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Experimental study on the solid suspension characteristics of coaxial mixers

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ABSTRACT

Coaxial mixers as novel mixers have the characteristics of high flexibility and wide adjustability. Three kinds of coaxial mixers consisting of an outer anchor and different inner impellers (six 45° pitched-blade turbine, propeller and Rushton turbine) and single-impeller mixers were investigated and compared in viscous systems. Effects of rotation and pumping modes, outer impeller speed, inner impeller diameter, liquid viscosity, solid volume fraction and particle diameter on the just-suspension impeller speed and power consumption were also studied. Results showed that the coaxial mixers were more energy efficient than the single-impeller mixers, and had greater advantage in systems of higher viscosity and solid volume fraction. Different from single-impeller mixers, adopting up-pumping mode was more energy efficient for coaxial mixers when the anchor speed was relatively high. In addition, the coaxial mixers with the inner up-pumping propeller and six 45° pitched-blade turbine had obvious superiority compared with the combination of anchor and Rushton turbine in terms of power consumption. Based on the experimental data, a new correlation for predicting just-suspension impeller speed of coaxial mixers was proposed.

1. Introduction

Solid–liquid mixing operations are used widely in chemical production, such as catalysis, crystallization, sedimentation, sewage treatment, etc. The purpose of solid–liquid mixing is to enlarge the contact areas between the solid and liquid phases by suspending the solid phase such as catalysts and reactants, so as to accelerate the reaction or mass transfer rate.

Solid–liquid mixing of single-impeller mixers has been widely studied. However, single-impeller mixers are usually applicable to special conditions and difficult to adapt to the working conditions with large variations of viscosity and phase holdup. The coaxial mixer consists of an outer wall-scraping impeller and an inner fast-dispersing impeller. Compared with traditional single-impeller mixers, coaxial mixers have the characteristics of high flexibility and wide adjustability, and can be applied to a wide range of conditions. Therefore, coaxial mixers are used widely in industrial production. Coaxial mixers have been extensively investigated in the past. Foucault et al. (2004, 2005) studied the power characteristics of coaxial mixers in Newtonian and non-Newtonian fluids. They found that outer impeller speed did not affect the power consumption of inner impeller, but the inner impeller speed was shown to affect the power consumption of outer impeller, and the outer impeller power consumption decreased and increased under co-rotation mode and counter-rotation mode, respectively. In addition, they proposed new correlations between the power number and the Reynolds number on the basis of the impeller geometry. Bao et al. (2011) and Pakzad et al. (2013a) also researched the relation between the power number and the Reynolds number, and presented different correlations. Rivera et al. (2006, 2009) and Farhat et al. (2007) found that the mixing time under co-rotation mode was less than that under counter-rotation mode. Pakzad et al. (2013b) investigated the mixing time in pseudoplastic fluids and found that there was a critical value of speed ratio (inner impeller speed/outer impeller speed). If a speed ratio exceeded the critical value, mixing time would not decrease any more with the increasing of the speed ratio, otherwise mixing time would be proportional to the 0.4th power of the speed ratio. Liu et al. (2013) assessed heat transfer characteristics of a coaxial mixer with a combined inner impeller in Newtonian fluids by simulation and experimental research. They discovered that the coaxial mixer had better heat transfer performance than single-impeller mixers, and the inner

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Nomenclature

b	Blade width (mm)
C	Impeller off-bottom clearance (mm)
d_p	Particle diameter (μm)
D	Diameter of inner impeller (mm)
D_a	Diameter of anchor impeller (mm)
g	Gravitational constant (m/s^2)
H	Liquid level height (mm)
l	Blade length (mm)
M_l	Loading torque (N m)
M_i	Idling torque (N m)
N	Impeller speed (rpm)
N_o	Outer impeller speed (rpm)
N_i	Inner impeller speed (rpm)
N_{js}	Just-suspension impeller speed (rpm)
P	Power consumption (w)
P_{js}	Just-suspension power consumption (w)
$\bar{R}^2$	Adjusted coefficient of determination
S	Proportionality constant
T	Tank diameter (mm)
w	Width of outer blade (mm)
X	Solid mass fraction (%)

Greek letters

η	Energy saving rate (%)
μ	Dynamic viscosity (mPa s)
υ	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
ρ_l	Density of liquid (kg/m^3)
ρ_s	Density of solid (kg/m^3)
$\Delta\rho$	$\rho_s - \rho_l$ (kg/m^3)
Φ_v	Solid volume fraction (%)

Abbreviations

RT	Rushton turbine
PBTU	Up-pumping six 45° pitched-blade turbine
PBTD	Down-pumping six 45° pitched-blade turbine
PropollerU	Up-pumping propeller
PropollerD	Down-pumping propeller

impeller had more influence on heat transfer coefficient than the outer impeller. Recently, Liu et al. (2016) investigated gas dispersion characteristics of coaxial mixers in gas–liquid systems by means of CFD. Results showed that coaxial mixers under counter-rotation mode could obtain higher total gas holdup and more uniform local gas volume fraction distribution. Hashemi et al. (2016a, 2016b, 2016c) studied the gas–liquid mixing of coaxial mixers by means of electrical resistance tomography (ERT). They concluded that coaxial mixers had shorter mixing times compared with single-impeller mixers, with the increasing of gas flow rate, the gassed power of the inner impeller and outer impeller decreased and increased, respectively. In addition, they proposed novel correlations for the gas flow number and power number. Pakzad et al. (2013c) introduced a novel configuration consisted of ASI and anchor, and the performance of the configuration was studied in yield-pseudoplastic fluids. Their results showed that the novel configuration was more efficient than other combinations in terms of power consumption. Although lots of studies on coaxial mixers have been done, most of them were focused on single-phase systems, and the reports on solid suspension characteristics of coaxial mixers were few.

The study of just off-bottom solids suspension condition is an important theme in the solid–liquid mixing. Zwietering (1958) first proposed the concept of just off-bottom solids suspension condition that no solid particles rest on the tank bottom for more than 1 or 2 s, and the corresponding impeller speed was just-suspension impeller speed (N_{js}). In addition, he proposed a correlation for determining N_{js} based on numerous experiments. Later on, many correlations were reported by different researchers (Ayranci and Kresta, 2014; Gates et al., 1976; Grenville et al., 2015; Nienow, 1968; Narayanan et al., 1969). Rao et al. (1988) researched the effects of impeller types, impeller clearance, particle size, solid volume fraction, and tank diameter on just-suspension impeller speed and power consumption. The results showed that N_{js} decreased with the decreasing of the impeller clearance and increased with the increasing of the particle diameter and loading. Moravec et al. (2006) studied the influence of bottom shape on N_{js} and power consumption, and discovered that N_{js} and power consumption in the flat-bottomed tank was higher than that in the dish-bottomed tank. Mishra and Ein-Mozaffari (2016, 2017) investigated the solid suspension performance of a Maxblend impeller by means of ERT and CFD techniques. They found that the maximum homogeneity of the Maxblend impeller was the highest compared with A200 and Rushton impellers. In addition, after reaching the peak level of homogeneity, the increasing impeller speed was detrimental to the mixing quality.

In this paper, in order to study the solid suspension characteristics of coaxial mixers, just-suspension impeller speed and just-suspension power consumption (P_{js}) of different coaxial mixers and single-impeller mixers were investigated and compared in viscous systems, and the study is meaningful considering advantages of coaxial mixers.

2. Experimental

A transparent stirred tank with a standard elliptical head was employed. The impellers included anchor, six 45° pitched-blade turbine (PBT), propeller (Propeller) and Rushton turbine (RT), which were used as the outer impeller, the mixed flow impeller, the axial flow impeller and the radial flow impeller, respectively. The anchor lower blade was close to the bottom, and the distance was 20 mm. Two groups of inner dispersing impellers were chosen, whose diameter were 135 mm (0.35 T) and 200 mm (0.53 T). The experimental system and structure of inner dispersing impellers are shown in Figs. 1 and 2, respectively. The overall size of the equipment and dimensional parameters of four impellers are listed in Table 1.

As Newtonian fluids, the malt syrup solutions were chosen in experiments, whose viscosity (μ) could be adjusted by changing the ratio of water and malt syrup. A densitometer and digital rotor viscometer were used to measure the density (ρ) and viscosity of malt syrup solutions, respectively. The physical parameters of three kinds of malt syrup solutions are listed in Table 2.

Two kinds of quartz sand were used as the solid phase: ordinary quartz sand (ρ = 2600 kg/m^3) and fused quartz sand (ρ = 2210 kg/m^3). The quartz sand had four classes with particle size between 55–60, 35–40, 26–30, and 24–28 sieve mesh. In order to obtain average particle diameter (d_p) of quartz sand, seven groups of quartz sand of each size class were

Table 1 – Dimensional parameters of equipment and impellers.

H (mm)	C (mm)	T (mm)	D_a (mm)	w (mm)
380	125	380	340	38
Inner impeller	D (mm)	d (mm)	l (mm)	b (mm)
RT	135	40	34	27
	200	55	50	40
PBT	135	40	/	28.5
	200	55	/	28.5
Propeller	135	40	/	/
	200	55	/	/