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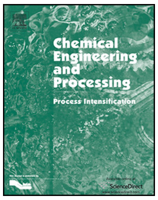

Computational simulation of mixing flow of shear thinning non-Newtonian fluids with various impellers in a stirred tank

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ABSTRACT

The main features of the flow generated by three axial flow impellers installed on the side of cylindrical tanks filled with pseudoplastic solutions exhibiting yield stress were exposed using computational fluid dynamics (CFD). The numerical results were evaluated using velocity vector maps obtained from particle image velocimetry (PIV) experiments. The models were able to predict macroscale flow structures and global mixing parameters under different operating conditions. However, limitations of the model to predict the symmetric flow observed during the experiments were identified at high rotational speeds. The operating conditions included angular speeds from 327 rpm to 684 rpm, and yield stresses and viscosity levels provided by three carbopol solutions (0.075, 0.09 and 0.1 w/w%). These conditions create mainly laminar flow inside the mixing domain. The results indicated that the operating conditions and the blade angle establish the structure of the impeller discharge, which in turn defines the shear rate distribution, some physical cavern properties, and the formation of segregated regions.

1. Introduction

One of the most common devices to perform mixing in industrial operations is the mechanically stirred vessel. Due to the wide variety of mixing requirements, many variations of the constituent parts of the stirred tank have arisen. It has been shown that operating conditions and geometrical properties of the impeller and vessel define the fluid dynamic inside the tank [9,25,34,42]. For instance, flow patterns of axial and hydrofoil impellers are characterized by one main circulation loop, and high velocities near the blade tip. Additional circulation loops might arise due to the interaction of the flow structures and the vessel walls [11]. The pumping capacity and the discharge direction of the axial-type impellers are significantly affected by low rotational speeds and small impeller sizes [7]. On the other hand, radial impellers show two loop structures located close to the impeller blades and sometimes a small reverse loop below the hub [24]. The shear and turbulence levels offer by these impellers are higher compared to axial discharge impellers, but the pumping capacity is lower [19].

Generally speaking, flow patterns and characteristic mixing numbers like flow number (parameter that represents the pumping capacity) and power number (parameter that represents the power requirements) are not only related to intrinsic properties of the impellers and vessels [25], but also to the distribution of the mechanical components inside the mixing device. Thus, it is important to separately study the available mixing configurations. To date, most of the attention has been caught by stirred tanks equipped with top entry impellers, and little has been done to elucidate the hydrodynamics and the mixing mechanisms in tanks with side entry impellers. This configuration is suitable for large storage vessels commonly used in the pulp and paper industry as well as blending and sludge control tanks in the oil industry, among others [9,19,21].

Another important aspect affecting the fluid dynamics inside stirred tanks is the fluid rheology. For simple low viscous Newtonian fluids, there is a comprehensive set of studies on the flow structures and the mixing mechanism for different mixing conditions [16,17,24,26,36]. However, many of the fluids present in industry are high viscous fluids or exhibit complex rheologies like shear thinning behaviour and yield stress. Studies on mixing of fluids with yield stress show the formation of segregated mobile zones around the impeller, known as caverns. An accurate prediction of the cavern size is vital to avoid poor mixing regions in the tank. As shown by [1] several expressions have been proposed to predict cavern sizes. However, their application seems to be restricted to specific conditions and requires mixing parameters, which are not readily available. In the case of shear thinning fluids, the flow conditions might be very complex due to the shear-rate dependency of the viscosity. This drastically affects

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Nomenclature

$\underline{D}$	Impeller diameter (cm)
$\overline{\overline{D}}$	Strain rate tensor
E	Impeller clearance from the side wall (cm)
H	Liquid level (cm)
k	Consistency index (Pa s)
L	Total velocity (m/s)
L^*	Normalized total velocity
n	Flow index
N	Rotational speed (rpm)
N_p	Power number
N_q	Pumping number
P	Power (W)
Q	Flow rate (m^3/s)
Re	Reynolds number
Re_y	Yield stress Reynolds number
T	Diameter of cylindrical tank (cm)
U_{tip}	Tip speed (m/s)
U	Axial velocity (m/s)
U^*	Normalized axial velocity
V	Vertical velocity (m/s)
V^*	Normalized vertical velocity
$v_{\dot{\gamma}}$	Volume of a fluid element with shear rate greater than $\dot{\gamma}$ (m^3)
V_c	Cavern volume (m^3)
X	Axial distance from front face of impeller hub (mm)
X^*	X/D
Y	Vertical distance from impeller center (mm)
Y^*	Y/D
Z	Radial position from the impeller center (cm)

Greek letters

ρ	Fluid density (kg/m^3)
η	Viscosity (Pa s)
τ	Shear stress (Pa)
$\dot{\gamma}$	Shear rate (s^{-1})
τ_y	Yield stress (Pa)
τ_{y^*}	The stress corresponding to shear rate value $\dot{\gamma}_0$ (Pa)

the momentum, mass and energy transfer conditions around the impeller, which adds complexity to the prediction of the flow structures and the mixing mechanisms. Some studies on mixing of non-Newtonian fluids have exposed segregated zones close to the impeller, and undesired flow patterns that affect mixing performance. The impeller discharge angle, and the size and position of the segregated zones have been found to be a function of the operating conditions [5,22,46].

The flow conditions that favor mixing mechanism are easily attainable in turbulent flows, where the non-steady condition of the velocity field yields a rapid homogenization. However, the flow time-dependency of the turbulent regime is not always achievable or appropriate for all mixing systems. At times, the high resistance to flow of some fluids or restrictions on shear levels confines the mixing process to the laminar regime. Laminar-transitional conditions in stirred tanks have been identified for Reynolds numbers (Eq. (1)) below 300 [8,20,26,45]. The use of the factor (1.6×10^{-6}) in Eq. (1) is to adjust the selected unit inputs.

$$\mathrm{Re} = 1.6 \times 10^{-6} \frac{\rho N D^2}{\eta} \tag{1}$$

In the laminar regime the mixing performance might be really low because there is not a constant reorientation of the flow. However, [27] showed chaotic regions inside the mixing domain, where there was a repeated change in the direction of the flow. This enhances the mixing performance, since the contact area between flow layers increases as the fluid folds [40]. The study of these regions requires first a large-scale characterization of the flow pattern. Some studies have used Eulerian approaches to show flow structures, velocity profiles and related properties of diverse mixing configurations. [6,22,26,17] have described flow paths, circulation loops, segregated zones and discharge angles for axial and radial impellers operated in the laminar regime.

Experimental and computational techniques have been applied to investigate the variables involved in mixing systems. Non-intrusive visualization techniques allow obtaining qualitative and quantitative information about the flow pattern. Particle image velocimetry (PIV) provides instantaneous velocity fields and related properties by measuring the displacement of tracer particles in a given interval of time. One mandatory condition for implementing this technique is the usage of transparent and clear work solutions. A suitable fluid commonly used in research and able to represent rheological properties proper of industrial fluids is a neutralized carbopol solution [14,18,31]. After neutralization, aqueous carbopol solutions show a shear thinning behaviour that depends on the initial carbopol concentration. [13] studied the flow patterns of a carbopol solution using PIV. The velocity fields obtained from this visualization technique are also commonly used to evaluate capabilities of computational models as presented by [5,13,24,37,43].

Computational fluid dynamic (CFD) uses numerical techniques to solve a matrix of equations that includes governing equations like momentum, heat and mass balances as well as boundary conditions and additional physical and chemical models. CFD models of mixing systems can provide information on hydrodynamic variables and mixing parameters that would be very expensive or simply impossible to obtain with the available experimental techniques. Some of the information extracted from these models includes shear rates, mixing structures, energy dissipation, power requirements, pumping capacities, velocity fields and mixing times, among others [20,23,22,25,46].

Despite many interesting benefits (asymmetric flow and less capital cost) offered by stirred tanks equipped with side-entry impellers [7,19], scarce information is available in the open literature about their performance. Therefore the main goal of this work was to develop a model for the simulation of the flow structures and relevant mixing variables inside a cylindrical tank equipped with a side-entry impeller. The capabilities of the CFD models were assessed using steady-state flow fields obtained from the PIV measurements. Three axial flow impellers and three shear-thinning fluids with yield stress were evaluated in the laminar-transitional regimes using PIV and CFD.

2. Materials and methods

The system under study was a cylindrical tank (diameter $T = 32.9$ cm and height $H = 35$ cm) equipped with a side-entry impeller placed at 7.4 cm from the tank bottom (Fig. 1). The E/D ratio (clearance from rear-wall to impeller diameter ratio) was set to 0.56 based on the results presented by [9,33,44].

Three axial flow impellers ($D = 9.652$ cm) used in side-entry configurations were evaluated, i.e., the A100, A312 and Maxflo Mark II impellers (Fig. 2). One notable difference among the three impellers is the pitch ratio (ratio between the axial distance traveled by the impeller in one revolution and the impeller diameter) at the blade tip, which ranges from 1.5 to 0.44.