Advanced Powder Technology 28 (2017) 2514–2523

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Design of impeller blades for efficient homogeneity of solid-liquid suspension in a stirred tank reactor

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ARTICLE INFO

Article history:
Received 22 April 2017
Received in revised form 6 June 2017
Accepted 29 June 2017
Available online 12 July 2017

Keywords:
Solid-liquid suspension
Stirred tank
CFD
Punched rigid-flexible impeller

ABSTRACT

Computational fluid dynamics (CFD) was used to investigate the hydrodynamics of solid-liquid suspension process in a stirred tank with rigid impellers, rigid-flexible impellers and punched rigid-flexible impellers. The effects of impeller type, impeller speed, flexible connection piece length, impeller spacing, particle size, and aperture size/ratio on the mixing quality were investigated. Results showed that the degree of solid-liquid homogeneity increased with an increase in impeller speed. A long flexible connection piece was conductive to solid particles suspension process. The solid particles could not obtain enough momentum to suspend to the upper region of stirred tank with small impeller spacing. Larger particle size resulted in less homogenous distribution of solid particles. The optimum aperture ratio and aperture diameter of punched rigid-flexible impeller were 12% and 8 mm, respectively, for solid particles suspension process. It was found that punched rigid-flexible impeller was more efficient in suspending solid particles compared with rigid impeller and rigid-flexible impeller at the same power consumption. In addition, less impeller power was consumed by punched rigid-flexible impeller compared with rigid impeller and rigid-flexible impeller at the same impeller speed.

1. Introduction

Solid-liquid suspension in stirred tanks is frequently encountered in the mineral, chemical, and pharmaceutical industries for leaching, crystallization, and polymerization operations. The main purpose of such an operation is to increase the contacting interfacial area between solid and liquid phases for facilitating mass transfer and chemical reaction [1,2]. However, problems such as the accumulation of solids and dead zones, cause poor interactions between solid and liquid phases, which may significantly affect product quality, yield, and process cost [3,4].

The suspension of solid particles has been studied extensively over the years. To obtain a good solid particles suspension quality, the most common way is to enlarge the stirring speed. However, excessive agitation may lead to a sharp increase in the motor load, and the shaft torque may exceed hardware capabilities. Since solids suspension and distribution were largely determined by the types and structures of the impeller, and many high-efficiency impellers were used in the solid-liquid mixing process. For example, Zhao et al. [5] applied an improved Intermig impeller in solid-liquid suspension process, and found that the improved Intermig impeller could promote the fluid circulation, create better solids suspension and consume less power compared with standard Intermig impeller. Zhu et al. [6] studied solid-liquid mixing characteristics in a stirred tank with a six shifted blades propeller (6SBP) and a six blades propeller (6BP), and found that 6SBP could shorten the mixing time and consume less power compared with 6BP. Xu et al. [7] applied a logarithmic helicoidal impeller in the solid-liquid mixing process, and found that logarithmic helicoidal impeller could improve the solid-liquid mixing performance compared with Rushton disc turbine impeller at the same power consumption. Liu et al. [8] applied a single rigid-flexible impeller in the electrolytic metal manganese process, and found that rigid-flexible impeller could enhance manganese leaching rate and shorten ore leaching time compared with rigid impeller at the same power consumption. The rigid-flexible impeller can enhance the interaction between impeller and fluid through the rigid-flexible-flow coupling movement behavior, and realize energy dissipation effectively. Combining with our previous study [9,10], and in order to further improve mixing efficiency of solid-liquid system

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http://dx.doi.org/10.1016/j.apt.2017.06.027
0921-8831/

Nomenclature

H	liquid height (m)
T	stirred tank diameter (m)
D	impeller diameter (m)
R	stirred tank radius (m)
Z	axial coordinate (m)
r	radial coordinate (m)
C_h	local solid volume fraction at height of h
C_{avg}	average solid volume fraction
n	number of sampling points
U	velocity (m/s)
d_p	particle diameter (m)
t	time (s)
g	gravitational acceleration (m/s^2)
P	pressure (Pa)
F	interphase momentum transfer term (N)
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$, C_μ	parameters in the standard k-ε model
k	turbulent kinetic energy (m^2/s^2)
F_{drag}	drag force (N)
C_D	drag coefficient
N	agitation speed (s^{-1})
P_w	power consumption (kW)
ξ	homogeneity
V_t	settling velocity (m/s)

Greek Letters

ρ_l	liquid density (kg/m^3)
ρ_s	solid density (kg/m^3)
ρ	density (kg/m^3)
α	volume fraction
α_l	liquid phase volume fraction
α_s	solid phase volume fraction
ε	turbulent energy dissipation rate
μ	viscosity (Pa·s)
μ_l	liquid phase viscosity (Pa·s)
μ_t	turbulent viscosity (Pa·s)
μ_{tl}	liquid phase turbulent viscosity (Pa·s)
σ_k, σ_ε	k and ε turbulent Prandtl number

on the basis of rigid-flexible impeller, a type of punched rigid-flexible impeller is proposed in this work.

The solid-liquid mixing characteristics are heavily governed by the hydrodynamics, which, in turn, is dependent on the impeller configurations and operating parameters. Therefore, understanding the hydrodynamics in stirred tanks will provide an insight for designing the impeller as well as for determining the operational parameters. Computational fluid dynamics (CFD) has proved to be a useful tool in analyzing the flow characteristics of solid-liquid mixing process [11–13]. For example, Qi et al. [14] investigated the effects of particle density, particle diameter, liquid viscosity, and initial solid loading on particle suspension behavior by using the Eulerian-Eulerian two-fluid model and standard k-ε turbulence model. Klenov et al. [15] applied CFD simualtions to study the effects of specific density of fine-dispersed solid phase and place of injection of solid with steady-state and time-dependent cases. Tamburini et al. [16] used CFD simualtions to describe the dynamic evolution of the suspension from start-up to steady-state conditions in a stirred tank equipped with a standard Rushton turbine impeller. Hosseini et al. [17] investigated the effects of impeller type, impeller off-bottom clearance, impeller speed, particle size, and particle specific gravity on the solid-liquid mixing quality by CFD simualtions. It can be found that CFD simulation is desirable to optimize impeller configurations and operating parameters.

In this work, the hydrodynamics of solid-liquid suspension process in a stirred tank with rigid impellers, rigid-flexible impellers, and punched rigid-flexible impellers were investigated by CFD technique. The effects of impeller type, impeller speed, flexible connection piece length, impeller spacing, particle size, and aperture size/ratio on the degree of homogeneity for the solid-liquid mixing process were discussed, and to compare the CFD results with the experimental data.

2. Experimental setup

The experimental system consisted of a cylindrical and flat-bottomed tank with vessel diameter T = 0.48 m, as depicted in Fig. 1. The liquid height H was equal to 0.8 m. Four baffles with width 0.1 T were mounted vertically on the tank wall. The schematics of rigid impeller, rigid-flexible impeller, and punched rigid-flexible impeller are shown in Fig. 2. The rigid impeller (Fig. 2a) is a six-bladed pitched blade disc turbine (PBDT) impeller. The rigid-flexible impeller (Fig. 2b) consisted of a PBDT impeller and six silicone flexible connection pieces, and the silicone flexible connection pieces were connected to the blades of PBDT impeller. The punched rigid-flexible impeller (Fig. 2b) had additional apertures on the surface of impeller blades compared with rigid-flexible impeller. The rigid PBDT impeller had a diameter of 0.26 m (D), and the impeller off-bottom clearance was set at T/3. The blade length (L_1) of rigid impeller was the sum of rigid blade length (L_2) and flexible connection piece length (L_3) of rigid-flexible impeller and punched rigid-flexible impeller. A torque transducer (DaYang Company, Model: HX-90D) was used to measure the impeller power consumption. The dispersion of glass bead particles of density ρ_s = 2470 kg/m^3 in tap water (ρ_l = 1000 kg/m^3, μ_l = 0.001 Pa·s) at room temperature was investigated. The mean solid loading of 5% (v/v) was used in both experiments and simulations.

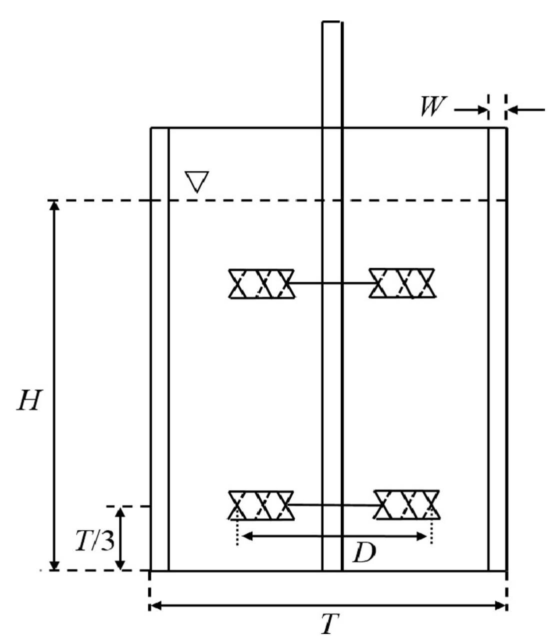

Fig. 1. Schematic of the stirred tank.