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An experimental and theoretical study on the size of bubbles formed between a rotating disc and a stationary wall

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HIGHLIGHTS

- Experimental and theoretical study on bubble size between a rotor and a stator.
- Liquid properties: 1000–1150 kg m^{-3} (density), 0.81–1.70 mPa s (viscosity).
- Bubble sizes are calculated via a force balance on the bubble and gas feedflow.
- The azimuthal liquid velocity is the single fitting parameter.
- The model correctly describes all bubble diameters (range: 3.32–15.3 mm).

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ABSTRACT

This paper comprises an experimental and theoretical study on gas bubble formation in a liquid in a spinning disc device. Measurements were done in a device with a rotor radius of 0.135 m and a distance of 2×10^{-3} m between the rotating disc and the stationary wall. Experiments have been performed at rotational velocities where the Von Kármán boundary layer at the rotor and the Bödewadt layer at the stationary wall interfere. It was found that the highest angular velocities resulted in the smallest average bubble diameters (3.32 ± 0.662 mm), while at the highest gas mass flow rate and lowest rotational velocities, the largest bubbles were produced (15.3 ± 1.89 mm). Variation of liquid density from 1000 to 1150 kg m^{-3} and liquid viscosity from 0.81 to 1.70 mPa s appeared to have a negligible effect on the bubble size. A model was derived from a mass and momentum balance, which incorporates the unsteady effects of added mass, gas momentum, bubble growth rate, drag force and centrifugal buoyancy. The general trends in calculated average bubble size are in agreement with the experimental results and the model calculations were able to simulate average bubble diameters within a single experimental standard deviation.

1. Introduction

Bubble formation in rotating liquids is fundamentally different than its counterpart in stationary or cross-flowing liquids. The effect of centrifugal buoyancy leads to additional detaching forces resulting in earlier bubble detachment and thus reduced bubble diameters (Harikrishnan et al., 1983; Goma et al., 2005). These smaller bubbles have a higher specific surface area which is beneficial for gas–liquid mass transfer near gas-inducing stirrers (Forrester et al., 1998), or in a novel type of multiphase reactor, called the rotor–stator spinning disc reactor (Meeuwse et al., 2010b).

The rotor–stator spinning disc reactor has proven to significantly increase gas–liquid and liquid–solid transport by simultaneously lowering the resistance to mass transfer and increasing the interfacial area through which mass transfer takes place (Meeuwse et al., 2010a, 2010b; Visscher et al., 2012b). The reactor consists of a rapidly rotating disc (the rotor) in a narrow cylindrical housing (the stationary wall). The distance between the rotor and the stator h is typically one to several millimeters, while the rotor radius R_D is of the order 5–15 cm. The rotating disc has a high angular velocity of up to $\Omega \approx 2 \times 10^3$ rpm, resulting in very high shear forces in the fluid in the narrow gap between the rotor and the stationary wall.[1] These shear forces trigger the early pinch-off of bubbles or droplets from their inlets, resulting in

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[1] The rotor–stator spinning disc reactor is in fact an improved version of the conventional spinning disc reactor where a thin liquid film is flowing over a freely moving rotating disc. A more elaborate comparison between a rotor–stator spinning disc reactor and a conventional spinning disc reactor can be found in Meeuwse (2011).

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smaller bubble/droplet diameters, and thus in an increasing specific surface area available for molecular transport.

Also, the high angular velocity of the disk invokes a high degree of turbulence, which allows for the rapid renewal of fluid elements near the surfaces of bubbles, droplets, and particles, lowering the resistance to mass transfer. It is the combination of these two effects that gives the rotor–stator spinning disc reactor its excellent mass transfer performance.

In fact, reported values for the liquid–solid mass transfer coefficient of $k_{LS}a_{LS} = 0.22\ m_L^3\ m_R^{-3}\ s^{-1}$ in the spinning disc reactor are one order of magnitude higher than typical values of $k_{LS}a_{LS} = 0.01–0.1\ m_L^3\ m_R^{-3}\ s^{-1}$ in packed bed columns (Meeuwse et al., 2010a; Delaunay et al., 1980; Comiti et al., 2000). For the case of gas–liquid mass transfer, values are reported of $k_{GL}a_{GL} = 0.95\ m_L^3\ m_R^{-3}\ s^{-1}$ in the spinning disc reactor, which are about four times higher than those for bubble columns (Meeuwse et al., 2010b), and twice as high as in conventional spinning disc reactors (Meeuwse et al., 2012). When the relatively low gas hold-up in the spinning disc reactor, typically of the order of $\varepsilon_G = 0.021\ m_G^3\ m_R^{-3}$ is taken into account, values of the rate of volumetric mass transfer per unit of volume of gas in the spinning disc reactor are calculated to be $20.5\ m_L^3\ m_G^{-3}\ s^{-1}$, which is about 40 times higher than typical values found in conventional bubble columns ($0.5\ m_L^3\ m_G^{-3}\ s^{-1}$) (van der Schaaf et al., 2007).

Recent endeavours in describing the mass transfer characteristics in this novel type of reactor mostly consisted of experimental observations, while a more fundamental description of the physical situation between the rotor and the stator is still lacking. Model equations to describe bubble size, gas hold-up and mass transfer coefficients based on a combination of experimental results and theoretical insights will greatly improve the design process for developing a rotor–stator spinning disc reactor. The present work will shed some light on the determination of the average bubble size, just after detachment from the orifice at the gas inlet.

The paper is structured as follows: first, the experimental setup is described along with the measurement procedure. Then, the theoretical model is derived, including a description of all relevant hydrodynamic forces and a discussion on bubble detachment criteria. The experimental results are subsequently discussed and compared with the model calculations. The paper ends with some concluding remarks on the observed experimental and theoretical trends.

2. Experimental setup and procedure

The experimental setup that is schematically depicted in Fig. 1 consisted of a stainless steel disc of radius $R_D = 0.135$ m which was encased in a cylindrical, transparent PMMA housing so that the distance between the rotating disc and the stationary wall equals $h = 2 \times 10^{-3}$ m, while the distance between the edge of the disc and the concentric shroud was 1 mm. Nitrogen gas was fed through an orifice of diameter $d_o = 1.5 \times 10^{-3}$ m in the bottom stator.

The density and the viscosity of the liquid could be finely tuned by producing binary mixtures of potassium iodide, sodium chloride, or glycerol in demineralised water (Goldsack and Franchetto, 1977; Kestin et al., 1981; Cheng, 2008; MacInnes and Dayhoff, 1952; Pawar et al., 2009; Visscher et al., 2012a). Depending on the solute molality, the desired liquid density and viscosity can be achieved according to Figs. 2 and 3.

In addition to the effect of liquid properties on bubble formation, the gas flow rate and the rotational velocity were varied as well. The nitrogen feed rate was set to $\phi_G^m = 5.82 \times 10^{-6}$, 8.58×10^{-6}, or $11.6 \times 10^{-6}\ kg\ s^{-1}$ with a mass flow controller (Bronckhorst, EL-FLOW Select IP-40), while the rotational velocity (Ω) of the rotor was set to a value in the range 15.7–68.1 rad s^{-1}

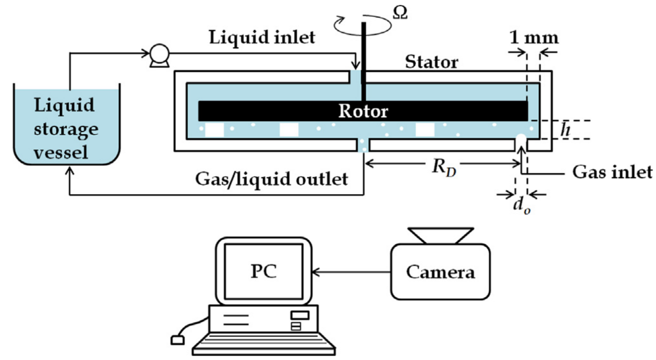

Fig. 1. The experimental setup consisted of a stainless steel disc in a transparent PMMA housing. The gap spacing between the rotating disc and the parallel stationary wall was equal to $h = 2 \times 10^{-3}$ m, while the rotor radius was $R_D = 0.135$ m. Gas was fed through an orifice of diameter $d_o = 1.5 \times 10^{-3}$ m in the bottom stator. With a Canon EOS digital 400D camera, images were taken from the bottom of the setup, which were digitally analysed to resolve the bubble diameters.

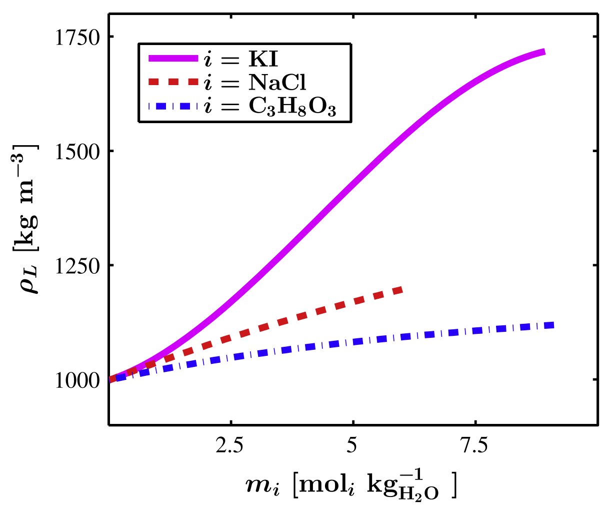

Fig. 2. The liquid density can be tuned by adding potassium iodide, sodium chloride, or glycerol in different molalities to demineralised water. The curves are obtained from interpolation by cubic splines of experimental data from MacInnes and Dayhoff (1952), Pawar et al. (2009), and Visscher et al. (2012a) for potassium iodide solutions, from Kestin et al. (1981) for sodium chloride solutions, and from Cheng (2008) for glycerol–water mixtures.

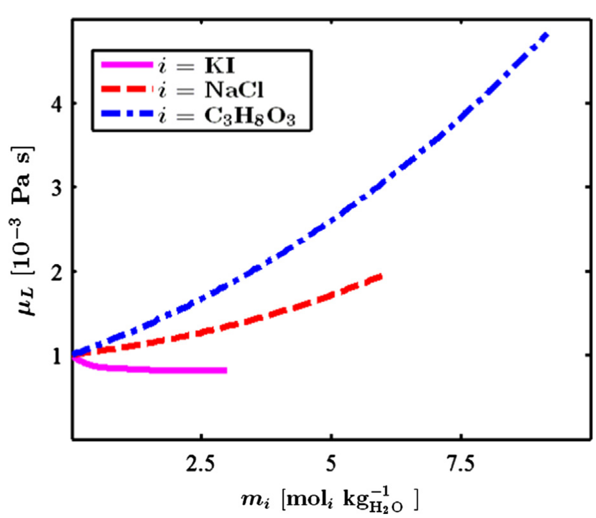

Fig. 3. The liquid viscosity can be tuned by adding potassium iodide, sodium chloride, or glycerol in different molalities to demineralised water. The curves are obtained from interpolation by cubic splines of experimental data from Goldsack and Franchetto (1977) for potassium iodide solutions, from Kestin et al. (1981) for sodium chloride solutions, and from Cheng (2008) for glycerol–water mixtures.