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Full Length Article

Agitation of yield stress fluids in different vessel shapes

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ABSTRACT

The Agitation of yields stress fluids with a six-curved-blade impeller (Scaba 6SRGT) is numerically investigated in this paper. The xanthan gum solution in water which is used as a working fluid is modeled by the Herschel–Bulkley model. The main purpose of this paper is to investigate the effect of vessel design on the flow patterns, cavern size and energy consumption. Three different vessel shapes have been performed: a flat bottomed cylindrical vessel, a dished bottomed cylindrical vessel and a closed spherical vessel. The comparison between the results obtained for the three vessel configurations has shown that the spherical shapes provide uniform flows in the whole vessel volume and require less energy consumption. Effects of the agitation rate and the impeller clearance from the tank bottom for the spherical vessel are also investigated. Some predicted results are compared with other literature data and a satisfactory agreement is found.

1. Introduction

Agitation is of a great importance and it is used in many industrial processes. In the various applications, stirred tanks are required to fulfill several needs like suspension of solid particles, dispersion of gases into liquids, heat and mass transfer, etc. Although many experimental as well as numerical studies on liquid flows in cylindrical vessels have been published, very little attention has been paid to the study of flow fields and energy consumption in fully closed vessels.

Nagata [1] proposes the use of hemispherical bottomed cylindrical reactors, envisaging probably the improvement of the reactor efficiency, due to the cancellation of the profile discontinuity at the wall-bottom junction. Other researchers [2–4] studied the power consumption in closed vessels for Newtonian fluids; they noticed a discrepancy between their results (closed vessels) and the same type of results for open vessels.

For a Newtonian fluid, Medek and Fort [5] studied experimentally the distribution of pressure along the lid of fully filled closed cylindrical vessels at mixing by high-speed impellers (a Rushton turbine or a pitched bladed turbine). They found that the power input is not greater than that of an open cylindrical reactor, and the pumping number of the same impeller is increased by approximately 10% probably due to the uniformization of the flow pattern at the top end of the reactor.

Armenante et al. [6] determined, by experiments and CFD simulations, the velocity profiles and the turbulent kinetic energy distribution for the flow generated by a pitched-blade turbine in an unbaffled, flat-bottom, cylindrical tank provided with a lid, and completely filled with water.

By numerical simulations, Ciofalo et al. [7] studied the Newtonian turbulent flow in closed and free surface unbaffled tanks stirred by flat-bladed impellers. For a low viscous Newtonian fluid and turbulent flow regime, Taca and Paunescu [8] studied experimentally the power input in a spherical closed vessel stirred by a Rushton turbine or six pitched blade impeller. Taca and Paunescu [9] reported that the optimum shape a vessel used for the suspension of solid particles should have is the spherical one. These authors reported also that some anomalies have also been noticed for the fully filled lidded cylindrical reactors, as compared to the open reactors: the decrease of the power number for turbulent regime ($Re > 75{,}000$), with the increase of Reynolds number and the impeller diameter.

By CFD simulations, Yapici and Basturk [10] studied the conjugate heat transfer and homogeneously mixing two immiscible different fluids in a stirred and heated hemispherical vessel. For a Newtonian fluid and turbulent flow regime, Ammar et al. [11] studied by numerical simulations the effect of vessel design on the flow pattern generated with a pitched blade turbine.

Agitation of yield stress fluids results in the formation of a cavern (well mixed region) around the impeller [12,13] and isolated regions far away. Some works have been published using curved blade impellers to evaluate the cavern size as a function of the power drawn by yield stress fluids including those by Galindo and Nienow [14,15] for Lightnin A315 and Scaba 6SRGT impellers; Amanullah et al. [16]

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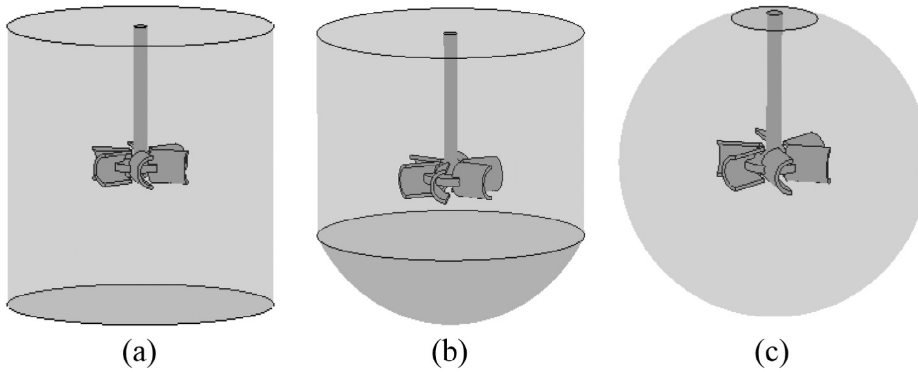

Fig. 1. Agitation system.

for axial flow SCABA 3SHPI impeller; Serrano-Carreon and Galindo [17] for four different impellers (Rushton turbine, Chemineer He-3, CD-6 and Scaba 6SRGT) in individual and dual arrangements; Pakzad et al. [13,18,19] and Ameur et al. [20] for SCABA 6SRGT impellers. Pakzad et al. [21] were interested with the agitation of viscoplastic fluids by Scaba-anchor coaxial mixers. For stirring shear thinning fluids, Ameur and Bouzit [22] studied the effect of curvature blade on the power consumption. They found that the curve bladed impeller requires less power consumption compared with the flat bladed impeller.

Our search in the literature shows that a little space has been reserved to the agitation of viscoplastic fluids by curved-bladed impellers within closed vessels. Therefore, the main purpose of this paper is to investigate the flow fields and the energy required for the agitation of viscoplastic fluids by a Scaba 6SRGT impeller. We focus on the effects of vessel design on the flow fields, cavern size and energy consumption. Three geometric configurations are realized to perform the test: a flat bottomed cylindrical vessel, a dished bottomed cylindrical vessel and a spherical vessel. Effects of the agitation rate and the impeller clearance within a closed vessel are also investigated.

2. Mixing system

Effects of the vessel design are investigated in this paper by realizing three types of vessels: a flat bottomed cylindrical vessel, a dished bottomed cylindrical vessel and a spherical vessel (Fig. 1). Each vessel is equipped by a Scaba 6SRGT impeller (Fig. 2) which consists of six curved blades fixed on a disc with 8 mm of thickness.

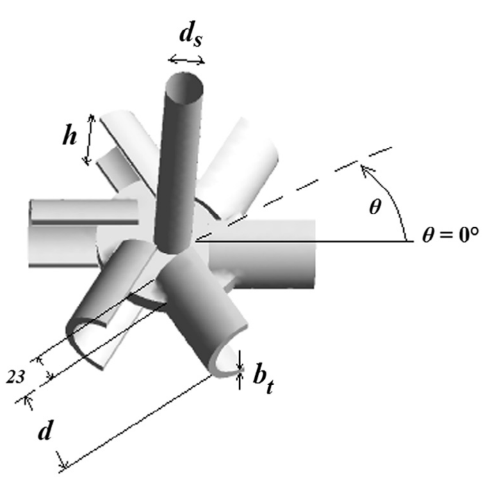

Fig. 2. Geometrical parameters of the impeller.

The disc is attached on a cylindrical central shaft of diameter $d_s/D = 0.05$. The vessel height (H) is equal to its diameter (D), $D = 400$ mm. All other parameters are listed in Table 1.

Effects of the impeller clearance from the tank bottom are also studied. Three different configurations are realized for this purpose and which are: $c/D = 0.2$, 0.35 and 0.5, respectively.

3. Mathematical background

The xanthan gum solution in water used in this study has a yield stress behavior modeled by the Herschel–Bulkley model [18].

Thus, its apparent viscosity (η) is given by:

$$\eta = \frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \quad (1)$$

where τ_y is the yield stress, $\dot{\gamma}$ is the shear rate, and K and n are the consistency index and the flow behavior index, respectively.

According to the measurements conducted by Galindo and Nienow [15], the rheological properties of the xanthan gum solution used were summarized in Table 2.

The Herschel–Bulkley model used causes a numerical problem during the CFD simulations because the non-Newtonian viscosity becomes unbounded at small shear rate. This behavior causes instability during computation [23]. Thus, the modified Herschel–Bulkley model was employed to avoid the numerical instability. It was assumed that the xanthan gum solution acts as a very viscous fluid with viscosity μ_o at $\tau \le \tau_y$ and the fluid behavior is described by a power law model at $\tau > \tau_y$ [23]:

$$\eta = \mu_0 \text{ at } \tau \le \tau_y$$
$$\eta = \frac{\tau_y + K\left[\dot{\gamma}^n - \left(\frac{\tau_y}{\mu_0}\right)^n\right]^n}{\dot{\gamma}} \text{ at } \tau > \tau_y \quad (2)$$

Table 1
Vessel parameters.

	D	H	d	d_s	d_t	b_t
[mm]	400	400	60	20	8	6

Table 2
Rheological properties of the xanthan gum solution used in this work.

Xanthan gum concentration % (in mass content)	K [Pa s^n]	n [–]	τ_y [Pa]
3.5	33.1	0.18	20.6