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Experimental and computational investigation of mixing with contra-rotating, baffle-free impellers

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ABSTRACT

This work experimentally and numerically investigates the intersection of two fields: (1) single axis, contra-rotating impellers and (2) buoyancy of solid suspensions. The main goals of this study are to (1) create a working model to quantitatively understand particle mixing, (2) characterize and compare contra-rotating single shaft impellers to single shaft co-rotating dual impellers, (3) improve quantification of particle mixing through image processing for both computational and experimental techniques, and (4) make design decisions with the computational analysis. Twelve cases were studied by changing the direction of impeller rotation, impeller pumping direction, and the presence of baffles. Particles with specific gravities (SG) of 0.866 and 1.050 were introduced into the experimental and computational systems in a finite and countable number. The numerical solution was obtained using the Lattice Boltzmann method and the Discrete Particle method. A commercial LBM solver, XFlow, was used for the simulation. The input torques and mixing efficiency with various flow configurations and specific gravities was used to find an optimal design. For the mixing of the lighter particles, the contra configuration with inward opposing flow gave optimal performance of highest mixing efficiency at lowest required torque. Co-rotating impellers with baffles gave the best performance of high mixing efficiency at lowest power input for the heavier particles.

1. Introduction

Mixing and agitation operations are widely used in industrial process such as pharmaceutics, agriculture, and food processing. Mixing is the manipulation of a heterogeneous physical system with the intent to make it more homogeneous (Paul et al., 2003). When a mixer uses a single or two co-rotating impellers to agitate the substances inside the mixer, a vortex is generally created (Paul et al., 2003; Regalbuto and Regalbuto, 2014). In order to eliminate the vortex, baffles are usually inserted into the mixer to interrupt the flow of the contents (Paul et al., 2003). The use of baffles required higher power input and are sometimes problematic in construction (as in glass-lined mixers) or in operation and maintenance. A contra-rotating impeller design potentially eliminates the need for baffles. The contra-rotating impellers design consists of two impellers rotating in opposite directions about the same axis. Two impellers are arranged one behind the other, and the power is transferred from the motor via bevel gear, planetary gear, or spur gear transmission (Regalbuto and Regalbuto, 2014; El-Sayed, 2016). Due to this mechanical structure, the contra-rotating impeller design has the advantages of high static pressure, high turbulent flow, and good performance in reversing fluid flow. Prior to this work, this contra-rotating design was studied and now being used in the aircraft and marine industries to improve thrust, reduce torque, and optimize aeroacoustics in the gas and/or liquid environment but not for the mixing of solid–liquid (Wang and Meng, 2016; Paik et al., 2015; Min et al., 2009; Gaggeroa et al., 2016; Grassi et al., 2010; Çelik and Güner, 2007).

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Nomenclature

$\vec{a}_{D(f-p)}$	Acceleration of the particle due to the drag force
$\vec{a}_{Ext_{f,p}}$	External acceleration affecting both phase
$\vec{a}_{Ext_p}$	External acceleration affecting only disperse phase
b	Probability distribution functions
c_s	Speed of sound in Lattice scale
C_D	Drag coefficient
d_p	Particle diameter
D_a	Impeller diameter
$\vec{e}_i$	Particle discrete set of velocities
eff	Mixing efficiency
f_{act}	Actual particle fraction
f_i	Particle distribution function in the i direction
f_{ideal}	Ideal particle fraction
$\vec{g}$	Gravity
M_{ij}	Transformation matrix to macroscopic moment
$\vec{n}$	Unit normal vector at control volume surface
n_r	Impeller rotation rate
N_{vis}	Number of particles visibly drawn into the liquid, particles
N_{ideal}	Total number of particles were fed into the liquid, particles
P	Macroscopic fluid pressures
$\vec{r}$	Radius vector of impeller
Re	Relative Reynolds number
Re_S	Reynolds number for rotation system
$\hat{S}_{ij}$	Diagonal relaxation matrix
t	Discrete times
Δt	Constant time step
T_r	Torque
$\vec{u}$	Macroscopic fluid velocity
$\vec{u}_f$	Fluid phase velocity
$\vec{u}_p$	Particle disperse phase velocity
$\vec{V}$	Fluid velocity
$\vec{x}$	Lattice node

Subscripts

f	Fluid phase
p	Particle disperse phase
act	Actual
vis	Visible

Greek symbols

μ	Molecular viscosity of the fluid
μ_i	Raw of the moment
μ_i^{eq}	Raw moment at equilibrium
σ_i	Degree of deviation from ideal mixing
δ_h	Degree of deviation in the horizontal
δ_v	Degree of deviation in the vertical
ν	Macroscopic kinematic viscosity
τ	Relaxation parameter
ρ	Macroscopic fluid density
Ω_i	Collision operator
Ω_i^{MRT}	Multiple relaxation time collision operator

For the past several decades, many researchers have attempted to quantify mixing efficiency. Danckwerts (1952) quantified the "goodness of mixing" with two statistically defined quantities, scale and the intensity of segregation, and noted that methods of measuring are key features which affect the efficiency of mixing processes. Kukukova et al. (2009, 2011) applied Danckwerts' method to define mixing and segregation based on three variables of segregation: intensity of segregation, scale of segregation, and rate of change of segregation. They also concluded that with these variables, it is possible to clearly quantify the mixing and segregation in mixing processes. Several studies related to solid–liquid mixing (Lacey, 1954; Larosa and Manning, 1964; Harnby, 1967; Lacey and Mirza, 1976; Dlugi et al., 2014) also used the intensity and scale of segregation to determine mixing efficiency. In solid–liquid mixing, there are a large number of techniques which can provide both qualitative and quantitative information on the dispersion of solids in the mixer, i.e., conductivity probe, process tomography, and visual observation (Paul et al., 2003). In this study, we utilized both visual observations and simulation of the dispersion of solid particles in water to calculate mixing efficiency with the improved intensity of segregation method.

The twelve cases that were studied are shown in Fig. 1 and include the little-studied configuration of contra-rotating impellers. The mixing models were distinguished by rotation patterns and mixer formats. Cases 1–4 are contra-rotating impellers without baffles. Cases 5–8 are co-rotating impellers without baffles. Cases 9–12 are the co-rotating impellers with baffles. The tank has a rounded bottom and a capacity of 25 l. The two impellers have 4 blades pitched at 45° and are driven by an adjustable speed motor. Many researchers have studied the variation of flow pattern, power consumption and mixing time with different reactor designs in order to develop an understanding of the effect of changing the design parameters (Kuboi and Nienow, 1986; Mahmoudi and Yianneskis, 1991; Mishra and Joshi, 1994; Hiraoka et al., 2001). These included the study of the impeller clearance from the bottom and the distance between the two impellers. The results of these studies showed that the power consumption depends on the distance between two impellers as well as the interaction of the impellers flows. However, the design optimization and the analysis of the flow paths of the particles in the reactor still need to be studied.

These studies analyzed the motion of the solid particles in the liquid to find the solid–liquid mixing efficiency and power consumption using three-dimensional (3D) computational fluid dynamics (CFD) modeling with the Lattice Boltzmann method (LBM). The free surface model and Discrete Phase Model (DPM) was also used in this work. LBM has many advantages over conventional CFD (Navier–Stoke equation) for modelling moving geometries. This method uses a meshless particle based LBM instead of the traditional meshing process for moving parts (i.e., Multiple Reference Frame and Sliding Mesh). The LBM simulation relies on a generated lattice element, which is organized in an Octree structure, and uses a Large Eddy Simulation (LES) turbulence model, which can reduce meshing operation and computational times (Holman et al., 2012). There are various modeling works on mixing, using impellers where LBM simulation was utilized (Guha et al., 2008; Sungkorn et al., 2012), which can model the movement of solid particles or bubble flow dynamics and predict the solids dynamics in a solid–liquid mixing tank. However, the mixing efficiency in these reactors need to be further investigated. The solid–liquid mixing efficiency of the simulation were calculated from the numerical results of the DPM by image analysis techniques (Satjaritanun et al., 2016). The relative impact of the factors affecting mixing efficiency and power consumption – rotation mode, rotation speeds and mixer designs – is clearly delineated and the advantages and disadvantages of contra-rotating impellers are discussed.

2. Experimental setup and procedure

The experimental setup is shown in Fig. 2a. It was constructed from two tanks, a cylindrical tank with a round bottom and an outer rectangular tank to eliminate distortion. The cylindrical tank is 0.30 m in diameter and 0.35 m in height. The rectangular tank is 0.40 m in diameter and 0.40 m in height. The cylindrical tank that was filled with water was installed inside the rectangular tank. Both tanks were filled with water