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Bubble characteristics measured using a monofibre optical probe in a bubble column and freeboard region under high gas holdup conditions

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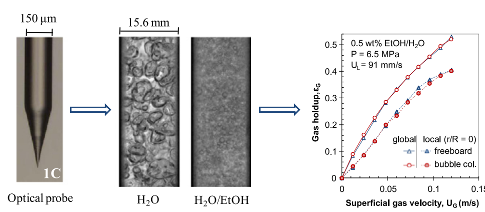
HIGHLIGHTS

- Local gas holdups, rise velocities and chord lengths measured using 1C optical probe.
- High gas holdup conditions achieved with elevated pressures and surfactant addition.
- Probe measurements were comparable to global values in water up to 9.0 MPa.
- Significant bubble size reduction with surfactant diminished probe's effectiveness.
- Freeboard and bubble column global hydrodynamics comparable at high gas holdups.

GRAPHICAL ABSTRACT



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ABSTRACT

Local bubble characteristics, including gas holdups, bubble rise velocities, and chord lengths, were measured using a monofibre optical probe manufactured to withstand elevated pressures. Previous studies have validated the use of single tip probes for simultaneous measurement of local bubble properties at atmospheric conditions; however no study has been currently reported for these probes at elevated pressures. Experiments were conducted in a 101.6 mm diameter column operating at pressures up to 9.0 MPa. Surfactant addition and operating pressure were studied to simulate high gas holdups observed in many industrial reactors containing liquid mixtures with surface-active compounds. Experiments were hence completed using two liquid phases: tap water and a 0.5 wt% aqueous ethanol solution. Liquid and gas superficial velocities were varied between 0–90 mm/s and 0–150 mm/s, respectively. Radial profiles at atmospheric conditions validated the probe measurements in water. Local holdups, rise velocities and chord lengths were adequately measured in water up to 9.0 MPa. The probe struggled in the aqueous ethanol solution due to its physical constraints (i.e., tip diameter and sensing length) when compared to the significant bubble size reduction (chord lengths below 0.5 mm). Comparisons with fluidized bed freeboard measurements demonstrated that flow through the bed enhanced bubble breakup for a coalescing system, but had a negligible impact with the added surfactant.

1. Introduction

Gas–liquid–solid flow is frequently encountered in chemical engineering processes. The fluid dynamic behavior of these systems must be studied to predict heat and mass transfer, flow

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behavior, and particle mixing. Bubble characteristics (e.g. bubble size distributions, bubble rise velocities, and local gas holdups) in industrial bubble columns and/or gas–liquid–solid fluidized beds are generally difficult to measure on-site due to their operating conditions. Vessels for such processes typically require materials that can withstand elevated temperatures and pressures, consequently limiting visual observations. The unit of interest for this study is the LC-Finer^{SM} hydroprocessor which operates at pressures and temperatures of approximately 11.7 MPa and 440 °C, respectively (McKnight et al., 2003). The hydroprocessor's liquid recycle pan in the freeboard region was previously redesigned with the aid of CFD simulations, where the goal was to reduce the quantity of recycled gas (McKnight et al., 2003). The size of all bubbles for the simulation was assumed to be 1 mm based on a force balance. As computational times for CFD modeling are continually reduced and measurement techniques are improved, the objective of this study is to measure local bubble properties under high gas holdup conditions to improve future gas–liquid separation predictions and techniques.

Bubble characteristics in gas–liquid and gas–liquid–solid systems have been previously investigated using various measurement devices (Boyer et al., 2002). These techniques are commonly categorized as non-invasive or invasive, where the former do not interfere with the flow conditions inside the studied system. Non-invasive techniques can be used to measure some of the desired bubble parameters for this study. For example, global phase holdups in bubble columns operated at elevated pressures have been determined using differential pressure transducers via pressure profiles (Behkish et al., 2007; Jin et al., 2004; Rudkevitch and Macchi, 2008). Non-invasive techniques (e.g. dynamic gas disengagement, photography, radiography, NMR, particle image velocimetry, laser Doppler anemometry) have also been used to measure bubble size distributions or phase velocities (Chaouki et al., 1997). As discussed by Boyer et al. (2002) however, these techniques are limited by the operating conditions, low gas holdup requirements, and/or relative costs. Invasive techniques were thus examined to measure the desired bubble characteristics using the available experimental system under high gas holdup conditions.

Needle, heat transfer, and ultrasound probes are invasive measurement techniques which have been previously used to measure bubble properties in gas–liquid and/or gas–liquid–solid systems (Boyer et al., 2002). Ultrasounds probes measure the desired bubble properties based on the laws of ultrasound wave propagation, either through transmitted or reflected waves in a gas–liquid system. Unfortunately, the technique does not normally allow the simultaneous measurement of all desired bubble characteristics. Furthermore, the effectiveness is reduced at gas holdups above 10–20% due to repeated reflections/scattering of the signal (Broering et al., 1991; Macchi et al., 2001). Gas holdups in a bubble column operating at elevated pressures were previously shown to exceed these limitations (Rudkevitch and Macchi, 2008), consequently restricting the use of ultrasound probes.

Heat transfer probes have been used to determine local gas holdups based on the heat exchanged between an electronically heated probe and the surrounding liquid medium. As a bubble interacts with the probe, the quantity of heat exchanged is reduced causing a noticeable signal change (Abel and Resch, 1978). By examining the magnitude and slope of the signal, Utiger et al. (1999) found that local bubble holdups determined with the heat transfer probe were comparable to those obtained with an optical probe. The main advantage for the heat transfer probes is the measurement of the liquid phase velocity and root mean square (RMS) fluctuations. Current heat transfer probes do not measure all desired bubble characteristics for this study.

Needle probes are capable of simultaneously measuring local gas holdups, bubble chord lengths and rise velocities. Two types of needle probes have been previously used for measurements in bubble columns: optical fiber and impedance/conductive probes (Boyer et al., 2002). Optical and impedance probes operate based on the differences in the refractive index or conductivity, respectively, of the liquid and gas phases. Signal fluctuations due to phase changes at the probe tip allow the measurement of local gas holdups and bubble frequency. Dual tipped probes were developed to measure the bubble chord length and rise velocities, where the distance between both probe tips is typically in the range of 0.5–5 mm (Chabot et al., 1998; Chaumat et al., 2007; Magaud et al., 2001; Moujaes, 1990; Shiea et al., 2013). Four-point optical probes were also developed and validated to improve bubble velocity vector measurements compared to dual tip configurations (Xue et al., 2008, 2003). Previous studies have shown that bubble size distributions become narrower while increasing the pressure up to 15 MPa (Lin et al., 1998), where a notable fraction of bubbles diameters can be in the range of 1 mm and lower. The distance between multiple tips may consequently be an issue under high gas holdup conditions, where bubbles pierced by the front tip may be less likely pierced by subsequent tips. As shown in Table 1, few studies were found in the open literature where bubble characteristics were measured at elevated pressures and/or temperatures using an invasive device. In addition, these studies were conducted with no liquid flow which does not effectively simulate an ebullated bed reactor.

An innovative monofibre optical probe developed by Cartellier (1992) eliminated the requirement that a bubble must be pierced by two consecutive tips to measure the rise velocity and chord length. Previous experiments demonstrated that the bubble rise velocity was inversely proportional to the signal rise time between the liquid and gas voltage levels when the probe was normal to the gas–liquid interface (Cartellier and Barrau, 1998a, 1998b). This relation is a function of the probe sensing length, a unique characteristic for each probe that must be determined prior to experiments. The monofibre optical probe's ability to simultaneously measure local gas holdups, bubble rise velocities and chord lengths has been validated at atmospheric conditions in a bubble column (Barrau et al., 1999; Cartellier, 1992) and in three-phase flow with particles of similar density to the liquid (Mena et al., 2008).

The main objective of this study is to investigate the use of a monofibre optical probe for bubble characterization in a bubble column and the freeboard region of an ebullated bed when operating under high gas holdup conditions (i.e., varying pressures up to 9.0 MPa, with and without the addition of a surfactant). In order to investigate the coalescing/heterogeneous and dispersed/

Table 1
Previous bubble characterization studies at elevated pressure and/or temperature using a probe.

Authors	Experimental system	Operating conditions	Comments
Chabot and de Lasa (1993)	0.2 m bubble column ($U_L=0$)	$P=0.1$ MPa, $T=100$ and 175 °C	Two spherical bulb optical fiber sensors
Soong et al. (1997)	0.10 m slurry bubble column ($U_L=0$)	$P\leq 1.36$ MPa and $T\leq 265$ °C	Dual conductivity hot-wire probe
Luo et al. (1999)	0.102 m slurry bubble column ($U_L=0$)	Up to 5.6 MPa	U shape double tipped optical probe