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Experimental and numerical study of gas hold-up in surface aerated stirred tanks

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Abstract

Although the distribution of gas hold-up in stirred tanks is a key factor to their design and operation, systematic experimental data on local gas hold-up of surface-aerated stirred tanks are not available in open literature. In this work, turbulent two-phase flow in a surface aeration stirred tank with a diameter of 0.380 m was investigated experimentally and numerically. The gas hold-up was measured with a conductance probe at various operating conditions. A surface baffle to improve the efficiency of surface aeration of a Rushton disk turbine was designed and tested. The experimental data suggest that the gas hold-up distribution in the surface aeration tank is very non-uniform, and the surface baffle improves the aeration rate particularly at a high agitation speed. A three-dimensional in-house computational fluid dynamic (CFD) two-fluid model with the standard k–ϵ–A_p turbulence model was used to predict the gas–liquid flow, and the impeller region was handled using the improved inner–outer iterative procedure. Based on Kolmogoroff's theory of isotropic turbulence, a constitutive equation for surface aeration strength was proposed. The numerical prediction, in combination with the measurements, gives insight to the surface aeration performance of stirred tanks. It was found that the simulation reasonably predicted the gas hold-up distribution in the upper tank, but underestimated it in the region below the stirrer.

Keywords: Stirred tank; Gas–liquid flow; Gas hold-up; Numerical simulation; Surface aeration; Rushton impeller

1. Introduction

Mechanically agitated gas–liquid tanks have been important gas–liquid mixing and/or reaction devices for many years, and extensively applied in chemical and related processes such as physical/chemical absorption and gas–liquid reactions. The design methodology for gas–liquid stirred tanks has been mainly relied on those empirical correlations of global quantities developed from bench-scale or/and pilot-plant-scale experiments. Although this global "correlation" approach have provided satisfactory answers to numerous practical stirred-tank designs, it has shown some limitations in the design innovation and in maximizing the potential of gas–liquid interactions.

Gas dispersion has been one of most active research subjects in stirred tanks due to its strong influence on gas–liquid mass transfer, which involves not only the local rate of gas input, but also the complicated interaction between the continuous and the dispersed phase. To fully understand and quantify the gas–liquid interactions and the mass transfer occurred in surface aeration stirred tanks, experimental researches on the local hydrodynamics such as local gas hold-up, interfacial area and bubble size distribution are essential. Moreover, the spatial distribution of these hydrodynamic parameters is needed for validation of hydrodynamics model.

Computational fluid dynamics (CFD) has been extensively applied in analysis of the complex turbulent single-phase and multiphase flow in stirred tanks. Many papers on simulation methods for stirred tanks have been published to date (Gosman et al., 1992; Bakker and van den Akker, 1994; Morud and Hjertager, 1996), and in particular, the modelling methods for multiphase flows deserve more intensive development due to their importance in process industries (Lane et al., 2002). Gosman et al. (1992) simulated the two-phase gas-liquid flow

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in a baffled, agitated vessel using a three-dimensional model with the k–ϵ turbulence model, and a simplified equation of the gas momentum. Pericleous and Patel (1987) modelled the flow in a stirred tank using an algebraic slip model. Momentum equations were solved using mixture properties, and the spatial distribution of bubbles was calculated by the concentration equations assuming constant bubble size. Experimental results and three-dimensional calculations of the flow in a stirred tank were presented by Bakker and van den Akker (1994). Patterson (1991) used the LDA technique to measure liquid velocities with and without gas sparging, and a three-dimensional simulation of the flow with the FLUENT CFD code was applied, in which individual bubbles were tracked by a Lagrangian approach. Bröring et al. (1991) used an improved ultra sound-Doppler technique for extensive measurements of bubble velocity components in stirred vessels equipped with one or three Rushton impellers, respectively. Morud and Hjertager (1996) simulated the two-dimensional gas–liquid and liquid–solid flow in a stirred tank employing the "black box" approach. Barigou and Greaves (1991) applied computerized conductivity probe technique to the local gas hold-up in a large diameter tank. Alves et al. (2002) measured the local gas hold-up and local bubble size distribution throughout the tank for three liquid media: tap water, aqueous sulphate solution, and aqueous sulphate solution with PEG. Lane et al. (2000) also used a multiple reference frame method to investigate the gas–liquid flow in mechanically stirred tanks.

To the authors' knowledge, there has been no literature in public domain on the local gas hold-up measurement and flow modelling in surface aeration stirred tanks. This paper addresses the research of the gas hold-up in surface aerated tanks. The local gas hold-up is measured with a conductance probe and the experimental data at different operating conditions are obtained, which offers a reference for further study of flow, mass transfer and numerical simulation. As the gas aspirating capacity is strongly limited by the immersion depth of the impeller, a surface baffle above the impeller is tested with respect to the gas–liquid dispersion, and the influence of the surface baffle on the local gas hold-up is investigated. The Kolmogoroff theory is used to give the tentative rate equation of gas uptake as a function of the local hydrodynamics and the two-fluid model is employed to simulate the flow field of the surface aeration stirred tank with the inner–outer iterative method.

2. Experimental

2.1. Experimental set-up and stirring configurations

The experimental apparatus is shown in Fig. 1. The gas is entrained from the free surface of the bulk liquid phase when the liquid in the tank is agitated vigorously. The conductance probe is used to measure the local hold-up.

The experiment was carried out in a cylindrical vessel with the diameter $T = 0.38$ m. Four wall baffles of width $T/10$ were mounted vertically onto the inner side wall. The geometry of the stirred vessel is depicted in Fig. 2. Water at room temperature was filled to the height equal to the tank diameter ($H = T$) in all experiments. Three impeller configurations consisting of a standard six-blade Rushton disk impeller were tested. The first configuration (A) included only a standard Rushton turbine with its diameter equal to $T/2$, which was placed $T/3$ below the free gas–liquid surface. The standard Rushton turbine with holes in the disk was used in the second configuration (B) and the turbine was placed $T/3$ below the free gas–liquid surface. A thin surface baffle of $T/2$ diameter with holes was set on the liquid surface and allowed to rotate around the impeller shaft, freely but passively, driven by the hydrodynamic impact of agitated liquid. The surface baffle is similar in principle to the patent design (Mao et al., 2000; Yu et al., 2002). The third configuration (C) is the standard Rushton turbine with the diameter of $T/3$, placed 80 mm below the free surface to strengthen its aerating capacity to an appreciable level.

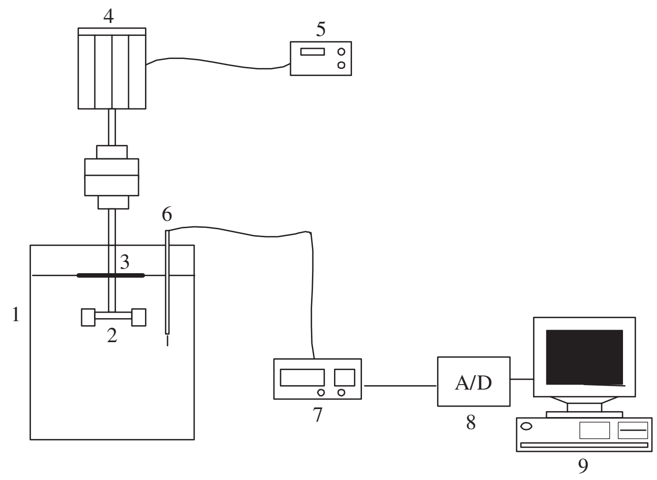

Fig. 1. Schematic of the experimental apparatus: 1. stirred tank, 2. Rushton disk turbine, 3. impeller baffle 4. motor, 5. speed controller, 6. conductance probe, 7. measurement circuit, 8. A/D converter and 9. computer.

The stirring speed was measured with an optic tachometer to the accuracy of 1 rpm.

2.2. Conductance probe for local gas hold-up

The conductance probe has an electrode made of a single 100 μm diameter stainless-steel wire, as presented in Fig. 3, and the tip is 0.3 mm protruded from the insulation material.

The principle of the conductance probe method is based on the difference in electrical resistance between the liquid and gas phases. The tiny stainless-steel needle is an electrode, while the conductive tubing strengthening the probe is the counter electrode, which is always at the same voltage as the continuous phase of water. Impedance of the measurement circuit varies as the probe tip is crossing the gas bubble surface, and the output signal of the circuit shows distinct spikes correspondingly. The high voltage level above the threshold voltage denotes that the probe is in gas and the low voltage means that the probe is in the liquid phase. The local gas fraction at the measurement