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Fluid Dynamics and Transport Phenomena

Measurment of gas-liquid two-phase slug flow with a Venturi meter based on blind source separation☆

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ABSTRACT

We propose a novel flow measurement method for gas–liquid two-phase slug flow by using the blind source separation technique. The flow measurement model is established based on the fluctuation characteristics of differential pressure (DP) signals measured from a Venturi meter. It is demonstrated that DP signals of two-phase flow are a linear mixture of DP signals of single phase fluids. The measurement model is a combination of throttle relationship and blind source separation model. In addition, we estimate the mixture matrix using the independent component analysis (ICA) technique. The mixture matrix could be described using the variances of two DP signals acquired from two Venturi meters. The validity of the proposed model was tested in the gas–liquid two-phase flow loop facility. Experimental results showed that for most slug flow the relative error is within 10%. We also find that the mixture matrix is beneficial to investigate the flow mechanism of gas–liquid two-phase flow.

1. Introduction

Gas–liquid two-phase flow exists widely in many industrial processes, such as power generation, thermal engineering, and petroleum and nuclear industry. Slug flow often occurs *e.g.* in transportation of oil–gas mixtures in pipes from wells to the reservoirs. In such environments, a frequently encountered flow pattern is slug flow, which is quite complicated. Slug flow occurs because of hydrodynamic instability and its formation is transient in nature, either in vertical or horizontal pipes. Slug flow is characterized by the stochastic alternation of large bubbles and liquid slugs containing small gas bubbles. Most of gas is located in large bullet-shaped bubbles which usually contain small dispersed bubbles. The liquid confined between the large bullet-shaped bubbles and the pipe wall flows around the bubble as a thin film.

Gas–liquid slug flow in horizontal pipes occurs over a broad range of gas and liquid flowrate. The unsteady nature of slug flow makes the prediction of pressure drop, voidage and individual phase flowrate which is of great importance a difficult task [1–7]. The existence of an easily changing interface between two phases is also a challenge for modeling.

The most reliable flow measurement technique is separating the mixture and then using conventional devices to measure the single-phase flow parameters. However, in many cases the separation is not practical from both technical and economical points of view [1,6]. An alternative solution is a two-phase flow measurement system, usually consisting of a combination of devices for phase fraction measurement and velocity measurement. Zheng *et al.* [8] proposed a method to identify the flow pattern and to estimate the total flowrate and water cut of gas–liquid two-phase flow with the combination of turbine flowmeter and conductance sensor. The water cut was predicted by using the SVM soft measurement model with some input features derived from the fluctuant conductance signals in terms of time and frequency domains.

Compared with other kinds of differential pressure (DP) devices, Venturi has little influence on flow patterns, the smallest pressure loss, and the shortest straight pipe upstream and downstream [7]. Considering the great technical importance as well as pure scientific interest, the Venturi meter has been widely used in gas–liquid two-phase flow measurement [9]. Most mass flow measurement relied on the accuracy of determined quality parameter. However, measuring the quality online is rather difficult at present; therefore, the mass flow measurement based on the quality is not practical, especially for the complicated gas–liquid slug flow. Recently, some researchers claimed that DP fluctuation signals contain some additional information related to quality of gas–liquid two-phase flow, hence the DP signals measured from the Venturi meter could lead to flowrate estimation when combined with the information from other devices [10–12]. Zhang *et al.* [13] analyzed the influence of mass flowrate, pressure, voidage and density on DP signals, and provided the relationship between voidage of gas–liquid two-phase flow and root-mean-square deviation of the DP fluctuating signals measured from a Venturi meter. Zhong *et al.* [14] discussed in detail the relationship between the information related to quality of gas steam and DP fluctuation signals, and proposed an orifice

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method for measuring the wet stream mass flowrate with the DP fluctuation signals.

Over the past few decades, some researches applied the independent component analysis (ICA) technique in two-phase flow study. ICA is a new statistical signal processing technique in the field of blind source separation. Unknown source signals could be predicted based on the observed signals obtained from devices in the case the theoretical model about the signals is not clear. Liu and Li [15] extracted the information of gas and liquid from the mixed signals from well logging data using the ICA method. Wu *et al.* [16] adopted the blind source separation technique combined with the particle swarm optimization algorithm and cross correlation method to estimate two-phase flow velocity. Xu *et al.* [17,18] using the ICA technique extracted the independent components corresponding to gas–liquid flow characteristics in two-phase slug flow, stratified flow and wavy flow with an Electrical Resistance Tomography (ERT) system. Xu and Geng [19] employed a couple of slotted orifices to execute the wet gas measurement by using the blind source separation (BSS) technique. In the proposed technique, the characteristic quantity of wet gas flow is extracted, and a relationship between the liquid flowrate and the characteristic quantity is established. Zhou and Gu [20] applied the fixed point algorithm of negative entropy to extract the characteristic parameters used in flow pattern identification.

Gas–liquid slug flow is one of the most complex flow patterns. Liquid slugs, small bubbles and large bubbles are heterogeneously distributed in the flow pipeline. The small bubbles are merged into a large bubble and a large bubble can also be broken into many small bubbles, which causes interface changes and interaction between the liquid and gas phases. Therefore, it is realized that slug flow can result in a severe fluctuation of voidage and pressure drop in the pipeline and lead to the great difficulty in gas–liquid two-phase slug flow measurement.

In this study, a partial phase flowrate measurement method is proposed by using the blind source separation technique [21–24] combining statistic characteristics of DP fluctuation signals. When modeling, the relationship between DP signals of gas–liquid two-phase flow and that of single phases is analyzed, and the expression of the mixture matrix is developed based on fluctuation characteristics of DP signals measured from the Venturi meters in the gas–liquid two-phase flow loop test facility.

2. Measurement Model

In single phase flow, mass flowrate is related to pressure drop across a Venturi meter by

$$M = \frac{C\varepsilon A_0}{\sqrt{1-\beta^4}}\sqrt{2\rho\Delta P} \tag{1}$$

where M is the mass flowrate; C is the Venturi discharge coefficient; A_0 is the area of the Venturi throat; β is the throat-to-pipe diameter ratio; ε is the compressibility coefficient of fluid, air–water fluid is considered incompressible at low pressure and ε is considered to be unity; ΔP is the DP across the Venturi meter (DP between the upstream pressure and the throat pressure); and ρ is the upstream density of the flowing fluid.

In two-phase flow, two-phase mass flowrate and pressure drop can be expressed in the form of Eq. (1) if an appropriate two-phase fluid density ρ_{tp} is used in place of the single-phase fluid density. Replacing ΔP with actual two-phase DP reading, two-phase mass flowrate is given by

$$M_{tp} = \frac{CA_0}{\sqrt{1-\beta^4}}\sqrt{2\rho_{tp}\Delta P_{tp}}. \tag{2}$$

Denoting

$$K = \frac{CA_0}{\sqrt{1-\beta^4}}\sqrt{2}$$

Eq. (2) can be written as

$$M_{tp} = K\sqrt{\rho_{tp}\Delta P_{tp}} \tag{3}$$

where the mixture density ρ_{tp} is related to the voidage and quality.

According to the separated (or "stratified") flow assumption, the gas phase and liquid phase completely separate along the pipeline. Hence, gas mass flowrate M_g and liquid mass flowrate M_l can be written as

$$M_g = K\sqrt{\Delta P_g\rho_g} \tag{4}$$

$$M_l = K\sqrt{\Delta P_l\rho_l} \tag{5}$$

where ΔP_g and ΔP_l are the superficial DP reading of the gas and liquid phases, and ρ_g and ρ_l are the gas density and liquid density, respectively.

Combining Eqs. (3) through (5), under the ideal flow conditions, the separated flow model can be derived as follows:

$$a_g\sqrt{\frac{\Delta P_g}{\Delta P_{tp}}} + a_l\sqrt{\frac{\Delta P_l}{\Delta P_{tp}}} = 1 \tag{6}$$

where $a_g = \sqrt{\rho_g/\rho_{tp}}$ and $a_l = \sqrt{\rho_l/\rho_{tp}}$ are often estimated by an experimental test. Eq. (6) can be rewritten as

$$a_g\sqrt{\Delta P_g} + a_l\sqrt{\Delta P_l} = \sqrt{\Delta P_{tp}}. \tag{7}$$

Eq. (7) denotes that DP reading of gas–liquid two-phase flow is the weighted reading of single gas phase DP and single liquid phase DP. Namely, ΔP_{tp} is a mixture signal sourced from the ΔP_g and ΔP_l. The true mixture density of two-phase flow could be expressed as

$$\rho_{tp} = \alpha\cdot\rho_g + (1-\alpha)\cdot\rho_l \tag{8}$$

where α is the voidage of two-phase flow, hence we have

$$\begin{aligned} a &= \sqrt{\rho_g/\rho_{tp}} = \sqrt{\rho_g/\left(\alpha\cdot\rho_g + (1-\alpha)\cdot\rho_l\right)} \\ b &= \sqrt{\rho_l/\rho_{tp}} = \sqrt{\rho_l/\left(\alpha\cdot\rho_g + (1-\alpha)\cdot\rho_l\right)}. \end{aligned} \tag{9}$$

Eq. (9) denotes the weighted coefficients a and b, which are related to the combination of single phase density and voidage of gas–liquid two-phase flow.

For two-phase flow measurement, it is rather difficult to estimate voidage. The quick closing valve method is a much more accurate and simple way to estimate voidage, but it is impossible for online measurement. In recent decades, researchers found that different fluctuations of DP indicate the change of the voidage [12,13,25,26]. There exist some relationships between statistic parameters of DP in time domain, such as variance, and the voidage of two-phase flow. Therefore, we can change Eq. (7) into the following expression:

$$a(\sigma)\sqrt{\Delta P_g} + b(\sigma)\sqrt{\Delta P_l} = \sqrt{\Delta P_{tp}} \tag{10}$$

where σ is the variance of DP, and $a(\sigma)$ and $b(\sigma)$ are related to the fluctuation characteristics of DP, respectively.