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Power consumption and mass transfer in a gas-liquid-solid stirred tank reactor with various triple-impeller combinations

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HIGHLIGHTS

- Solid particles found to influence power consumption and k_La in different ways.
- Different optimal impeller combinations found in two-phase and three-phase systems.
- Power consumption and mass transfer measured in gas-liquid-solid stirred tanks.
- N_{PG} and k_La correlations regressed for five triple-impeller combinations.

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ABSTRACT

Five triple-impeller combinations were used to study the effects of impeller combination on gassed power consumption and volumetric mass transfer coefficient k_La in a baffled gas-liquid-solid stirred tank reactor with air, water, and 12 vol% of glass beads. The bottom impeller was chosen from two radial flow type impellers of half-elliptical-blade disk turbine (HEDT) and parabolic-blade disk turbine (PDT), and the upper two impellers were chosen from four axial flow type impellers with different blade widths and pumping modes, forming five different triple-impeller combinations: HEDT + $2WH_U$, HEDT + $2WH_D$, PDT + $2WH_D$, PDT + $2CBY_W$, and PDT + $2CBY_N$. The experimental results show that the addition of solid particles has little effect on the relative power demand (*RPD*), but significant effect on k_La. k_La in a three-phase system is smaller than that in a two-phase system, and HEDT + $2WH_U$ with two up-pumping upper impellers shows the best mass transfer performance in these five triple-impeller combinations at various superficial gas velocities u_G, much different from what HEDT + $2WH_U$ behaves in two-phase systems. The bottom impeller mainly influences the absolute power consumption, but the two upper impellers play a more important role on the change of *RPD* than the bottom impeller. The impeller combinations with a higher power number and larger projection cross-sectional area can lead to a higher k_La. The effect of operating conditions (e.g., power consumption and superficial gas velocity), the bottom impeller, the blade width and pumping mode of the two upper impellers, and solid particles were investigated and discussed in detail. To better explain the difference of mass transfer performance between impeller combinations HEDT + $2WH_{D/U}$, the Eulerian-Eulerian formulation of the *k*-ε turbulence model with the population balance model (PBM) was used to simulate the flow field in gas-liquid systems.

1. Introduction

Gas-liquid-solid three-phase mechanically stirred tank reactors are widely applied in many industrial processes, such as hydrogenation reaction with slurry of catalyst particles in oil, Fischer-Tropsch synthesis, coal liquefaction, halogenations, polymerization, mineral processing, sewage treatment, and aerobic fermentation. Since the gas liquid mass transfer is often the rate-limiting step in low solubility gases, the volumetric mass transfer coefficient, k_La, is considered as a key parameter for operation, design, and scale-up of stirred tank reactors. In this case, the determination of k_La for gas-liquid-solid three-phase system is important to industrial design. Also, the power consumption of agitators, which is vital for industrial design, is an indispensable parameter to determine the hydrodynamic and mass transfer performance in the stirred tank.

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Nomenclature

C_{Ai}	equilibrium concentration of oxygen at the gas-liquid interface [mol m^{-3}]
C_{As}	oxygen concentration in the bulk liquid with sulfite solution fed continuously [mol m^{-3}]
C_s	concentration of sulfite in the feed solution [mol m^{-3}]
D	impeller diameter [m]
Fl_G	gas flow number, $Fl_G = Q_g/ND^3$ [–]
Fr	Froude number, $Fr = N^2D/g$ [–]
g	gravitational constant [ms^{-2}]
H	height of the liquid without gas input [m]
H_s	depth of the sparger below the free surface [m]
H_T	height of the stirred tank reactor [m]
k_La	volumetric mass transfer coefficient [m s^{-1}]
M	torque [N m]
N	agitation speed [s^{-1}]
N_{CD}	just complete dispersion speed [s^{-1}]
N_P	power number, $N_P = P_0/\rho_L N^3 D^5$ [–]
N_{PG}	gassed power number, $N_{PG} = P_g/\rho_L N^3 D^5$ [–]
P_0	ungassed agitation power [W]
P_g	gassed agitation power [W]
P_{gm}	agitation power per mass [W kg^{-1}]
P_e	potential energy of sparged gas [W]
P_T	total power consumption [W]
P_{Tm}	mean total specific energy dissipation rate [W kg^{-1}]
Q_g	inlet gas flow rate [m^3 s^{-1}]
Q_s	feed rate of the sulfite solution [m^3 s^{-1}]
RPD	relative power demand, $RPD = P_g/P_0$ [–]
T	stirred tank reactor diameter [m]
u_G	superficial gas velocity [m s^{-1}]
V_L	volume of liquid phase [m^3]

Greek symbols

α, β	exponent in correlation (5) [–]
ρ_L	liquid density [kg m^{-3}]

Abbreviations

CBY_W	CBY wide blade
CBY_N	CBY narrow blade
HEDT	half-elliptical hollow-blade disk turbine
PDT	parabolic-blade disk turbine
WH_U	four-wide-blade hydrofoil impeller pumping up
WH_D	four-wide-blade hydrofoil impeller pumping down

With the large scaling of equipment, single-impeller agitators cannot meet the requirements for good mixing and good circulation. Multi-impeller agitators are widely used in industrial processes due to the advantages such as increased gas hold-up, long residence times of gas bubbles, superior liquid flow characteristics, and low power consumption per impeller. According to flow patterns, triple-impeller agitators can be classified as radial flow impeller combination, axial flow impeller combination, and combined flow impeller combination. In the combined flow impeller combination, the radial flow impeller is often used as the bottom impeller to disperse gas and suspend solid, while the axial flow impellers are used as the upper impellers to circulate the multiphase flow. In recent years, various hydraulic and mass transfer characteristics using multi-impeller in gas-liquid stirred tank reactors have been extensively studied. Moucha et al. (2003) used 18 triple-impeller combinations to study the gas hold-up, mixing intensity of dispersion, and volumetric mass transfer coefficient, and found that the impeller combinations with a low power number provided high dispersion mixing intensities, while the impeller combinations with a high power number provided good mass transfer performance. Fujasová et al. (2007) used 28 impeller combinations and reported that the axial flow impeller combinations provided more effective homogenization than the combinations with combined or radial flow impellers, while the combined or radial flow impellers showed more efficient mass transfer performance than the axial flow ones. Moucha et al. (2009) used 23 impeller combinations and presented that the radial flow impellers exhibited 20–50% higher oxygen transfer efficiency than axial flow ones. Labík et al. (2014) carried out the scaling-up study for various impeller types in multiple-impeller gas-liquid contactors. Xie et al. (2014a) used 6 impeller combinations to study the power consumption, local and average volumetric mass transfer coefficient (k_La). It shows that the radial flow impellers have a better mass transfer performance but worse homogenization (Markopoulos et al., 2007; Fujasová et al., 2007; Xie et al., 2014b), while the axial flow impellers exhibit a better homogenization but worse mass transfer performance. Compared to the radial flow impeller combinations or axial flow impeller combinations, the combined flow impeller combinations behave better in both homogenization and mass transfer performance at the same power consumption. Therefore, we studied the reactor impeller configuration on power consumption and mass transfer performance in gas-liquid stirred tank reactors using only combined flow impeller combinations (Zhang et al., 2016).

In combined flow impeller combinations, the Rushton turbine (RT) has been a traditional radial flow impeller widely used since the 1960s (Moucha et al., 2003, 2009; Fujasová et al., 2007; Xie et al., 2014a,b), but it has a weakness of more than 50% fall in gassed power consumption (Vasconcelos et al., 2000), causing a potential loss of mass transfer efficiency. This weakness can be remedied by retrofitting the RT with streamlined impellers, such as the concave-bladed disk turbine (CD) (Vasconcelos et al., 2000), half elliptical-blade disk turbine (HEDT) (Zhao et al., 2011a,b), and parabolic blade disk turbine (PDT) (Bao et al., 2015). The latter two impellers, HEDT and PDT, developed by our research group, were used as the radial flow impeller in this study. In this study, the axial flow impellers we used were a four-wide-blade hydrofoil impeller (WH) operating pumping up or pumping down, and a three-blade hydrofoil impeller (CBY) with two different blade widths. Five different triple-impeller combinations, composed of the above six impellers, were used in our previous research in gas-liquid two-phase systems (Zhang et al., 2016). When solid particles are added in gas-liquid systems, the better understanding of solid suspension and mass transfer is important to the design and scale-up of gas-liquid-solid stirred tank reactors. The solid suspension performance was widely studied while using multi-impeller combinations (Dohi et al., 2004; Bao et al., 2006). However, the mass transfer performances in gas-liquid-solid three-phase systems with multi-impeller combinations are still short of systematical research. Whether the optimal combination obtained in gas-liquid two-phase systems still behaves the best in gas-liquid-solid three-phase systems and whether the addition of solid particles affects the mass transfer performance are still unclear and need further investigations. In this study, we used these five triple-impeller combinations to study the effects of the bottom impeller, the blade width and the operating mode of the two upper impellers, and the addition of solid particles on the power consumption and k_La at various superficial gas velocities