Journal of Magnetic Resonance 249 (2014) 16–23

Contents lists available at ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

MR relaxometry of micro-bubbles in the vertical bubbly flow at a low magnetic field (0.2 T)

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ARTICLE INFO

Article history:
Received 24 April 2014
Revised 30 September 2014
Available online 17 October 2014

Keywords:
Susceptibility
Gaussian
Bubbly flows
Micro-bubbles
Bubble size
MRI

ABSTRACT

Measurements of the vertical bubbly flow were performed at a low magnetic field of 0.2 T. The void fraction data were acquired. The susceptibility-induced changes in T_2 relaxation time were analyzed using the previously introduced approaches by Sukstanskii et al. and Ziener et al., originally developed for the Magnetic Resonance analysis of randomly distributed and isolated spherical inclusions, and a simple model of a spherical particle, respectively. The CPMG signal decay due to the presence of spherical inclusions was approximated as linear vs. CPMG inter-echo times to extract the average inclusion's size information.

Two equations were derived for a simplified analysis of gas–liquid systems with basic T_2 measurements, and without prior knowledge on the gas–liquid susceptibility or a need for the magnetic gradient setup. They can provide estimates for the void fraction and the average inclusion size, provided the CPMG inter-echo time requirements are met.

For the control samples, there was a good agreement with the theory. For the bubbly flows, a good agreement was observed between the Magnetic Resonance and optics-based estimates for the slowest airflow rate. The deviation, however, increased for higher airflow rates.

The introduced approach lends itself to the characterization of multi-phase systems such as cavitating media and well-separated bubbly flows.

1. Introduction

Multi-component systems in which a gaseous phase is dispersed throughout a liquid, known as gas–liquid systems, are commonly found in both nature and industry. These systems occur in many situations of theoretical and practical interest: from foams and cavitation (both hydraulic and acoustic) to cooling systems and oil transport pipelines. Relative flow rates, fluid properties, and geometries determine the structure of a gas–liquid flow [1]. In this work, we investigate the vertically upward bubbly flow regime, a subset of gas–liquid flows. Mass transfer units and two-phase pipe flows are two examples of industrial processes that employ bubbly flow.

Void fraction, or voidage (i.e. the fraction of the volume of the liquid phase occupied by gas) and bubble size distribution are two properties of interest in such systems. Various experimental techniques have been developed to study these parameters. The most prominent are photographic techniques, which are employed for the quantification of the bubble size by obtaining photographs of system through a transparent section of the column [2]. Recently developed acoustical techniques are used for the indirect measurement of the bubble size distribution in a pulsed acoustic field wherein the total dissolution time of bubbles is used for the bubble size calculation [3]. However, these methods have certain limitations. Optical methods require transparency of the media, suffer from the light reflection from the bubble–liquid interface, have limited measurement depth, and are limited to the relatively low gas fractions. Acoustical techniques do not provide a direct way of measurement, and, like optical techniques, fail at high void fractions. For the measurement of bubble sizes in systems with high void fractions, many invasive probes such as hot film anemometry have been developed. However, their intrusive nature is a source for systematic errors [4].

Magnetic Resonance Imaging (MRI) is a promising technique to study gas–liquid systems, as its non-invasive nature does not interfere with the gas–liquid interface, it can be used for the study of optically and acoustically opaque systems, it is inherently a 3D

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http://dx.doi.org/10.1016/j.jmr.2014.10.001
1090-7807/

method, the information-carrying signal comes directly from the bulk of the sample, and it can be rendered sensitive to various parameters like spin density and relaxation rates.

There are a limited number of MRI studies of gas–liquid systems in the literature. Lynch et al. first examined bubbly flows using Magnetic Resonance (MR) [5]. They demonstrated the linear relationship between the MR signal intensity and the volume-averaged void fraction in a vertical bubbly flow using a continuous wave MR spectroscopy. Abouelwafa et al. subsequently measured the void fraction and flow rate in two-phase water–oil and water–air flow systems using the similar method [6]. Leblond et al. measured the volume-averaged void fraction and the velocity propagator of the liquid phase using the basic Pulsed Field Gradient (PFG) SE sequence [7]. Le Gall et al. also used PFGSE to study liquid velocity fluctuations in the bubbly flow in different geometries [8]. Daidzic et al. obtained a spatially resolved void fraction map in stationary water column in a permanent magnet using a spin-warp pulse sequence [9]. Holland et al. determined bubble sizes from the MRI signal using a Bayesian technique [10]. Reyes obtained 2D temporally resolved measurements in gas–liquid slug flow [11]. Gladden et al. demonstrated both spatial and temporal resolution MRI measurements on a gas–liquid system [12]. They performed quantitative visualization of these dynamic, optically opaque, and magnetically heterogeneous systems using a modified version of the frequency encoding based Turbo Spin Echo sequence. Visualizing the movement of bubbles in ceramic monolith over a very short time scale of 146 ms enabled them to track individual gas bubbles and obtained information about bubble size distribution and velocity. Taylor et al. used a low angle snapshot Spiral imaging method for the measurement of spatially and temporally resolved velocity fields of instable flow systems and assessed the method as an "auspicious basis" for the study of these kinds of samples [13]. They doped the liquid phase with a paramagnetic salt to suppress the magnetic susceptibility induced distortions.

Instead of removing the susceptibility difference in the system with paramagnetic salts, one can exploit it to obtain information about the bubble sizes and density. This approach, complementary to tracing individual bubbles, has been applied to measurements of stabilized gas-filled micro-bubbles. Bubbles as pressure sensitive MR contrast agents can be employed, for example, for in vivo evaluation of cardiovascular pressures or pressure mapping in porous media. Alexander et al. did preliminary research in the effects of pressure-stable liposome micro-bubbles filled by several different gases and gas concentrations on MR and relaxation times at various pressures through the conventional spin echo and gradient echo pulse sequences [14]. Dharmakumar et al. have derived analytical expressions which take into account the void fraction, diffusion, and average bubble radius to qualitatively explain the functional behavior of T_2 and T_2^* decays [15]. Morris et al. has presented an MRI-based technique for spatially resolved pressure mapping in porous media with a multi slice multi echo pulse sequence using air-filled liposome micrometer-sized bubbles as pressure sensitive MR contrast agents [16,17]. Sukstanskii et al. has provided a detailed theoretical description of the free induction decay (FID) and Spin Echo (SE) signal formation in the framework of the Gaussian phase distribution approximation for permeable and impermeable spherical and infinitely long cylindrical inclusions [18,19]. Ziener et al. analyzed the CPMG transverse relaxation rate as a function of inter-echo time in Gaussian approximation framework for a simple model of a spherical particle [20].

There are also MRI studies of gas–liquid systems using pure phase encoding MRI techniques. These methods, unlike frequency-encoding MRI techniques, are immune to the time domain artifacts as they freeze the signal time evolution [21]. Sankey et al. studied the horizontal bubbly flow using the pure phase encoding SPRITE MRI technique [22]. They acquired quantitative liquid velocity maps and an approximate void fraction of gas–liquid flow. Mastikhin et al. studied the dynamics of acoustically cavitated liquid with Conical SPRITE MRI to obtain spatially resolved velocity and void fraction maps of cavitating distilled water and surfactant solutions [23]. Arbabi and Mastikhin in [24] obtained bulk and spatially resolved T_2 relaxation and mechanical dispersion information of the vertical bubbly flow at various airflow rates with Conical SPRITE and SE-SPI, and estimated average bubble sizes using analytical expressions, originally developed by Dharmakumar et al.

Most of above mentioned studies were performed at high magnetic fields. The studies employed advanced MRI techniques that required fine-tuned pulse sequences with a sophisticated manipulation of magnetic field gradients. Direct implementation of such techniques at low-field instruments is difficult if not impossible. At the same time, a quantitative MR measurement performed on a low-field system could be of major practical interest, as such systems are commonly used in the industry-oriented research.

In the present work, we performed bulk measurements of the vertical bubbly flow at a low magnetic field of 0.2 T. The void fraction measurement was straightforward. The susceptibility-induced modulation of the CPMG decay was quite considerable. To find out if a quantitative analysis of that modulation was possible, we applied the Gaussian approximation approaches originally developed by Sukstanskii et al., for randomly distributed, randomly oriented, and isolated impermeable spheres, and Ziener et al., for a simple model of a spherical particle.

First, the accuracy criterion of the Gaussian approximation was discussed, and its adequateness was verified by control measurements of two different suspensions of Silica beads with the same void fraction and different bead radii, 1 and 3 μm. We analyzed the MR SE and CPMG signal attenuation functions that relate the void fraction, relaxation rate, spins' randomness, and average microsphere radius, in both long and short-time limits. The control measurements of the Silica bead suspensions showed that long "characteristic measurement times" (i.e. inter-echo times) and smaller inclusion sizes permit describing the CPMG relaxation rate in the long-time limit regime as linear vs. inter-echo times, and obtain estimates on the average inclusions' size with a good accuracy.

Two simplified equations were extracted from the short and long-time regimes of the CPMG transverse relaxation rate expressions, which can, for appropriate inter-echo time values τ_{180} yield estimates of the void fraction and R^2/D with the basic relaxometry, without prior information on the system's diffusion or mechanical dispersion, or gas–liquid susceptibility difference.

For the bubbly flows, the much more complex dynamics of the system, along with shorter range of echo times (employed due to the limited signal lifetime), added an extra error to the estimates due to the inherent limitations of the theory, and led to estimates deviating from the optically measured bubble sizes from 3% for the slowest airflow rate to a factor of 2 for the fastest airflow rate. The simplified equations provided the void fraction estimates in an excellent agreement with those measured from the FID, and better bubble size estimates than those obtained with the long-time limit equation.

This approach seems a well-suited means for the study of multiphase systems like cavitating media and ideally separated bubbly flows.

2. Theory

Magnetic susceptibility is a measure of the magnetization of a material placed in a magnetic field that either increases or decreases the magnetic field in the material. When a magnetized object is embedded in a given medium with a different magnetic susceptibility, it perturbs the present uniform static magnetic field