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A novel fuzzy-logic based method for determination of individual bubble velocity and size from dual-plane ultrafast X-ray tomography data of two-phase flow

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A B S T R A C T

Ultrafast X-ray tomography enables non-invasive imaging of gas-liquid flows with high spatial and temporal resolution. While it is relatively straightforward to extract e.g. gas fraction profiles from cross-sectional tomographic images, the extraction of bubble and gas-liquid interface information requires advanced image processing techniques. Thereby it is an important necessity to transform the temporal scale in the scanned sequences into a corresponding length scale for obtaining correct volumetric information. For bubbly flows this means that the velocity of the dispersed phase, e.g. the gas bubbles, has to be determined from dual-plane scans. A common and widely applied method to obtain gas phase velocities is cross-correlating the image sequences of the two scanning planes. This gives an averaged velocity for each position in the cross-section. In the present work, a new method is introduced, which determines the velocity of individual gas bubbles. This new method is termed as "bubble twinning method", because it tries to identify twin-bubbles in both scanning planes. The developed algorithm compares essential bubble parameters, that is, volume, position and residence time in the slice, by applying a fuzzy-logic based membership function approach. The algorithm was tested for bubbly flow as well as slug flow conditions. Results are compared with established theoretical predictions as well as the cross-correlation method.

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1. Introduction

Gas-liquid flows occur in many industrial devices, such as bubble column reactors, heat exchangers or oil and gas pipelines, and are hence of some scientific and engineering interests. Especially the rapid development of Computational Fluid Dynamics (CFD) tools for simulation of two-phase flows call for experimental data with highest temporal and spatial resolution (Hampel et al., 2013; Lucas et al., 2007, 2016; Prasser, 2008). Gas-liquid flows are characterized by high dynamics and swift movement of both phases including their interface structures. This is a challenge for any measurement technique. In previous decades, studies of gas-liquid flow patterns were performed with a number of different sensor types employing various concepts and ideas. For dilute flows, optical methods are common. They can capture flow phenomena with quite satisfying quality at high speed and resolution, as reported in a comprehensive review by Tayali and Bates (1990). However, for flows with higher gas fraction many measurement techniques are incapable to capture gas-liquid flow phenomena in sufficient detail and accuracy. As the topic of this paper is on gas phase velocity measurement in two-phase flow, we will in the following give a brief review of the state-of-the art of the same.

Videometric or photographic measurement of bubble velocities is one of the oldest and most common techniques. There a camera takes photos or obtains an image sequence of the moving bubbles and by image analysis one can extract information, such as the projective bubble size and center-of-mass trajectory. Using a stereoscopic configuration, the 3D motion of the particle can be resolved. The instantaneous bubble velocity can be obtained by proper differentiation, e.g. by dividing the spatial displacement of the center of mass by the temporal sampling interval. The publications of Haberman and Morton (1953) and Staniszewski (1959) may serve as examples for such very early two-phase experiments. More recent examples of these kinds of experiments are found in the works of Amaral et al. (2013), Hiscock and Ching (2001), Mayor et al. (2007) or Valecillos et al. (2012). As it is

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Nomenclature

Latin letters

A	area
b	bubble
D	pipe diameter
d	bubble diameter (sphere equivalent)
f	frequency
g	gravitational acceleration
j	superficial velocity
L	length from sparger along the pipe axis
ΔL	lateral displacement
l	pixel edge length
N	number
n	coefficient for liquid velocity profile
p	pressure
Re	Reynolds number
R	pipe radius
r	radial position
t	time
V	volume
u	velocity
x, y, z	Cartesian coordinates
Δz	vertical distance

Greek letters

ε	gas volume fraction
η	numerator for lateral displacement membership
θ	coefficient for velocity membership
ν	kinematic viscosity
ρ	density
σ_L	surface tension
σ	standard deviation
Φ	total membership function
φ	individual membership function

Subscripts

a	azimuthal
avg	averaged
D	drift
E	expected
eq	sphere equivalent
FF	falling film
G	gas
i,j	cluster indices
in	injected
L	liquid
m	measured
N	normalized
P	pixel
r	radial
S	Scan
TB	Taylor bubble

Superscripts

(COM)	center of mass
(LD)	lateral displacement
(U)	velocity
(V)	volume

reported there, full bubble trajectories can be reconstructed by applying advanced tracking algorithms (Appel, 2004; Cheng and Burkhardt, 2006; Zaruba et al., 2005; Zhang and Finch, 2001). A limit of high-speed videometry is given by the gas volume fraction. With a growing number of bubbles in the scene the probability of a visual obstruction increases. This fact can lead to a failure of the applied image processing algorithms.

In case of high gas fractions researchers often use invasive sensors, such as needle probes. Their clear disadvantage is a certain flow disturbance. Hence, data of needle probes have to be interpreted with some care. There are different working principles of such probes. Optical probes (Cartellier, 1992; Guet et al., 2003; Saberi et al., 1995) respond to a change of the refractive index at the probe tip, conductivity probes (Ceccio and George, 1996; Lucas et al., 2004; Revankar and Ishii, 1992; Van Der Welle, 1985) to a change of electrical conductivity and capacitance probes (Da Silva et al., 2007) to a change of electrical permittivity. This way such probes obtain the phase indicator directly at the tip position in the flow, mostly with very high sampling rate.

So called double needle probes are an arrangement with two sensitive tips being aligned one behind the other in the main flow direction. A bubble hitting two sensor tips does this with a temporal displacement, which encodes its velocity. Hence bubble velocities can be obtained by cross-correlating the signals. To measure three bubble velocity components four-tip probes were developed (Kim et al., 2000; Luther et al., 2004).

To obtain data from multiple positions in the flow one choice is to perform single probe measurements at different positions. While this may be a solution for few spatial points it is not feasible for full cross-sectional measurements. For such wire-mesh sensors are appropriate (Prasser et al., 1998, 2001). Wire-mesh sensors are available as conductivity as well as capacitance sensors (e.g. da Silva and Hampel, 2013). The void distribution is measured in each of the crossing points via conductivity or capacitance measurement with high speed. The usage of two sensors with a small axial displacement allows obtaining cross-sectional gas phase velocities in bubbly flow by cross-correlation of images between the upstream and the downstream sensor.

For some flow regimes alternative methods are available. Thus Kuwahara et al. (2009) presented a method to measure non-invasively the velocity of gas slugs using electromagnetic induction. There the liquid phase was mixed with a magnetic fluid. The velocity measurements were validated against optical visualization results and gave good agreement.

Particle image velocimetry, which is a common measurement technique for single-phase flows, has often been used in the recent past for studying velocity fields in two-phase flow. Hassan et al. (1998) presented results of liquid velocity, kinetic energy and Reynolds stress profiles around a bubble that enters the investigated volume. Similar experiments were conducted by e.g. Dias and Reithmuller (2000) and Brücker (2000). Cheng et al. (2005), Lindken et al. (1999) and Lindken and Merzkirch (2000) have improved the PIV technique for use in two-phase flows. They obtained velocities from both the liquid and the gas phase. Lindken et al. (1999) and Lindken and Merzkirch (2000) separated the bubbles from the seeding particles by a size threshold in binarisation of the images. Cross-correlation was utilized for both particle size classes. Liquid as well as gas velocity vectors were obtained. Cheng et al. (2005) developed a recursive cross-correlation algorithm, which is repeating the calculation from large to small interrogation areas. They get better results especially for bubble plumes when tracking identified bubbles. However, as PIV is also basing on visible light, it has the same limitations as high-speed videometry. That is, it fails at higher gas fractions.

Non-invasive measurement techniques like X-ray imaging can solve this problem, because they do not need any optical access as presented by Im et al. (2007) and Lee and Kim (2003). For velocity estimation they used cross-correlation algorithms like PIV. A wide overview for flow visualization and measurements with X-ray applications is given by Heindel (2011). He concluded that X-ray flow visualization techniques are useful tools for multiphase flow

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