped with a stainless steel dual impeller with two flat blades on each position. The diameter of the impeller was 37 mm while the distance between the blades was 14 mm. The geometry was chosen because it resembles that of industrial mixers for highly-viscous fluids.

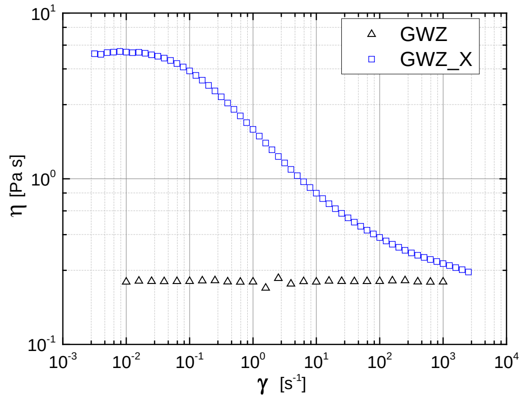

Figure 1: Viscosity curves for the two fluids

The cylindrical tank is enclosed in a square tank, made of acrylic, which is filled with glycerol. The outer tank is necessary to match the refractive index of the processing fluids and the vessel.

The PIV set-up includes a dual cavity Nd:Yag green laser (532 nm) (Litron Laser®, 15 Hz, 1200 mJ) and a straddling CCD camera with 2048 × 2048 pixels (TSI PowerView™ Plus) and a maximum frequency of 16 frames per second, equipped with an AF Nikkor 50 mm f/1.8D prime lens (Nikon®). We used fluorescent polymer particles (melamine resin based) coated with rhodamine B (20 µm) as tracers. At the experimental conditions explored the tracer relaxation time is negligible compared to the convection time (St ≪ 1). To ensure that only the emitted light from the particles (maximum emission at 590 nm) was recorded by the camera, we used an orange filter with a cut-on wavelength at 570 nm. The laser and the camera were synchronized by means of a Laser Pulse Synchronizer (Model 610035 TSI) and they were controlled via the Insight 4G (TSI) software. The laser beam was passed through a collimator (Model 610026 TSI) and two cylindrical lenses (25 mm, and 15 mm) to transform it into a narrow plane of 1 mm thickness. The generated laser plane was reflected on a 45° silver coated mirror and entered the stirred vessel from the bottom. Figure 1 shows a photo of the set-up.

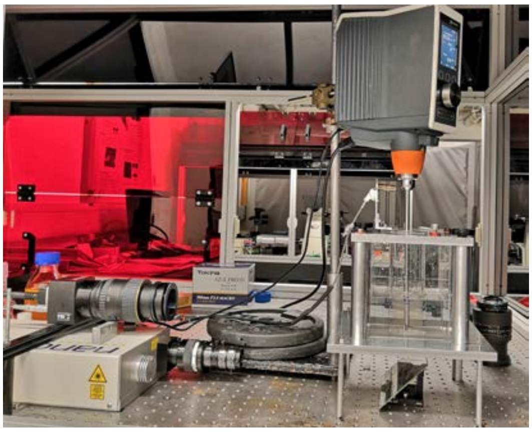

Figure 2: Photograph of the PIV set-up for the studies in the stirred vessel.

Each fluid was stirred at two different impeller speed 400 and 650 RPM for the GWZ fluid, 700 and 1000 RPM for the GWZ_X.

Results and Discussion

In this study we first employed an image processing technique called Circular Hough Transform (CST) to detect the position of the solid particles in the vessel (see figure 3). Preliminary results have shown that for the Newtonian fluid the spheres are drawn down and dispersed homogeneously into the flow, although the buoyancy forces prevent them to reach the bottom of the tank (see figure 3). In the GWZ_X fluid, the particles tend to accumulate in specific position in the tank. An analysis of the fluid flow field reveals that the spheres accumulate at the core of the vertical structures for the non-Newtonian case as it is shown in figure 4.

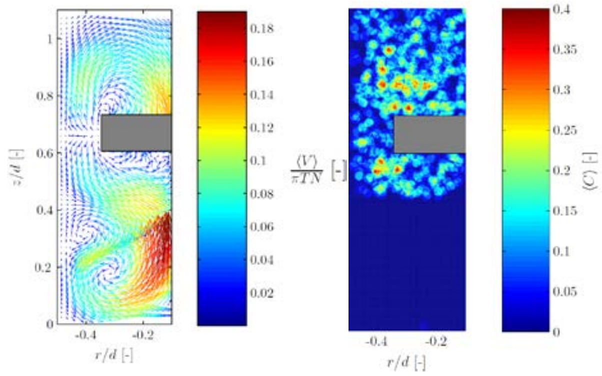

Figure 3: Fluid velocity field (left) and solid concentration (right) for the GWZ liquid and 1% vol PMMA and 600 RPM

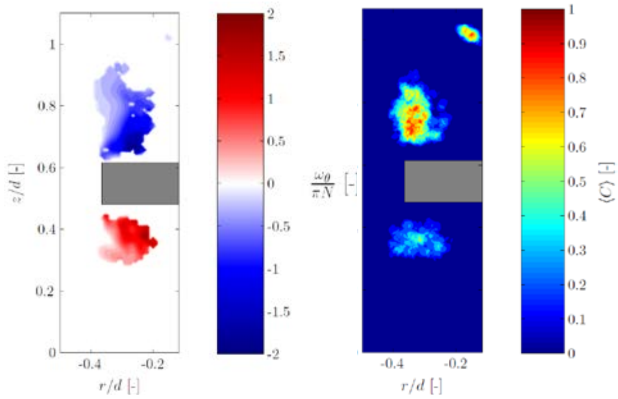

Figure 4: Fluid vorticity field (left) and solid concentration (right) for the GWZ_X liquid and 1% vol PMMA and 700 RPM

Conclusions

In this work, the concentration profiles of solids suspended in non-Newtonian and Newtonian media were studied at various solid volume fractions and in laminar flow conditions. Fluid mixtures were used that could match the refractive index of the PMMA solid particles. The experimental investigations showed that the particles tend to accumulate at the core of the vortices in the flow for a non-Newtonian background fluid. The patterns will be compared with those obtained with smaller particles and different non-Newtonian liquids.

Acknowledgments

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