

Numerical Simulation of Two-Phase Mixing Tank for Gas Holdup and Concentration Analysis

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Abstract

Multiple impellers are preferred over single impeller and have been widely used in mixing tanks for various biological processes like fermentation, water treatment and pharmaceutical production. Validation of simulation results is a key factor for further utilization of equipment design. In the present study an aerated three Rushton turbine is validated for gas holdup for different rotational speeds and different gas injection rates. The effect of spacing between impellers on gas holdup and mixing behavior is then investigated using OpenFOAM. The simulation results are in good agreement with experiment data for gas holdup. The results further show that spacing between impellers is important factor for mixing behavior and gas holdup.

Keywords: OpenFOAM, Rushton turbine, Two-phase, Mixing, RANS

1. Introduction

Gas-liquid interaction is considered as one of the most vital operations in chemical process industries. The gas-liquid phases in mixing or agitated vessels are widely implemented in various processes in chemical, pharmaceutical and biotechnological industries [1, 2]. Agitation in mixing tank is necessary to increase heat and mass transfer rates to prevent particle settlings, to obtain emulsions and to even out all physical properties [3]. Gas-liquid processes, in particular, like fermentation and aeration process need a large gas handling capacity and effective gas dispersion to generate as large interfacial area as possible [4]. In present study we are considering various impeller spacing of three Rushton turbine to study their effect on gas holdup and dispersion at different rotational speeds. The same cases are investigated for mixing behavior by introducing a tracer and calculating homogeneity at different points in the tank. Based on the founding, a new turbine configuration is suggested for turbine spacing and number of impellers in order to have a better results in both gas holdup and mixing behavior.

2. Numerical Method

The Euler-Euler approach was chosen to simulate two phases mixing tank where both phases are treated as a continua. Governing equations are solved separately for each phase with same pressure equation for both phases and coupled with momentum exchange interfacial forces such as drag force and virtual mass. The governing equations are:

the continuity equation,

$$\nabla \cdot (\alpha_q \rho_q u_q) = 0$$

and the momentum equation,

$$\frac{\partial}{\partial t}(\alpha_q \rho_q u_q) + (\alpha_q \rho_q u_q . \nabla) u_q - \nabla . (\alpha_q D_q^{eff} \nabla u_q) = \nabla p + \alpha_q \rho_q g + F_D + F_M$$

where α_q is phase fraction, D_q^{eff} is effective diffusivity, F_D is drag force and F_M is virtual mass force. The drag model used in this study is Schiller-Naumann and drag coefficient is calculated by the following equations:

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$$C_D = \begin{cases} \dfrac{24(1+0.15Re^{0.687})}{Re} & Re \le 1000 \\ 0.44 & Re > 1000 \end{cases}$$

where C_D is the drag coefficient and Re is the Reynolds number. The Reynolds number is calculated at each cell in the domain by the following equation:

$$Re = \frac{\rho_l |u_g - u_l| d_g}{\mu_l}$$

where u_g and u_l are the gas and liquid velocities and d_g is bubble diameter which is a fixed value. Whereas impeller Reynolds number is defined as:

$$Re_i = \frac{Nd^2}{v}$$

where N is rotational speed, d is impeller diameter and v is kinematic viscosity. OpenFOAM free software with k-ω SST model is used for calculation. The tank is of a cylindrical shape fully baffled with ellipse shape at the bottom. The air is injected with uniform velocity from a sparger below the bottom impeller as shown in Fig 1. The mesh grid size is 2.5 million hexahedral cells. Six bladed three Rushton turbine with three different spacing between impellers are used. The term S/d is used to describe the spacing as the ratio between impellers spacing (S) and turbine diameter (d). For case1 the S/d value is 1.66 between bottom and middle impeller and 1.48 between middle and top impeller. The S/d values for case2 and case3 are (1.5, 1.3) respectively. Water initial level is at 0.82m while tank height extends to 0.97m to account for water level increase. Three different impeller rotational speed (31, 47, 52 rad^{-1}) which corresponds to (300,450,500 rpm) with gas injection rate (50 L/min.) are simulated for each impeller spacing to calculate the gas holdup as shown in Table 1.

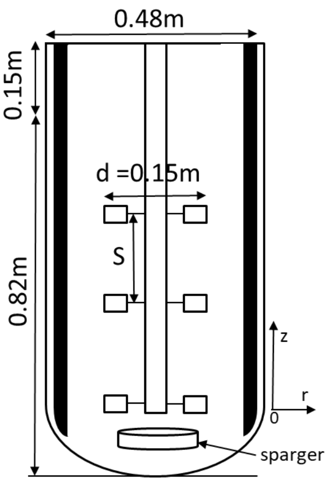


Fig 1: Tank geometry

Table 1: Simulated cases

Case ID	S/d	RPM	Injection rate (L/min)	Bubble diameter (mm)
case1	1.66|1.48	300	50	1
		450		0.5
		500		0.5
case2	1.5	300	50	0.5
		450		0.5
		500		0.25
case3	1.3	300	50	0.5
		450		0.5
		500		0.25

The simulation results for gas holdup for case1 are validated with experiment data. To ensure accuracy, data are sampled after 20 seconds of fully developed flow of gas holdup. For the other cases, data are sampled after 10 seconds to reduce calculation cost. The reduction in sampling time does not give the accurate gas holdup but it is enough to illustrate the differences if any qualitatively. In the experiment a surfactant is added to reduce surface tension. Hence, reduce bubble size and increase gas holdup in the system. Schiller-Naumann drag model is restricted with fixed bubble size, thus different bubble sizes are used to calculate drag coefficient for different rotational speeds based on experimental data provided where at current running condition the bubble diameter is observed to decrease with an increase in impeller rotating speed. For the cases 2 and 3, the bubble diameter used for the 500 rpm is reduced to 0.25mm to investigate the effect of bubble size on drag model behavior of the solver and hence gas holdup results. For the cases where rotational speeds exceeds 1000 rpm the opposite is observed to happen [5]. This is explained by an increase in the gas rate with higher impeller speeds and corresponds to increase in bubble size [6]. To investigate the mixing behavior, a tracer is injected at the side bottom of the tank at height of z = 0.15m. The tracer is analyzed for concentration distribution and local concentrations at different points in the tank.

3. Results and Discussion

The experiment showed that gas injection has a small effect on the gas hold up in the system. In this case the increase of injection rate from 30 to 50 L/m accounts for an average increase on gas holdup in the tank of 1%.On the other hand there is a linear increase of gas holdup with increase in rotational speed with 50 rpm increase accounts for 1.5% on average with an advantage of better gas dispersion. The data from simulation is in a good agreement with experiment and shows also the effect of rotational speeds on gas hold up with a good accuracy as shown in Fig 2. Nevertheless, since the current scope of work does not consider mass transfer calculation, the qualitative results is believed to be reliable to conduct the simulation for different impeller setups. The simulation data for gas holdup of case2 (S/d 1.3) and case3 (S/d 1.5) shows the advantage of higher impeller spacing for gas holdup as shown in Fig 3. This can be justified for one part due to higher interaction at water surface with air when top impeller is placed closer to the water surface. A further study is required to justify any other factors that contribute to this phenomena. Furthermore, the data shows a sudden increase in the gas volume fraction which is due to change in bubble diameter to 0.25mm. This is done purposely to investigate the effect of bubble size diameter used by drag model on the results. This observation shows that carful choice of bubble diameter based on experimental data are valuable to better utilize the limitation of Schiller-Naumann fixed bubble diameter drag model. Injected tracer shows better uniform distribution of lower impeller spacing as shown in Fig 4. Lower spacing between impellers allows for more interaction of flow fields and hence higher turbulence diffusion and homogeneity. This was observed by previous studies conducted by Mahmoudi and Yianneskis where they found an increase in mixing time up to 40% for longer spacing compared to lower spacing [7]. This influence is observed in all types of impeller configurations as the spacing significantly affects the produced flow fields inside the tank [8, 9]. From Fig 3 and Fig 4 results we suggest the addition of another turbine with lower spacing between impellers and top impeller placed higher than present S/d=1.5 for better mixing and gas holdup.

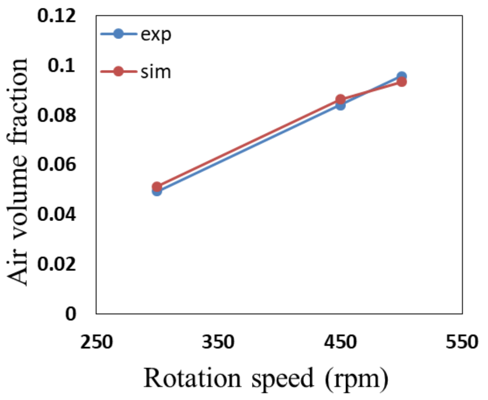


Fig 2: Gas holdup against impeller speed for case1

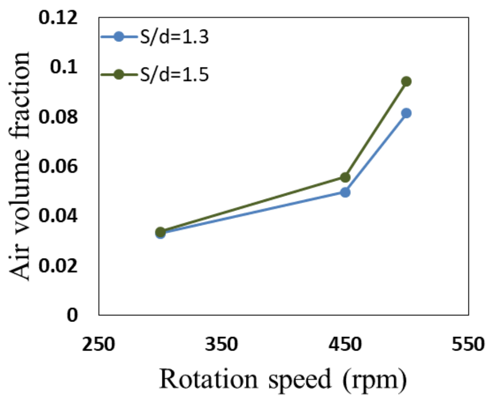
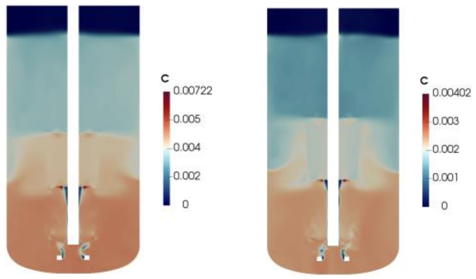


Fig 3: Gas holdup for different S/d ratio for case2 and case3



(a) (b)

Fig 4: Concentration distribution after 10 seconds:
(a) S/d=1.3 case3 and (b) S/d=1.5 for case2

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