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Determination of flow regime and gas holdup in gas–liquid stirred tanks

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HIGHLIGHTS

- Identification of flow regime in gas–liquid stirred tanks.
- Linear relationship of the Froude number with gas holdup quantified.
- Measurement errors of the probe used were found negligible.

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ABSTRACT

This work provides an in-situ method for determining the flow regime in a lab scale gas–liquid stirred tank reactor based on optical probe measurements. Tapered (conical) end optical fibers, which can distinguish which phase their tips are surrounded by, were employed over the whole range of practical operating conditions achievable in our Chemical Reaction Engineering Laboratory (CREL). After checking for sources of error associated with the rise and fall times of the measured signals, gas holdup and bubble count profiles were obtained by processing the time-series data with appropriate in-house developed algorithms. The data were presented in terms of the two dimensionless numbers, the Flow Number (*Fl*) and the Froude Number (*Fr*). All experiments were executed with an air–water system but the technique can be employed with all liquids and gases. The results suggest that the optical probe, when strategically positioned, can successfully and readily determine which state of dispersion the reactor is in. This reveals the technique's potential usefulness as an important research and control tool.

1. Introduction

Quantifying transport–kinetic interactions in gas–liquid stirred tank reactors (STRs) has been a crucial part of multiphase reaction engineering for several decades due to the tank's wide spread use in practice. STRs have been known to be one of the most effective gas–liquid contactors capable of handling numerous duties (Harnby et al., 1985), from the very basic chemical and petrochemical processes to the newly developed biochemical and biological processes. In 1991, it was estimated that nearly half of the chemical industry's output had passed through a STR at one point (Tatterson, 1991).

In general, process efficiency of a gas–liquid STR highly depends on the degree of interfacial contacting. As the gas–liquid interfacial area per unit liquid volume (a) changes, so do other important operating parameters such as volumetric heat and mass transfer coefficients. Naturally, much effort was invested in developing useful correlations for these parameters via means of proven experimental techniques and computational simulations (Cents et al., 2005; Ford et al., 2008; Khopkar and Ranade, 2006; Lane et al., 2002, 2005; Mueller, 2009; Mueller and Dudukovic, 2010; Wang et al., 2000, 2006). For a standard fully baffled gas–liquid STR equipped with central Rushton impeller which we investigated, several flow patterns (regimes) have been identified based on major bubble trajectories and are shown in Fig. 1.

In the literature, three regimes have been reported and described using two dimensionless numbers. These three regimes are flooding, loading, and fully recirculated regimes (Bombač et al., 1997; Harnby et al., 1985; Tatterson, 1991), and the two dimensionless numbers are the Flow Number (Fl) and the Froude Number (Fr). The Fl number is the ratio between the gas flow rate and the impeller driven flow rate; the Fr number is the ratio between the impeller driven acceleration and gravity. In equation form,

$$Fl = \frac{Q_g}{ND^3} \tag{1}$$

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$$Fr = \frac{N^2 D}{g}, \tag{2}$$

where Q_g is the gas flow rate from the sparger, N is the impeller rotational rate, D is the turbine diameter, and g is the gravitational constant. As the Fr number increases, *i.e.*, by providing more acceleration by means of increased impeller rotational rate, the flow regime transitions from a less to a more dispersed state. Likewise, as the Fl decreases, *i.e.*, by introducing less gas to be dispersed or by providing more acceleration by means of increased impeller rotational rate, the flow regime transitions from a less to a more dispersed state. A complete flow regime map for an air–water system has been provided by several researchers (Bombač et al., 1997; Jade et al., 2006; Khopkar and Ranade, 2006; Mueller, 2009; Warmoeskerken and Smith, 1985) and is shown in Fig. 2.

In the flow regime map, cavity structures observed behind the impeller blades are also indicated, as different cavity structures have been well known to be associated with each flow regime (Bombač et al., 1997; Tatterson, 1991). VC represents the vortex clinging structure, S33 represents the small "3–3" structure, L33 represents the large "3–3"structure, and RC represents ragged cavities. The two transition lines, from flooding to loading and loading to fully recirculated regime, were first determined by observing at which operating conditions dominant bubble trajectories had changed, and later confirmed by determining the cavity structures. In dimensionless form, the two transition lines are

$$\text{Transition from flooding to loading regime} = Fl_F = 30Fr(T/D)^{-3.5} \tag{3}$$

$$\text{Transition from loading to recirculated regime} = Fl_{CD} = 13Fr^2(T/D)^{-5}. \tag{4}$$

Over recent years, the demand for more reliable experimental techniques for identification of the flow regimes has risen considerably partly due to ever increasing computational power and many computational fluid dynamic (CFD) models being readily available. As concluded by Rammohan (2002), Guha et al. (2007), and Mueller (2009), even the most detailed results obtained by the CFD models are subject to validation via proven experimental techniques due to numerous assumptions and closure models associated with them. While much success in modeling gas–liquid STRs had been reported, (e.g., Bakker and Van den Akker, 1994; Zhang et al., 2008), the results are almost always verified only at very few operating conditions. Whether the reported models can be used over the whole range of operating conditions remains to be verified, especially in the loading and fully recirculated regimes where most processes are operated and

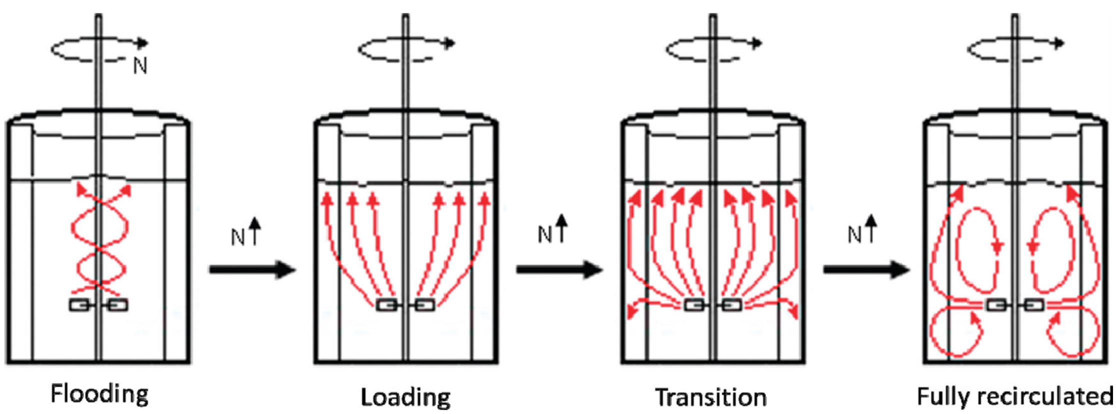

Fig. 1. Flow regime transition from flooding to loading to the fully recirculated regime. As N (impeller rotational speed) increases, gas bubbles occupy more regions within the tank. Adapted from Mueller and Dudukovic (2010). Copyright 2010 American Chemical Society. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

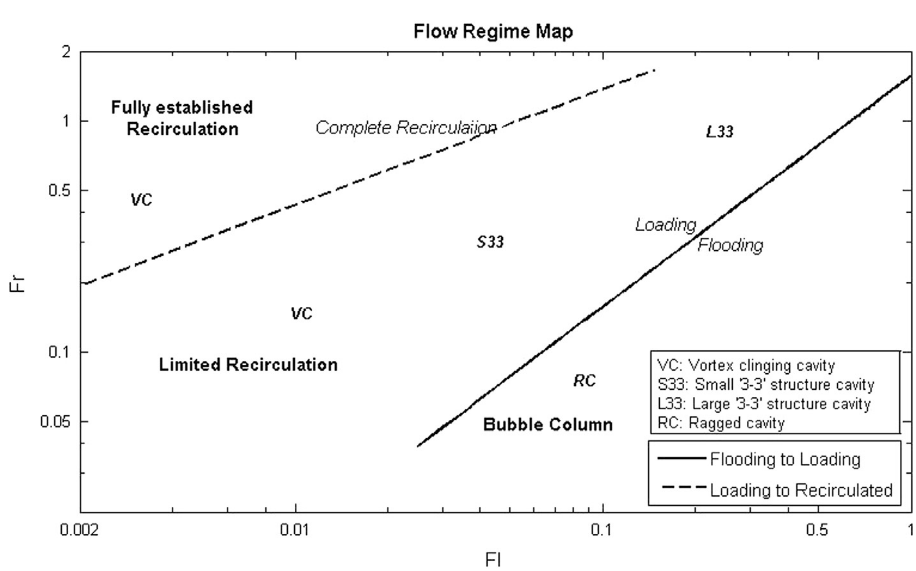

Fig. 2. Complete flow regime map for a standard fully baffled air–water STR.