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Investigation of hydrodynamic performances of coaxial mixers in agitation of yield-pseudoplasitc fluids: Single and double central impellers in combination with the anchor

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HIGHLIGHTS

- Performance of DSAC mixer in mixing of yield-pseudoplastic fluids was analyzed.
- CFD and tomography techniques were utilized to evaluate the mixing performance.
- Power consumption, mixing time and velocity profiles were quantified for this mixer.
- DSAC mixer was more efficient than SSAC mixer at the same power consumption.
- Use of DSAC mixer resulted in a more uniform distribution of the shear rate.

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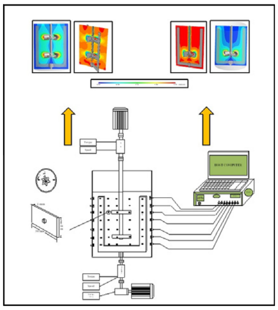
GRAPHICAL ABSTRACT



ABSTRACT

The hydrodynamic performance of coaxial mixers, the single and double Scaba impellers in combination with an anchor impeller, was investigated in the mixing of yield-pseudoplastic fluids (xanthan gum solutions) in the laminar – transitional regime in the co-rotating mode. To explore and determine the efficiency of the coaxial mixers, both numerical and experimental approaches were adopted. The fluid rheology was described by the Herschel–Bulkley rheological model. Electrical resistance tomography (ERT) with seven planes of electrodes was applied to measure the mixing time and visualize the flow pattern inside the vessel. The flow domain of the fluid was simulated three-dimensionally applying the computational fluid dynamics (CFD). The developed model was then validated through experimentally measured torque and the mixing time. The performances of the investigated coaxial mixers in this work were compared at the constant power input and similar fluid rheology with respect to the mixing time, fluid velocity profiles, and mixing efficiency. Applying the previously published correlations for the power and Reynolds numbers of the coaxial mixers showed that Pakzad et al. (2013) model was valid for a wide range of the speed ratios for the double Scaba-anchor coaxial mixer, while Bao et al. (2011) model was only appropriate for the higher speed ratios. Considering the mixing efficiency criteria, it was found that the double Scaba-anchor coaxial system was more efficient than the single Scaba-anchor coaxial mixer in the mixing of yield pseudoplastic fluids with regard to the mixing time and power drawn.

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Nomenclature

D_a	anchor diameter impeller (m)
D_m	molecular diffusivity ($m^2\ s^{-1}$)
D_c	central impeller diameter (m)
$f_{p(a)}$	anchor impeller power fraction
H	tank height (m)
H_a	anchor height (m)
K	consistency index (Pa s^n)
K_s	Metzner–Otto constant for calculating shear rate
$K_{s(s)}$	Metzner–Otto constant for Scaba impeller
$n-1$	exponent constant
n	power-law index
N_a	anchor impeller speed (s^{-1})
N'	characteristic speed (s^{-1})
N_p	power number
N_c	central impeller speed (s^{-1})
N_{Co}	coaxial rotational speed (s^{-1})
P_{tot}	total power (W)
Re	Reynold number
Re_m	Reynolds mixing time
R_n	speed ratio (N_c/N_a)
t	time (s)
t_a	anchor impeller thickness (m)
t_m	mixing time (s)
T	tank diameter (m)
$\bar{v}$	mean velocity factor
V	fluid volume (m^3)
V_θ	tangential velocity (m/s)
V_z	normal velocity (m/s)
wa	anchor impeller width (m/s)
w	local mass fraction
Greek letters	
$\dot{\gamma}$	shear rate (m/s)
η	non-Newtonian viscosity (Pa s)
ρ	density (kg/m^3)
τ_y	yield stress (Pa)
π & π_2 & π_3	constants

1. Introduction

Mixing of highly viscous non-Newtonian fluids is a key operation, which is extensively applied in many industries such as polymer, biotechnology, cosmetic, food industries, water treatments, and pulp and paper. The efficient mixing is difficult to achieve due to the complex rheological behavior exhibited by the non-Newtonian fluids during the mixing processes. The most important class of this type of fluids is called pseudoplastic fluid possessing yield stress. Due to a dramatic increase in fluid viscosity at the shear stresses less than the yield stress, the mixing of this type of fluid creates many challenging mixing problems such as the formation of gel, fouling and buildup on the walls, low heat transfer, higher mixing time, forming well-mixed region close to impeller (called cavern) with dead and/or stagnant zones in the rest of the tank [2–7]. The generation of these glitches affects the efficiency of the mixing process, which affects significantly the product quality. Therefore, the elimination or reduction of the aforementioned problems requires the proper selection and design of the stirred system for the agitation of non-Newtonian yield-pseudoplastic fluid, which by itself is not an easy task. The effective mixing of such complex fluids demands the use of more advanced hybrid agitated system such as the planetary mixers or multi-shaft mixers [1,2,7].

One class of these multi-shaft mixers is called coaxial agitated system. This system enhances the mixing quality through the combination of the effectiveness of a high speed impeller (such as the Scaba), which is suitable for the low viscosity fluids, with a low speed close-clearance impeller (such as the anchor) suitable for the high viscosity fluids. The two impellers rotate independently on the same central axis with different rotational speeds to provide a wide range of the speed ratios. Although the coaxial mixers are broadly used in industry such as biochemical processes in pharmaceutical and biotechnology industry [8], paper coating fluid preparation in paper industry [9], and gellan production in polymer industry [10], the scarce information can be found in the literature regarding the mixing of the highly viscous non-Newtonian fluids especially the yield-stress fluids with the coaxial mixers.

To assess and characterize the fluid flow generated by means of the coaxial mixers in a variety of industries, the critical parameters such as power drawn and blending time need to be determined. The characterization of the power consumption for the coaxial mixers compared with that for the classical mixer is a challenging task. In this mixing configuration, because of the use of two different kinds of impellers with different diameters and speeds, the definition of characteristic length (D) and rotational speed (N) for the power number and Reynolds number are considered as a difficult task. The power number and Reynolds number are also affected by the rotating mode of the impellers and rheological factors of the non-Newtonian fluids. These parameters must be embodied into the power and Reynolds numbers. Thibault and Tanguy [11] studied a coaxial system, which was a combination of an anchor with a group of rods placed 90° from one another and a pitched blade turbine impeller with two blades positioned at the bottom of the tank. They chose the diameter (D_a) and rotational speed (N_a) of the anchor as a characteristic length and characteristic speed, respectively. The effective rate of deformation was calculated using Metzner and Otto [12] concept and a master power curve, which was not dependent on the speed ratio, was then developed. Foucault [13] used the diameter (D_c) and rotational speed (N_c) of the central impeller as the characteristic length and speed, respectively. Based on this approach, the correlations for the power and Reynold numbers as a function of the speed ratio in the counter-rotating mode was developed using Rieger and Novak method [14] for Newtonian fluids. In 2007, Rudolph [15] conducted a research work to characterize the power drawn of a coaxial mixer including of an anchor with two pitched blade turbine impellers. They followed the study of Thibault and Tanguy [11] and developed new generalized Reynolds number and power number for power-law fluids assuming anchor rotational speed and diameter as the characteristics factors. Bao et al. [2] worked on the coaxial agitated system and realized that the effect of the anchor on the total power consumption at the higher speed ratio became weaker. Thus, the diameter of the central impeller (D_c) was chosen as a characteristic length and a modified expression for the characteristic speed (N') was defined as follows:

$$N' = \begin{cases} N_c + \frac{N_a}{R_n} : \text{counter-rotating} \\ N_c - \frac{N_a}{R_n} : \text{co-rotating} \end{cases} \tag{1}$$

By using the above mentioned characteristic length and speed, they proposed the following power number and Reynolds number for the power-law fluids: