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On the accuracy of gas flow rate measurements in gas–liquid pipe flows by cross-correlating dual wire-mesh sensor signals

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ABSTRACT

This article presents an assessment of the accuracy of gas flow rate measurement in gas–liquid pipe flows by cross-correlating dual wire-mesh sensor signals. The differences between the estimated and the actual gas superficial velocities in different flow regimes were analyzed. It was demonstrated that this gas flow rate measurement method is susceptible to significant systematic errors, some of which are inherent to the use of cross-correlation and others which are specific to wire-mesh sensors. It was concluded that this method would be accurate only for flow conditions within narrow ranges.

Introduction

In many multiphase flow applications, the gas flow rate in gas–liquid pipe flows has been estimated from the cross-correlation function of the outputs of two sensors , separated by a streamwise distance and capable of detecting gas–liquid interfaces (Beck, 1981). In most studies (Thorn et al., 1997; Prasser et al., 2005a; Dong et al., 2006; Beyer et al., 2010) the cross-correlation velocity was calculated as the ratio of the distance between the sensors and the time lag corresponding to the peak in the cross-correlation function between the signals provided by the two sensors; then, the time-averaged gas superficial velocity (which is equal to the time-averaged gas flow rate divided by the pipe cross-sectional area), was obtained by integrating the product of the measured time-averaged void fraction and the cross-correlation velocity over a cross-section. Measuring systems that have been used for gas flow rate measurements by the cross-correlation method include conductivity probes, microwave sensors, gamma-ray densitometers, wire-mesh tomographs and electrical resistance tomographs. Despite the apparent success of this method in several applications, its accuracy has been questioned. In particular, some authors have challenged the use of the cross-correlation velocity as a surrogate for the gas velocity and have proposed the use of models to correlate the cross-correlation velocity with the gas flow rate (Lucas and Walton, 1998; Lysak et al., 2008; Shaban and Tavoularis, 2015a). A review of the literature has revealed no systematic scrutiny of all assumptions made for the direct application of the cross-correlation method.

In the present work, we have investigated analytically and experimentally the accuracy of measurements of the gas flow rate in difference regimes of gas–liquid flows by applying the cross-correlation method to the output of a dual wire-mesh sensor (WMS). In particular, we have examined whether the cross-correlation method provides a gas velocity that is an accurate surrogate of the true gas superficial velocity under different two-phase flow conditions. We first present an analytical comparison of these two velocities, which is applicable to any measurement systems that use cross-correlation for measuring gas flow rates, and then proceed to evaluate the accuracy of measurements obtained in the bubbly, slug, churn and annular flow regimes using WMS, as well as the importance of other sources of error that are particular to WMS. We hope that this note will help clarify the significance of the cross-correlation method in a broader sense, as well as testing its accuracy in a specific experimental setup.

Analytical background

Gas superficial velocity

The time-averaged gas superficial velocity j_g through a pipe with an inner radius R can be calculated as

$$j_g = \frac{Q_g}{\pi R^2} = \frac{1}{T}\frac{1}{\pi R^2}\int_{t=0}^{T}\int_{r=0}^{R}\int_{\theta=0}^{2\pi} U(r,\theta,t)\alpha(r,\theta,t)r\,d\theta\,dr\,dt, \quad (1)$$

where Q_g is the gas volumetric flow rate, t denotes time, r and θ are, respectively, the radial and azimuthal coordinates, T is a time interval that is sufficiently long for the time averages to converge, U is

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the instantaneous local velocity and α is the local void fraction; it is noted that $\alpha = 1$ and $U = U_g$ when the location of concern is occupied by gas, whereas $\alpha = 0$ and $U = U_l$ when this location is occupied by liquid. In the following discussion, the subscripts l and g denote the liquid and gas phases, respectively.

Eq. (1) shows that, to determine j_g, one would require the spatial and temporal distributions of both the instantaneous local gas velocity U_g and the instantaneous local void fraction α. The spatial and temporal distributions of void fraction may be measured with the use of several different sensors; these include single-point sensors (*e.g.*, conductivity probes) traversed across the pipe, multi-point sensors (*e.g.*, wire-mesh sensors), which provide outputs at nodes of a transverse grid, and tomographic sensors (*e.g.*, electrical resistance tomographs), which use reconstruction algorithms to obtain the spatial distribution of the flow properties from discrete measurements. In contrast, the temporal and spatial distributions of gas velocity cannot be measured directly by any of these methods.

Gas velocity vs. *interfacialvelocity*

Instead of calculating the gas velocity, by analyzing the void fraction output of a single sensor, one may identify the passage of a gas–liquid interface through each measurement point (a sharp rise/drop in void fraction); by analyzing the outputs of dual sensors, one may, in principle, estimate the interfacial velocity. The interfacial velocity is equal to the velocity of the liquid and gas in contact with a gas–liquid interface at a measurement location. Note that the interfacial velocity is a discrete function and is only defined at phase interfaces, as opposed to the gas and liquid velocities, which are piecewise continuous functions. Consequently, the interfacial velocity at best represents the gas velocity at certain instants in time and it cannot take into account gas motion in continuous gas structures, such as within bubbles and in the gas core of annular flows.

Let us consider two sensors separated by a distance Δx and let Δt be the time required by an interface to traverse the distance between the two sensors (Fig. 1a). The velocity of an individual gas–liquid interface, to be denoted as U_{int}, can be estimated as

$$U_{int} = \frac{\Delta x}{\Delta t}. \tag{2}$$

Ideally, individual interfaces may be identified by comparing the outputs of two sensors in tandem, however, especially for intrusive sensors, this approach would only be practical for relatively narrow ranges of liquid and gas flow rates, due to flow distortion between the sensors, caused by the first sensor or by turbulent fluctuations in the flow. This flow distortion makes it very difficult to match the interfaces in the signals from the two sensors (Fig. 1b).

Interfacial velocity vs. *cross-correlation velocity*

As a surrogate for the interfacial velocity, the cross-correlation velocity U_{xc} can be easily calculated using the cross-correlation function (CCF) of the signals of these sensors as

$$U_{xc} = \frac{\Delta x}{\Delta t_{CCF_{max}}}, \tag{3}$$

where $\Delta t_{CCF_{max}}$ is the time lag corresponding to the peak in the cross-correlation function between the void fraction signals at two corresponding measurement locations in the two measurement sections. Unlike U_{int}, which is a discrete function, U_{xc} is a single-valued property, which is equal to the most probable value (mode) of U_{int}. Thus, depending on the probability density function of the interfacial velocities, U_{xc} may or may not be equal to the time-averaged interfacial velocity.

To reduce the non-uniformity of the radial gas velocity profiles, Prasser et al. (2005a) proposed that the nodal cross-correlation functions be azimuthally averaged to produce the azimuthally averaged

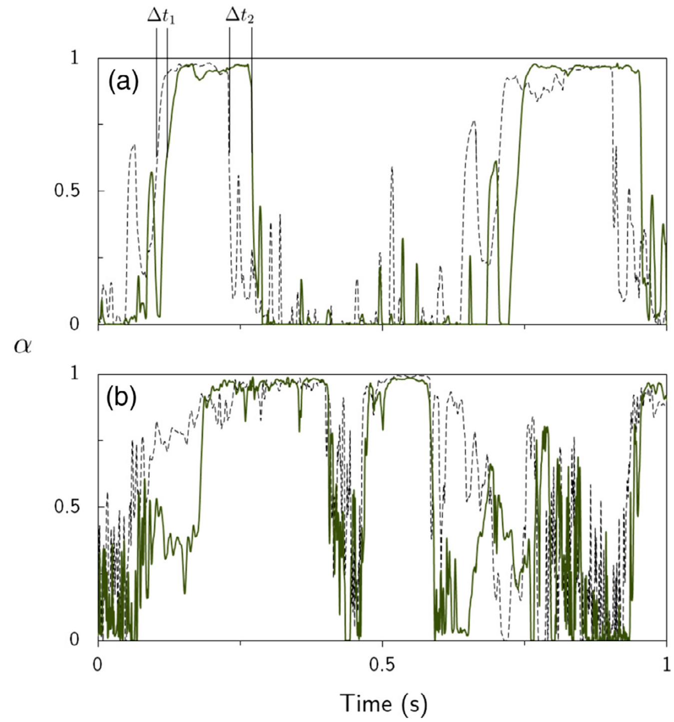

Fig. 1. Time histories of void fraction at corresponding locations on an upstream sensor (dashed line) and a downstream sensor (solid line) in a dual WMS unit: (a) at low liquid flow rate ($j_l = 0.15$ m/s) and (b) at intermediate liquid flow rate ($j_l = 0.8$ m/s). Δt_1 and Δt_2 are the time lags at the front and back of a Taylor bubble, respectively.

cross-correlation velocity $U_{xcr}(r)$. A gas superficial velocity estimate, to be denoted as j_{xc}, can then be determined as

$$j_{xc} = \frac{1}{\pi R^2} \int_0^R U_{xcr}(r) \alpha_r(r) 2\pi r \, dr \tag{4}$$

where $\alpha_r(r)$ is the temporally and azimuthally averaged void fraction.

Effect of void fraction and gas velocity fluctuations on the cross-correlation velocity

Starting from Eq. (1), one may apply a modified Reynolds decomposition to decompose the instantaneous local fluid velocity and void fraction into mean and fluctuating parts as

$$U(r, \theta, t) = \overline{U}_r(r) + U'(r, \theta, t) \tag{5}$$

and

$$\alpha(r, \theta, t) = \overline{\alpha}_r(r) + \alpha'(r, \theta, t), \tag{6}$$

where the temporally and azimuthally averaged fluid velocity and void fraction are defined as, respectively,

$$\overline{U}_r(r) = \frac{1}{T} \frac{1}{2\pi} \int_{t=0}^{T} \int_{\theta=0}^{2\pi} U(r, \theta, t) d\theta \, dt \tag{7}$$

and

$$\overline{\alpha}_r(r) = \frac{1}{T} \frac{1}{2\pi} \int_{t=0}^{T} \int_{\theta=0}^{2\pi} \alpha(r, \theta, t) d\theta \, dt, \tag{8}$$

and primes indicate fluctuations. Substituting Eqs. (5) and (6) into Eq. (1), one gets

$$j_g = \frac{1}{T} \frac{1}{\pi R^2} \int_{t=0}^{T} \int_{r=0}^{R} \int_{\theta=0}^{2\pi} [\overline{U}_r(r) \, \overline{\alpha}_r(r) + U'(r, \theta, t) \alpha'(r, \theta, t) \\ + \overline{U}_r(r) \, \alpha'(r, \theta, t) + \overline{\alpha}_r(r) \, U'(r, \theta, t)] r \, d\theta \, dr \, dt. \tag{9}$$