

Fluid Dynamics and Transport Phenomena

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



Weiwei Wang*, Xiao Liang, Mingzhu Zhang

College of Information and Control Engineering, China University of Petroleum, Qingdao 266580, China

ARTICLE INFO

Article history:

Received 21 December 2014

Received in revised form 23 March 2015

Accepted 8 May 2015

Available online 22 May 2015

Keywords:

Two-phase slug flow

Flow measurement

Differential pressure

Blind source separation

Independent component analysis

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.

© 2015 The Chemical Industry and Engineering Society of China, and Chemical Industry Press. All rights reserved.

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

☆ Supported by the National Natural Science Foundation of China (51304231) and the Natural Science Foundation of Shandong Province (ZR2010EQ015).

* Corresponding author.

E-mail address: wangww@upc.edu.cn (W. Wang).

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

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

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

$$M_{tp} = \frac{CA_0}{\sqrt{1-\beta^4}} \sqrt{2\rho_{tp}\Delta P_{tp}} \quad (2)$$

Denoting

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

Eq. (2) can be written as

$$M_{tp} = K \sqrt{\rho_{tp}\Delta P_{tp}} \quad (3)$$

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

$$M_g = K \sqrt{\Delta P_g \rho_g} \quad (4)$$

$$M_l = K \sqrt{\Delta P_l \rho_l} \quad (5)$$

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:

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

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

$$a_g \sqrt{\Delta P_g} + a_l \sqrt{\Delta P_l} = \sqrt{\Delta P_{tp}} \quad (7)$$

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

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

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

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

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:

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

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

For ΔP_g and ΔP_l estimation, at least two ΔP_{tp} values should be acquired. The relationship is

$$\begin{cases} a(\sigma)\sqrt{\Delta P_g} + b(\sigma)\sqrt{\Delta P_l} = \sqrt{\Delta P_{tp1}} \\ c(\sigma)\sqrt{\Delta P_g} + d(\sigma)\sqrt{\Delta P_l} = \sqrt{\Delta P_{tp2}} \end{cases} \quad (11)$$

where $c(\sigma)$ and $d(\sigma)$ are the weighted coefficients, and ΔP_{tp1} and ΔP_{tp2} are acquired at different locations along the pipeline using DP devices. Eq. (11) could be rewritten as

$$\mathbf{A} \times \begin{pmatrix} \sqrt{\Delta P_g} \\ \sqrt{\Delta P_l} \end{pmatrix} = \begin{pmatrix} \sqrt{\Delta P_{tp1}} \\ \sqrt{\Delta P_{tp2}} \end{pmatrix}, \text{ with } \mathbf{A} = \begin{pmatrix} a(\sigma) & b(\sigma) \\ c(\sigma) & d(\sigma) \end{pmatrix} \quad (12)$$

where the mixture matrix $\mathbf{A}$ denotes the interaction between the gas phase and liquid phase. Until now, it is a hard work to provide the specific expression of $\mathbf{A}$. The present experimental setup is suitable and the matrix is guaranteed to be non-singular.

When running measurement, ΔP_{tp1} and ΔP_{tp2} can be obtained using DP transducers. Considering $\mathbf{A}$, ΔP_g and ΔP_l are unknown, we will transfer the task into a blind source separation problem.

3. Blind Source Separation and ICA

The blind source separation (BSS) method, which separates source signals from observed signals without the knowledge of the mixture model, is widely used in data analysis.

According to Eq. (12), the mixture of the gas phase and liquid phase could be simplified as

$$\mathbf{X} = \mathbf{A} \times \mathbf{S} \quad (13)$$

$$\mathbf{S} = \begin{pmatrix} \sqrt{\Delta P_g} \\ \sqrt{\Delta P_l} \end{pmatrix}, \mathbf{X} = \begin{pmatrix} \sqrt{\Delta P_{tp1}} \\ \sqrt{\Delta P_{tp2}} \end{pmatrix}.$$

Here $\mathbf{S}$ is the source signal, and $\mathbf{X}$ is the observed signal.

For two-phase flow measurement in this study, the idea from BSS is that $\mathbf{X}$ is acquired from two DP sensor sources. The task of BSS is to obtain the separation matrix $\mathbf{W}$, which is the estimation of $\mathbf{A}^{-1}$, and to retrieve the sources by observed outputs. That is

$$\mathbf{Y} = \mathbf{W}\mathbf{X}. \quad (14)$$

However, there exist problems that $\mathbf{W}$ cannot be derived from unknown $\mathbf{A}$, and $\mathbf{W}$ is uncertain. Ideally $\mathbf{W}$ should be equal to $\mathbf{A}^{-1}$ so that $\mathbf{Y}$ is a copy of source signals. Practically, output components are considered as independent as possible. Various statistical and signal processing techniques have been proposed to obtain the separation matrix $\mathbf{W}$ [22,23].

ICA as a classical BSS method has been applied in gas–liquid two-phase flow data processing and analysis [15–20]. The key of ICA estimation is non-Gaussianity. Maximizing the non-Gaussian $\mathbf{W}^T \mathbf{X}$ gives one of the independent components. Because the different independent components are uncorrelated, other independent components could be solved by constraining the search to the space which gives estimates uncorrelated with the previous ones. According to the central limit theorem, the signal is more independent when its non-Gaussianity is stronger. Typically, negentropy can be used to measure the non-Gaussianity.

The main point of this problem is to get an accurate estimation of noise-free separation signals. The sum of the negentropy of the noise-free separation signals is regarded as the objective function:

$$f(\mathbf{y}) = \sum_{i=1}^N J_G(y_i) = \sum_{i=1}^N [E\{G(y_i)\} - E\{G(\mathbf{v})\}]^2 \quad (15)$$

where y_i represents the i th source signal estimation, $\mathbf{v}$ is the Gaussian standardized variable, and G is a non-quadratic function. The larger $f(\mathbf{y})$ is, the more independent the signal is. Hence, the separation matrix is solved on the basis of maximizing non-Gaussianity of the separation signals, which transforms solving BSS problem to a numerical optimization problem.

The IWO algorithm, which is a numerical stochastic search algorithm mimicking natural behavior of weed colonizing in tillage space, is considered as a tool to deal with the numerical optimization problem above. So Eq. (15) is regarded as fitness function of the IWO algorithm, which is employed to optimize the objective function shown in Eq. (15). And then, $\mathbf{Y}$ is estimated. Based on the BSS technique, the developed measurement model is

$$\begin{pmatrix} \sqrt{\Delta P_g} \\ \sqrt{\Delta P_l} \end{pmatrix} = \begin{pmatrix} e & f \\ g & h \end{pmatrix} \times \begin{pmatrix} \sqrt{\Delta P_{tp1}} \\ \sqrt{\Delta P_{tp2}} \end{pmatrix} \quad (16)$$

where $\begin{pmatrix} e & f \\ g & h \end{pmatrix}$ is the separation matrix, and the elements of the matrix are related to the statistic characteristics of ΔP_{tp1} and ΔP_{tp2} .

4. Experimental Facilities

A series of experiments were carried out in the 76 mm diameter, 300 m long multiphase flow test loop at China University of Petroleum, as shown in Fig. 1. Air and water were used as the media. Air is supplied from an air compressor, then flows into a surge tank under a given pressure, and then flows through a calibrated rotameter into a two-phase mixer. Water is supplied from a pump, and flows through a calibrated Coriolis mass flowmeter into the two-phase mixer. The gas and liquid phases are mixed through a horizontally installed baffle plate with the length of 500 mm.

Before flowing into the test section, the two-phase mixture passed through a long enough straight pipe to ensure a fully developed flow

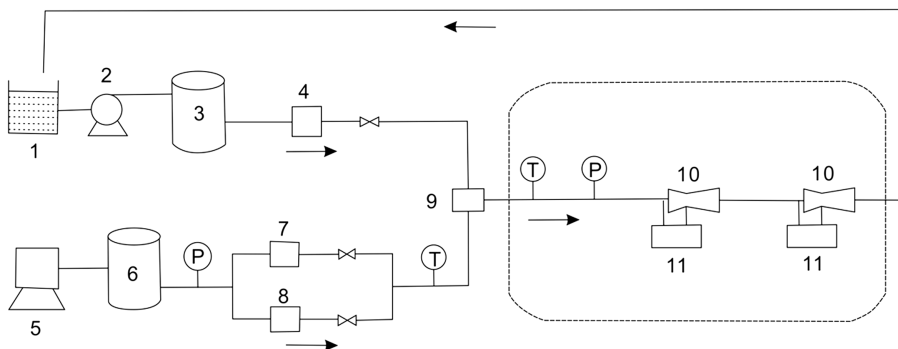


Fig. 1. Two-phase flow loop test facility in China University of Petroleum. 1–water tank; 2–pump; 3–water surge tank; 4–Coriolis flowmeter; 5–air compressor; 6–air surge tank; 7–rotameter; 8–vortex flowmeter; 9–mixer; 10–Venturi meter; 11–DP transducer.

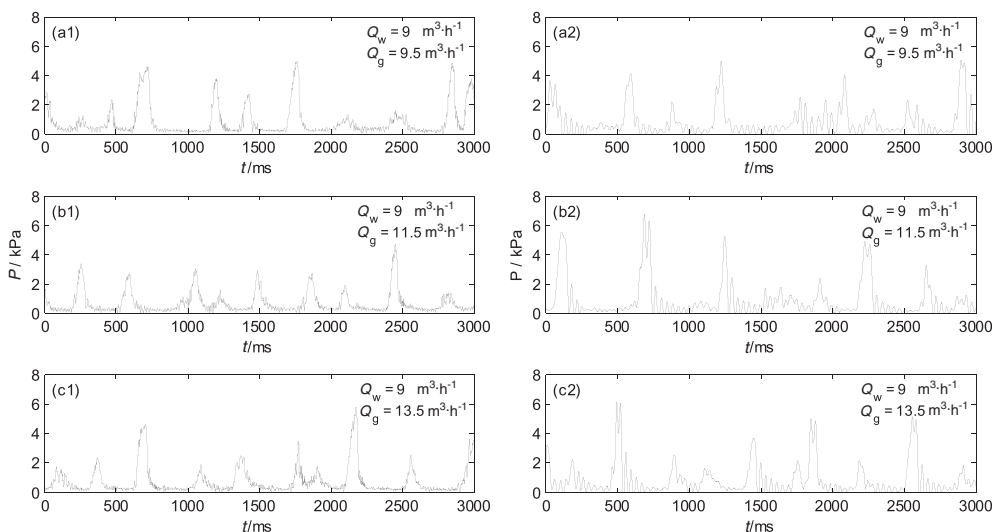


Fig. 2. Fluctuation of DP signal for slug flow.

pattern. Normally, the straight pipe length for flow pattern development is about $100D$ – $200D$, where D is the diameter of the pipe. In the measurement involved in this paper, the pipe diameter is 76 mm, and the straight pipe is more than 20 m long. The rotameter with 1.0% accuracy and vortex flowmeter with 1.0% accuracy as the gas reference flowmeter are used to measure the gas flowrate before mixing. The Coriolis flowmeter with an accuracy of 0.2% as the liquid reference flowmeter is used to measure the liquid flowrate before mixing.

After flowing out of the test section, the two-phase mixture was separated by a gas–liquid separator. Then air was discharged into the atmosphere, while water flowed into a water tank for recycling.

According to the experimental observation and data analysis result from different Venturi meter intervals, it is found that a big difference between 2 DP signals can be ensured if the interval between 2 Venturi meters is more than 3 liquid slugs in the experimental conditions. Hence, two LGW Venturi meters of 1.0% accuracy are installed horizontally with a 3 m interval in the test section. Two Rosemount 3051 DP transducers were installed to measure the differential pressures across the two Venturi meters. Through an A/D converter, the DP signals

were fed into a computer for processing. During the test, the pressure was from 0.25 MPa to 0.40 MPa, the gas volume flowrate ranged from 2 to $25 \text{ m}^3 \cdot \text{h}^{-1}$, and the liquid volume flowrate ranged from 4 to $18 \text{ m}^3 \cdot \text{h}^{-1}$.

5. Results and Analysis

In the experiment, at first the water flowrate was set to a constant value and then the gas flowrate was gradually increased. With the changes in gas flowrate, bubble flow, slug flow and annular flow were observed successively in the test section.

In bubble flow, the liquid is flowing in the pipe as the continuous phase, and gas is distributed in the continuous liquid phase as the dispersed phase. In annular flow, a liquid film forms at the pipe side wall with a continuous central gas. These two flow patterns are often simplified to homogeneous flows and the fluctuations of the corresponding DP signals are not strong. Using the method provided in this study to predict the fraction flowrate for these two flow patterns will cause a

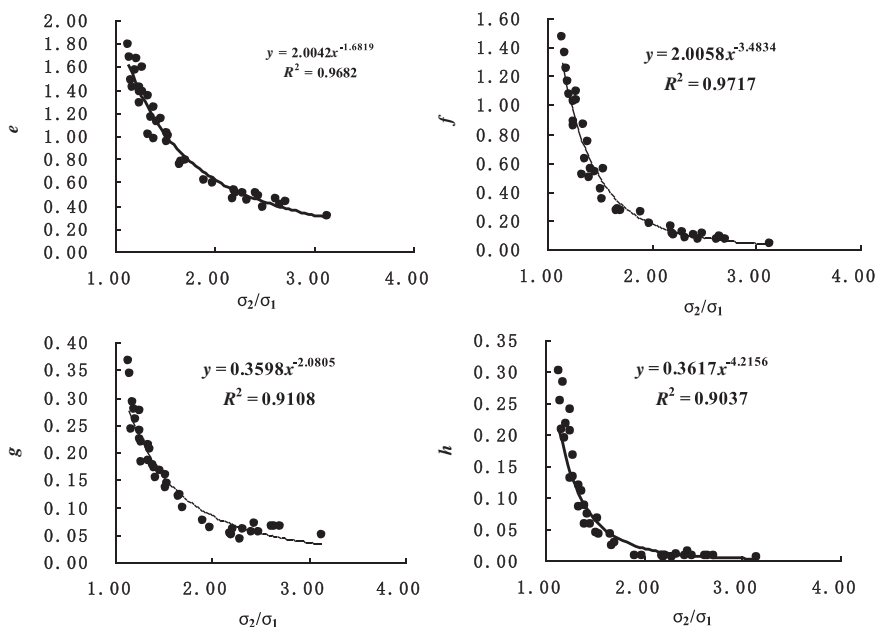


Fig. 3. The relationships between e, f, g, h and σ_2/σ_1 .

much bigger error because there exists a small difference between the two DP signals.

In slug flow, the liquid flow is contained in liquid slugs which separate the successive gas bubbles. Generally, the liquid slugs may contain small isolated gas bubbles. So, the fluctuation of the DP signal is strong and the difference between the two DP signals is big, as shown in Fig. 2, where (a1), (b1) and (c1) correspond to the DP signals acquired from the upstream Venturi meter, and (a2), (b2) and (c2) correspond to that from the downstream Venturi meter. It is suitable to predict the fraction flowrate using the method provided in this study.

Fig. 3 denotes the relationships between σ_2/σ_1 and the elements of the separation matrix for slug flow. Finally, the fraction flowrate measurement model for slug gas–liquid two-phase flow can be expressed as the following equations:

$$\begin{aligned} M_g &= K \sqrt{\Delta P_g \rho_g} \\ M_l &= K \sqrt{\Delta P_l \rho_l} \\ \begin{pmatrix} \sqrt{\Delta P_g} \\ \sqrt{\Delta P_l} \end{pmatrix} &= \begin{pmatrix} e & f \\ g & h \end{pmatrix} \times \begin{pmatrix} \sqrt{\Delta P_{tp1}} \\ \sqrt{\Delta P_{tp2}} \end{pmatrix} \\ \begin{pmatrix} \ln e \\ \ln f \\ \ln g \\ \ln h \end{pmatrix} &= \begin{pmatrix} 2.0042 & -1.6819 \\ 2.0058 & -3.4834 \\ 0.3598 & -2.0805 \\ 0.3617 & -4.2156 \end{pmatrix} \begin{pmatrix} 1 \\ \ln \sigma_2/\sigma_1 \end{pmatrix} \end{aligned} \quad (17)$$

where $\sigma_2/\sigma_1 > 1$, and σ_1 and σ_2 are variances of ΔP_{tp1} and ΔP_{tp2} , respectively. The parameters in the matrix are determined by data fitting from the experimental data.

Based on the method provided in this paper, the experimental results of the water and gas flowrate estimation for bubble flow, slug flow and annular flow are illustrated in Fig. 4. The quality estimation result is shown in Fig. 5. The proposed method exhibits a good fraction flowrate and quality prediction performance. Especially for the complicated slug flow, the relative errors of fraction flowrate estimation and quality prediction are within 10%.

In Figs. 4 and 5, water fraction flowrate, gas fraction flowrate and quality from 108 experimental conditions are predicted, including 35 bubble flow conditions, 42 slug flow conditions and 31 annular flow conditions. p is defined to describe the relative error distribution as follows:

$$p = \frac{n}{N} \times 100\% \quad (18)$$

where n denotes the condition numbers corresponding to the error range in the specific flow pattern, and N denotes the total condition numbers corresponding to the specific flow pattern.

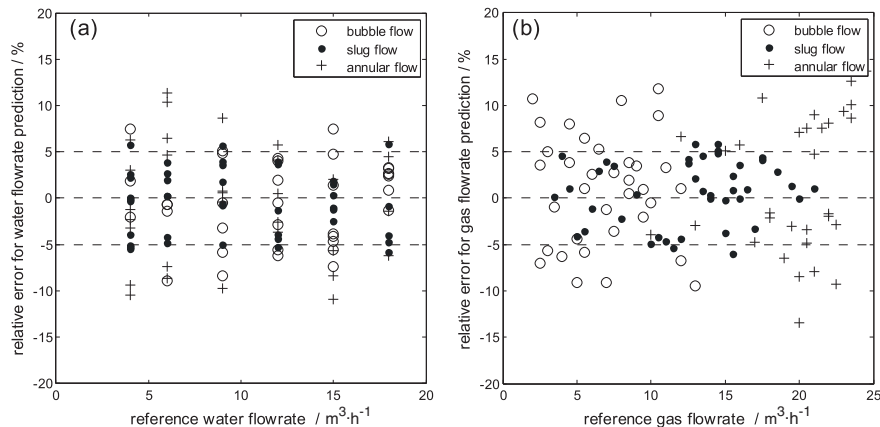


Fig. 4. Evaluation of flowrate measurement.

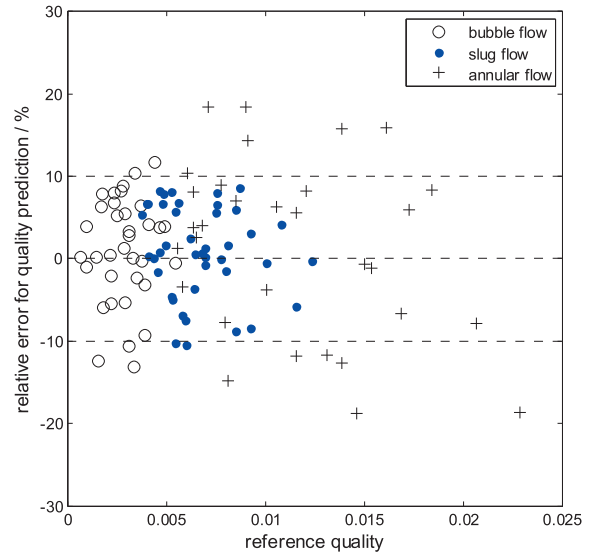


Fig. 5. Evaluation of quality measurement.

Table 1 shows the fraction flowrate and quality prediction relative error distribution in the bubble flow, slug flow and annular flow conditions. There exists a big difference between the calculated and the reference parameters for the annular flow.

The large errors are from the model simplifying assumptions. One is the separated flow assumption, the other is that the DP signals of the single phase are mixed linearly and the mixture result is the DP signal of two-phase flow. Although the mixture matrix is a nonlinear expression related to the fluctuation characterization of DP signals, it is still not sufficient to present the complicated interactions between two phases. Especially for the slug flow, the velocity field violates the fully developed rectilinear velocity field assumptions and the interactions between the gas and liquid phases vary. In particular, the error became significant when the tail of a slug bubble passed by the Venturi meter because of the strong varied interaction. This could be the main source in 10% error.

In the researches related to ICA and two-phase flow mentioned above, it was noticed that the amount of information around/along the test pipeline was acquired for measurement or identification of two-phase flow [15–20]. The amount of information processing causes a terrible real-time performance. The technique proposed in this paper implements gas–liquid two-phase flowrate measurement combining the throttle principle and the statistical experimental relationships between statistical characteristics of DPs across Venturi meters and

Table 1
Prediction relative error distribution

Flow pattern	Relative error for water flowrate prediction		Relative error for gas flowrate prediction		Relative error for quality prediction	
	$ RE \leq 5\%$	$5\% < RE < 10\%$	$ RE \leq 5\%$	$5\% < RE < 10\%$	$ RE \leq 5\%$	$5\% < RE < 10\%$
Bubble flow	71.4%	28.6%	51.4%	40%	48.6%	37.1%
Slug flow	83.3%	16.7%	88.1%	11.9%	50%	45.2%
Annular flow	48.4%	38.7%	38.7%	45.2%	25.8%	35.5%

elements of separation matrix, which improves the real-time performance of measurement.

6. Conclusions

A novel method for fraction flowrate measurement of gas–liquid two-phase slug flow is presented. The flowrate measurement model is developed based on the static and dynamic characterizations of two-phase flow. The flowrate measurement is achieved using two DP signals measured from two Venturi meters. The experimental results show that the performance of the provided method is satisfactory. A flowrate measurement model based on the blind source separation method is independent upon the relationship between voidage and quality. In other words, the relationship between voidage and quality is embedded in the model expressions. Correspondingly, the interaction between the gas and liquid phases is represented in the separation matrix.

Furthermore, the separation matrix is found closely related to the difference between two DP signals from two Venturi meters, and there exists a satisfactory fraction flowrate prediction performance based on the separation matrix for slug flow. Hence, it is hopeful to investigate the hydrodynamic characteristics of slug flow through the separation matrix and the difference of DP signals from Venturi meters.

References

- [1] H.Q. Li, Measurement of Two-phase Flow Parameter and Its Applications, Zhejiang University Press, Hangzhou, 1991. (in Chinese).
- [2] H.Q. Li, Z.Y. Huang, Special Measurement Technology and Application, Zhejiang University Press, Hangzhou, 2000. (in Chinese).
- [3] J.W. Murdock, Two-phase flow measurements with orifices, *J. Basic Eng.* 84 (1962) 419–433.
- [4] R. James, Metering of steam–water two-phase flow by sharp-edged orifices, *Proc. Inst. Mech. Eng.* 180 (1965) 549–566.
- [5] D. Chisholm, Two-phase flow through sharp-edged orifices, *J. Mech. Eng. Sci.* 19 (1977) 128–130.
- [6] Z.H. Lin, Measurements of steam quality and flow rate in steam–water mixture flow with Herschel Venturis, *J. Xi'an Jiaotong Univ.* 16 (3) (1982) 25–34 (in Chinese).
- [7] Z.H. Lin, Gas–Liquid Two-phase Flow and Boiling Heat Transfer, Xi'an Jiaotong University Press, Xi'an, 1987. (in Chinese).
- [8] G.B. Zheng, N.D. Jin, X.H. Jia, P.J. Lv, X.B. Liu, Gas–liquid two phase flow measurement method based on combination instrument of turbine flowmeter and conductance sensor, *Int. J. Multiphase Flow* 34 (11) (2008) 1031–1047.
- [9] R.N. Steven, Wet gas metering with a horizontally mounted Venturi meter, *Flow Meas. Instrum.* 12 (2002) 361–372.
- [10] Z.H. Lin, Characteristics of Gas–Liquid Two-phase Flow in Pipelines and Their Engineering Applications, Xi'an Jiaotong University Press, Xi'an, 1992. (in Chinese).
- [11] J.D. Sherwood, Potential flow around a deforming bubble in a Venturi, *Int. J. Multiphase Flow* 26 (2000) 2005–2047.
- [12] L.J. Xu, J. Xu, F. Dong, T. Zhang, On fluctuation of the dynamic differential pressure signal of Venturi meter for wet gas metering, *Flow Meas. Instrum.* 14 (2003) 211–217.
- [13] H.J. Zhang, W.T. Yue, L.B. Ma, H.L. Zhou, Relationship between fluctuating differential pressure and void fraction of gas–liquid two-phase flow in Venturi tube, *J. Chem. Ind. Eng. (China)* 56 (11) (2005) 2102–2107 (in Chinese).
- [14] S.P. Zhong, Y.X. Tong, W.R. Wang, Measurement of gas/liquid two-phase flow using differential pressure noise of Orifice plate, *J. Tsinghua Univ.* 37 (5) (1997) 15–18 (in Chinese).
- [15] H.L. Liu, H.S. Li, ICA and its application in the identification of gas/liquid two-phase flow, *J. Jilin Univ. (Earth Sci. Ed.)* 39 (1) (2009) 31–36 (in Chinese).
- [16] X.J. Wu, C.Y. Cui, S. Hu, Z.H. Li, C.D. Wu, The velocity measurement of two-phase flow based on particle swarm optimization algorithm and nonlinear blind source separation, *Chin. J. Chem. Eng.* 20 (2) (2012) 346–351.
- [17] Y.B. Xu, H.X. Wang, Z.Q. Cui, Phase information extraction of gas/liquid two-phase flow in horizontal pipe based on independent component analysis, *CIESC J.* 60 (12) (2009) 3012–3018 (in Chinese).
- [18] Y.B. Xu, Z.Q. Cui, H.X. Wang, F. Dong, X.Y. Chen, W.Q. Yang, Independent component analysis of interface fluctuation of gas/liquid two-phase flows – experimental study, *Flow Meas. Instrum.* 20 (2009) 220–229.
- [19] P.X. Xu, Y.F. Geng, Wet gas flow metering based on differential pressure and BSS techniques, 2010 International Conference on Electrical Engineering and Automatic Control (ICEEAC 2010), vol.1 2010, pp. 270–273.
- [20] Y.L. Zhou, Y.Y. Gu, Flow regime identification of gas/liquid two-phase flow based ICA and RBF neural networks, *CIESC J.* 63 (3) (2012) 796–799 (in Chinese).
- [21] P. Comon, C. Jutten, J. Hérault, Blind separation of sources, part II: statement problem, *Signal Process.* 24 (1) (1991) 11–20.
- [22] P. Comon, Independent component analysis. A new concept? *Signal Process.* 36 (1994) 287–314.
- [23] J.F. Cardoso, B. Laheld, Equivariant adaptive source separation, *IEEE Trans. Signal Process.* 44 (12) (1996) 3017–3030.
- [24] L.F. Cai, X.M. Tian, N. Zhang, A kernel time structure independent component analysis method for nonlinear process monitoring, *Chin. J. Chem. Eng.* 22 (11/12) (2014) 1243–1253.
- [25] L.Y. Lao, H.J. Zhang, Y.X. Wu, D.H. Li, Z.C. Zheng, Influence of void fraction on dynamic characteristics of pressure drop fluctuation in horizontal gas–liquid two-phase flow, *J. Chem. Ind. Eng. (China)* 51 (4) (2000) 547–550 (in Chinese).
- [26] G.Q. Shen, Z.H. Lin, A dynamic method for dual parameter measurements of gas–liquid biphasic flow, *J. Chem. Ind. Eng. (China)* 44 (2) (1993) 140–145 (in Chinese).