Experimental Thermal and Fluid Science 96 (2018) 311–320

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

A new model for volume fraction measurements of horizontal high-pressure wet gas flow using gamma-based techniques

Yanzhi Pan[a,b], Yugao Ma[c], Shanfang Huang[c,*], Pengman Niu[a], Dong Wang[a], Jianhua Xie[b]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Haimo Technologies Group Corp., Lanzhou 730050, China
[c] Department of Engineering Physics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
High-pressure wet gas flow
Slip ratio
Equal-diameter double-circle model
Gamma ray attenuation method
Gas volume fraction

ABSTRACT

The accurate predictions of void fraction and gas volume fraction are important in characterizing wet gas flow, as they are the basic input for determining other key flow parameters, such as flow velocity and flow rate of each phase. In previous studies, empirical relationships were used to predict void fraction and gas volume fraction, which have limited applicability due to the lack of detailed structural and dynamic information involved in two-phase flow. Hence, in this work, attempts are being made to develop a model based on a simplified two-phase interfacial structure. A slip ratio based equal-diameter double-circle model is proposed to predict the void fraction and gas volume fraction using gamma ray attenuation method for high-pressure wet gas conditions. Model predictions were verified against experiments in a 172.0 mm inner diameter horizontal pipe. Nitrogen and kerosene were used as the test fluids with gas volume fractions ranging from 92% to 100%. The relative errors in the line-averaged void fraction predicted by the slip ratio based model were within ± 2%. In addition, this model can be used to explain the relationship between the key flow parameters and further to predict the optimal measuring angle of the gamma rays. The line-averaged void fraction measured by the gamma ray attenuation method at a proper angle predicted by the model is equal to the gas volume fraction for these high-pressure wet gas conditions, with an average relative error of 0.2%.

1. Introduction

Wet gas flows are defined as any gas-liquid two-phase flow with a gas volume fraction more than 95% [1], which occur widely in nature and in industries. In recent years, the rapid development of both traditional and emerging industries, such as the petroleum industry, nuclear industry, aerospace industry and metallurgical industry, has led to more stringent requirements on wet gas flow measurements which has stimulated development of wet gas measurement techniques [2–4]. In wet gas flows, the design of pipelines requires the formidable task of predicting the phase distribution, where one of the critical parameters is the gas volume fraction.

One method to measure wet gas flowrates in industry is to separate the mixture and measure separately [6]. However, separation method is expensive, large-scale, and difficult to apply in transport systems especially in the cases of large flow rates [7]. Therefore, the non-separation methods have been developed in recent decades. Normally, non-separation methods employ combined meters or sensors [8]. The majority of these meters are made up of differential pressure devices, e.g., Venturi meter, and other measurement sensors, e.g., gamma ray sensor. Non-separation methods do not need to separate the components of the flow. They are used to measure the phase distribution and flowrate in situ. Recently, there has been an increasing interest in developing non-separation measurement methods for wet gas flows.

As a subset of gas-liquid two-phase flow, wet gas flow is much more complicated than single-phase flow owing to the variety of flow regimes and the gas-liquid slip. Normally, the wet gas flow regimes in a horizontal pipeline can be divided into stratified flow, wavy stratified flow, annular flow, and mist flow [9,10]. Still there is no effective technique to identify the two-phase flow regimes and it is even difficult to capture the accurate phase distribution [11]. The slip between the gas and liquid phases is complex as a consequence of the existence of relative movement on the interfaces and interactions between two phases. Despite the wide investigations in the gas-liquid slip, for instance, the slip ratio correlation developed by Lockhart and Martinelli [12], Chisholm [13], Hamersma and Hart [9], Lin [14], and Jia and Cai [15], the physical mechanism is still not fully understood. In fact, in industry, there always exits a difficult task of choosing the “right” correlation among the many available correlations [5]. Therefore, the choice of a suitable, reliable slip ratio model is also an important part of work to

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[*] Corresponding author.
E-mail address: sfhuang@mail.tsinghua.edu.cn (S. Huang).

https://doi.org/10.1016/j.expthermflusci.2018.03.002
Received 20 October 2017; Received in revised form 6 February 2018; Accepted 2 March 2018

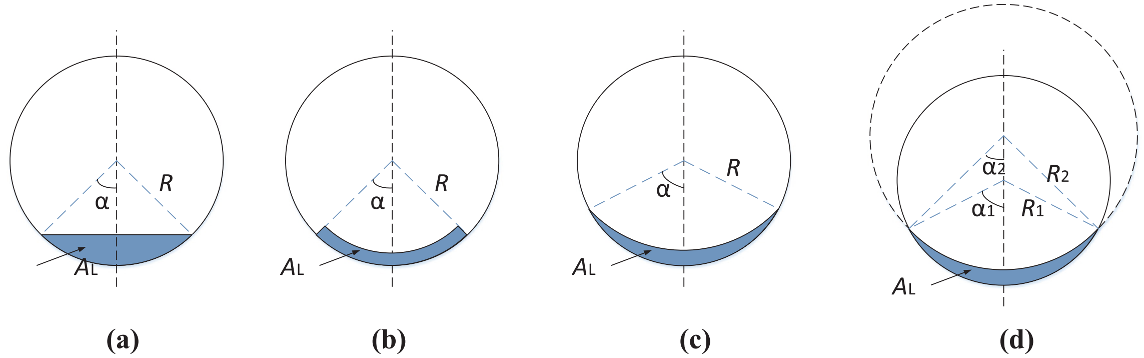


Fig. 1. Schematics of the classical interface models: (a) Taitel-Dukler model [26]; (b) Hart et al. model [10]; (c) Grolman-Fortuin model [28]; (d) Double-circle model [27].

establish the model in this article. In summary, wet gas flow includes all the complexity of single-phase convective transport (e.g., transition to turbulence, instabilities) and additional elements resulting from the motion of the gas-liquid interface, and interactions between the phases [16].

Due to these complexities, most researches on wet gas flows have focused on empirical correlations [12,17–20] to predict liquid holdup (ε_l) or void fraction ($1-\varepsilon_l$). These correlations have a typical accuracy range within ± 30% [21]. Most previous experiments were carried out in small diameter pipelines with inner diameters generally less than 77.9 mm and near atmospheric pressure [22,23]. However, in industrial fields, the multiphase flows may occur in larger diameter (100–1000 mm) pipelines at higher pressures (up to 15 MPa) [22,24]. Therefore, existing empirical correlations will result in large errors due to the mismatch of geometrical size and operation conditions.

Mechanistic models for gas-liquid pipe flows have been developed since the 1970s. For mechanistic modeling, the prescription of the interface shape is a basic input to initiate the solution of the multiphase transport phenomena [25]. Taitel and Dukler [26] presented a flat surface model to describe the interface in stratified gas-liquid flows. Afterwards, Hart et al. [10], Chen et al. [27], and Grolman and Fortuin [28] improved the gas-liquid interface model. Recently, there has been renewed interest in model building for wet gas metering [29–31].

Various approaches have been developed for on-line wet gas flow metering with common techniques such as the electrical impedance, gamma radiation attenuation, microwave, and optical approaches [32]. Among these methods, the gamma ray attenuation technique is considered to be a good option for getting the details of the multiphase flow structure [33] due to its accuracy, good penetration and non-intrusive characteristics. It has been widely used in many commercially available multiphase metering systems [34] since the 1980s. The measurement of component ratios in multiphase flows using gamma-ray attenuation was first suggested by Abouelwafa and Kendall [35] and they examined various static mixture of oil–water–gas using a gamma-based system. Abro and Johansen [36] performed an experimental study using a multi-beam measurement devices and presented an improved void fraction determination method based on the assumption of a flat oil–gas interface. Tesi [37] applied high-speed gamma densitometers to measure the gas and liquid phase distribution in a vertical pipeline and a horizontal pipeline. Cadalen and Lance [30] carried out a wet gas flow metering study in the vertical riser pipe at NEL (National Engineering Laboratory, Glasgow, Britain), with an upward vertical Venturi and a multienergy gamma ray hold-up meter at the Venturi throat. Hanus [38] studied the application of Hilbert Transform in the correlation measurements of the random time delay. Based on the values of time delay obtained by gamma ray densitometry, they calculated gas phase average velocity. Nazemi et al. [39] proposed a method for void fraction measurement in two-phase flows using gamma-ray attenuation system. They examined various static mixture of gas and liquid at a Pyrex-glass pipe with an inner diameter of 9.5 cm. Although gamma-ray attenuation methods have been studied for decades, the phase distribution was rarely investigated under high pressure wet gas conditions in horizontal pipeline using gamma densitometers.

The objective of this paper is to study the on-line measurements of horizontal wet gas flows and to develop a method to predict the phase distribution, based on the flow regimes, a gas-liquid interface model and a suitable slip ratio correlation. A slip ratio based equal-diameter double-circle model is therefore developed for high-pressure wet gas flow metering. The model was evaluated based on tests in a horizontal pipeline using a Venturi meter and a gamma ray attenuation system. The model can predict the average void fraction along the line of sight and the optimal measuring angle, as verified by the experimental data. The investigations of present study are helpful to resolve the difficulties of measuring for wet gas flows concerning to the horizontal high pressure conditions.

2. Theoretical model

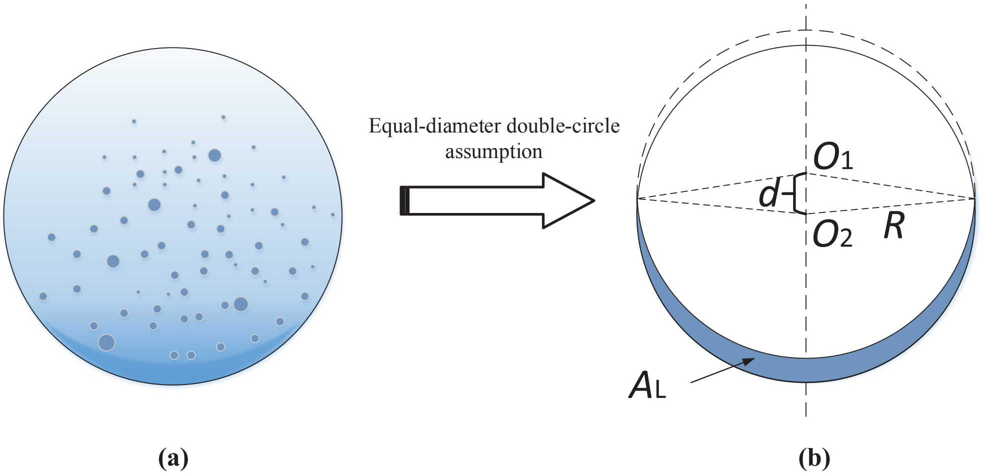
The process of gas volume fraction metering based on the gamma ray attenuation methods is as follows: First, gamma ray attenuation system is used to obtain the line-averaged void fraction. Second, based on a suitable interface model, the line-averaged void fraction can be transformed into the void fraction. Then, gas volume fraction can be calculated by the slip ratio model. Finally, the gas volume fraction predicted by the model is compared with the experimental data. If the error of prediction satisfies the measurement precision, the model is validated. Than the interface model and the slip ratio model will be selected and examined for further experiments.

The most critical steps of the process above are to establish a suitable gas-liquid interface model and to choose a proper empirical slip ratio correlation.

2.1. Interface model

An interface model is necessary in this study to develop a mechanistic model for the wet gas flow rate measurement. The existing interface models shown in Fig. 1 will be investigated, including Taitel-Dukler model [26], Hart et al. model [10], Grolman-Fortuin model [28], and the double-circle model [27]. A new model will then be developed based on the existing models to be applied to the working conditions in the present study.

Taitel-Dukler model [26] shown in Fig. 1(a) is the first gas-liquid interface model which regarded the interface as a flat plane. The deficiency of this model is that it ignores the influence of the gas flow rate. In addition, the flat interface assumption has been found to be inaccurate, particularly at high gas phase velocities. Hart et al. model [10] shown in Fig. 1(b) then assumes a uniform-distributed liquid film flush to part of the pipe wall. However, this model does not take the influence of gravity into account. Further studies have shown that the uniform-distributed film assumption also does not accurately model the



(a) (b)

Fig. 2. Schematic of the actual phase distribution and a simplified model. (a) Two phase flow with entrained droplets; (b) equal-diameter double-circle model.

liquid film [40]. Grolman-Fortuin model [28] shown in Fig. 1(c) and the double-circle model [27] shown in Fig. 1(d) take the impact of gravity into consideration. In the double-circle model [27], the upper gas-liquid interface is assumed to be a portion of an imaginary eccentric circle as shown in Fig. 1(d), which was shown to more accurately represent the actual gas-liquid interface shape [22]. However, the interfacial configuration of the double-circle model [27] is complicated and the diameter of the imaginary eccentric circle must be determined by an iterative procedure. In addition, the convergence of the double-circle model [27] is very sensitive to the initial value [24]. There are similar problems to the iterative solution procedure in Grolman-Fortuin model [28].

In addition, measurements of high-pressure wet gas flow rates must also consider the influence of droplet entrainment shown in Fig. 2 since the gamma rays will be attenuated by both the liquid entrained in the gas core and the liquid film flush to the wall. The current model assumes that all the liquid resides on the bottom surface with a simple interface as shown in Fig. 2(b). The liquid film diameter in the double-circle model [27] approaches the inner pipe diameter as the gas volume fraction increases. For high-pressure wet gas flow, the liquid film at the bottom of the pipe can be neglected and the diameter of the imaginary concentric circle can be assumed to be the same as the pipe diameter. The double-circle model then degenerates into the equal-diameter double-circle model shown in Fig. 2(b).

According to the geometrical relations in Fig. 2(b), the liquid holdup, ε_L, can be calculated by

$$\varepsilon_L = \frac{A_L}{\pi R^2} = \frac{1}{\pi}\left(\frac{d\sqrt{4R^2-d^2}}{2R^2} + \frac{d}{R} + \frac{d^3}{24R^3}\right) \tag{1}$$

where R is the inner pipe radius, d is the eccentricity, and A_L is the liquid cross-sectional area.

With the simplifications in this model, the liquid holdup is a unique function of the eccentricity and the iterations are therefore avoided. In addition, since this model is closely related to the wet gas flow characteristics, the model can be easily adapted to high-pressure wet gas flows.

2.2. Slip ratio model

After establishing the interface model, the line-averaged void fraction can be transformed into the void fraction over the pipe cross section. The gas volume fraction is related to the slip ratio in the separated flow model as:

$$\beta = \frac{1}{1 + \frac{1-\alpha}{\alpha}\frac{1}{S}} \tag{2}$$

where β is the gas volume fraction, S is the slip ratio, and α is the void fraction.

The slip ratio in multiphase flows is normally determined from empirical correlations. Several models are introduced here, including Lockhart-Martinelli model [12], Hamersma-Hart model [9], Lin model [14], Jia-Cai model [15], and Chisholm model [13].

2.2.1. Lockhart-Martinelli (L-M) model [12]

Lockhart-Martinelli [12] proposed a correlation for the liquid holdup as:

$$\varepsilon_L = \left[1 + 3.57\left(\frac{u_G}{u_L}\right)^{0.64}\left(\frac{\rho_G}{\rho_L}\right)^{0.28}\left(\frac{\mu_L}{\mu_G}\right)^{0.07}\right]^{-1} \tag{3}$$

where u_G and u_L are the gas and liquid superficial velocities, μ_G and μ_L are the gas and liquid viscosities, and ε_L is the liquid holdup. The slip ratio, S, can be then calculated by:

$$\alpha = 1-\varepsilon_L \tag{4}$$

$$S = \frac{(1-\alpha)/\alpha}{(1-\beta)/\beta} \tag{5}$$

2.2.2. Hamersma–Hart model [9]

Hamersma and Hart [9] measured the flow rates in a 50 mm I.D. horizontal pipe with an air/water system. Their correlation of their experimental data is:

$$\varepsilon_L = \left[1 + 3.81\left(\frac{u_G}{u_L}\right)^{2/3}\left(\frac{\rho_G}{\rho_L}\right)^{1/3}\right]^{-1} \tag{6}$$

The slip ratio can be then calculated by Eqs. (4)-(6).

2.2.3. Lin model [14]

Lin [14] suggested the following correlation for the slip ratio for high-pressure steam-water two-phase flow

$$S = 1 + \frac{0.4 + \beta^2}{\sqrt{u_{sl}}}\left(1-\frac{P}{22.1}\right) \tag{7}$$

where u_{sl} is the equivalent flow velocity assuming that the total mass flow rate is converted into that of the liquid phase, and P is the working pressure, MPa.

2.2.4. Jia-Cai model [15]

Jia and Cai [15] used a combination of a Venturi meter and a void fraction sensor to measure oil-gas-water three-phase flow rates with high air void fractions (>80%). They modified Lin model [14] and proposed the following correlation:

$$S = 1 + \frac{m + n\alpha^2}{\sqrt{u_{sl}}}\left(1 - \frac{P}{22.1}\right) \tag{8}$$

where m and n are the empirical constants determined from the experimental data.

2.2.5. Chisholm model [13]

Chisholm [13] used the Lockhart-Martinelli parameter, χ, in an empirical correlation of the slip ratio [13,41]:

$$\begin{cases} S = \left(\frac{\rho_L}{\rho_G}\right)^{0.25}, & \chi \leqslant 1 \\ S = \left[1 + x\left(\frac{\rho_L}{\rho_G} - 1\right)\right]^{0.5}, & \chi > 1 \end{cases} \tag{9}$$

These five models will be evaluated to select the most suitable one for the current test conditions in Section 4.

3. Experimental facility and techniques

3.1. Flow test loop

A schematic of the two-phase flow test loop is presented in Fig. 3. The two-phase flow rates were measured in a horizontal test section. The operating pressure is controlled between 5.9 and 6.1 MPa. The temperature is controlled between 19.8 and 20.2 °C. Nitrogen and kerosene (Exxsol D80) were used as the test fluids with their properties listed in Table 1. In this experiments, the ranges of liquid superficial velocity and gas superficial velocity are 0–0.58 m/s and 4.75–14.41 m/s, respectively.

The nitrogen was driven by a 200 kW fully enclosed blower. The gas flow rate was regulated by the blower and measured with a gas ultrasonic flow meter (± 0.3% uncertainty). Kerosene was supplied from a liquid storage tank by an eleven-stage 130 kW centrifugal pump. The liquid flow rate was controlled by two regulating valves and measured with a metering manifold (± 0.2% uncertainty). The gas and liquid temperatures were both kept constant by using a chilled-water supplied shell-and-tube heat exchanger with an accuracy of ± 0.1 °C. The metered gas and the metered liquid were mixed at the inlet of the horizontal pipe to form a nitrogen-kerosene two-phase flow. The two-phase flow entered a gas-liquid separator at the end of the test section to be separated and recycled.

The inner diameter of the horizontal test pipe, D, was 172.0 mm, and the Venturi diameter ratio was 0.582. The straight length in front of the Venturi tube was more than 10D to make the flow fully developed, and more than 6D after the Venturi tube to help the flow pressure recover [42]. For each test, the time duration was more than 10 min to obtain an accurate line-average void fraction by averaging the readings. The gamma ray attenuation system was located at the Venturi nozzle throat as shown in Fig. 4. The gamma ray detector was set at various angles, θ, of 0°, 30°, 45° or 90° as shown in Fig. 5. The meter accuracies are listed in Table 2.

Table 1
Properties of fluids.

Fluid	Density (kg m^{-3})	Viscosity (mPa s)
Nitrogen	74.54	0.00185
Kerosene	804.4	2.58

3.2. Measurement principles of Venturi meter and gamma ray attenuation method

Venturi tubes are commonly used for flow rate measurements of gas, liquid, and vapor in industry. Fig. 4 shows the structure of the Venturi meter.

The gamma ray attenuation method to measure the component ratios in multiphase flows is based on the exponential attenuation of the gamma rays in the fluids [35]. The transmitted intensity, I, is determined by

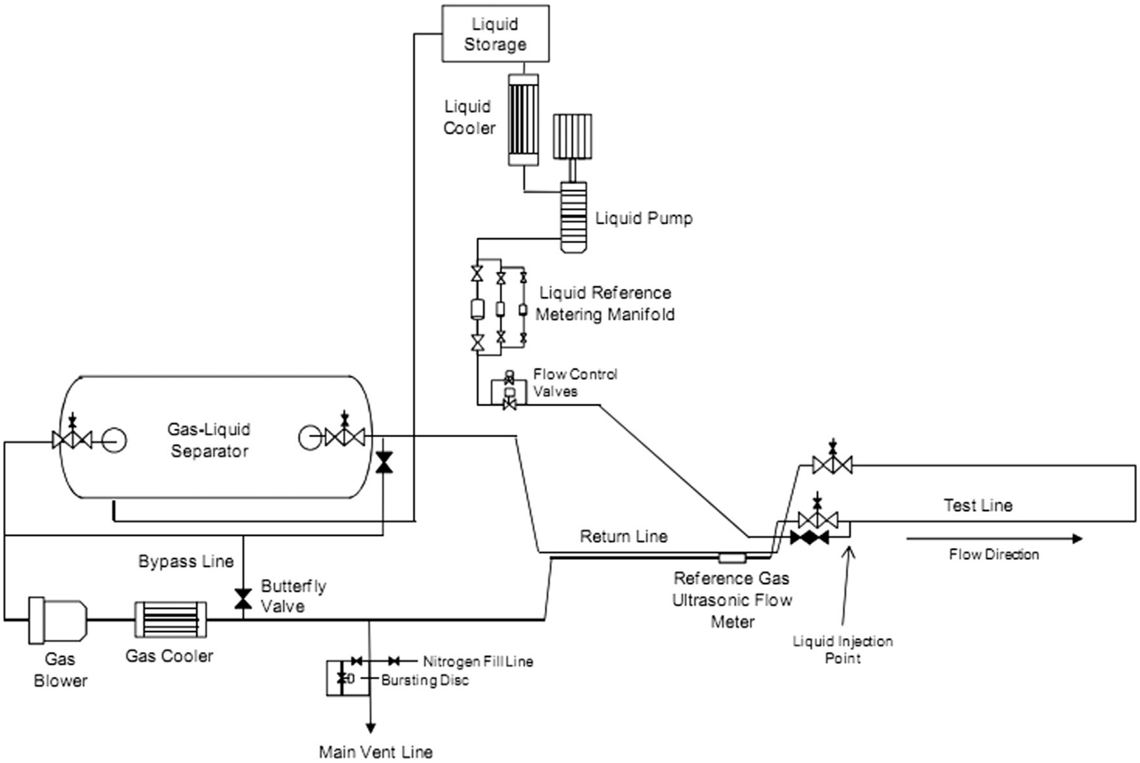


Fig. 3. Schematic of wet gas flow measurement system.

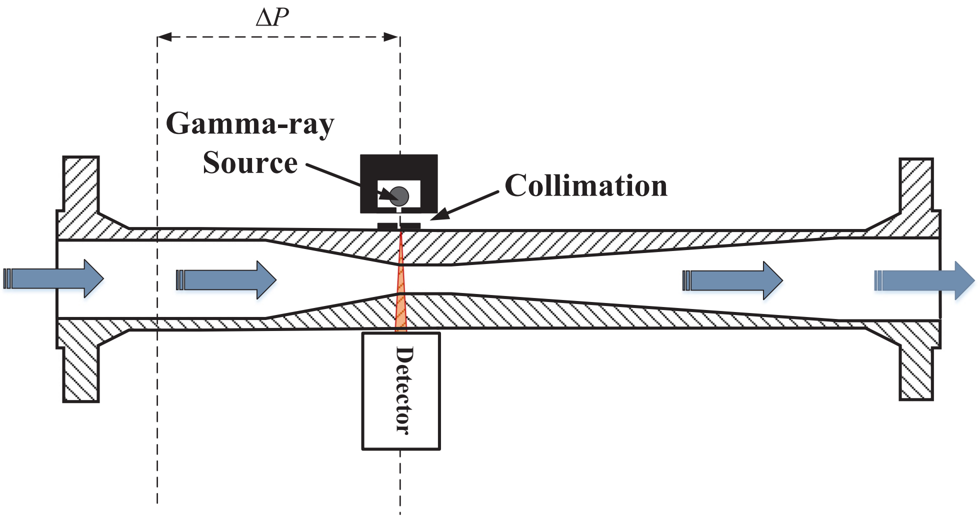


Fig. 4. Schematic of a Venturi test section.

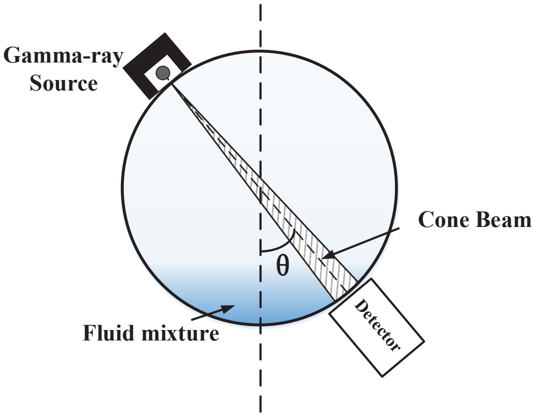


Fig. 5. Schematic of gamma ray attenuation system.

Table 3
Calculated slip ratios by the five models and the reference slip ratio.

Model	Range of calculated slip ratio
Hamersma-Hart [9]	1.68–5.03
Lockhart-Martinelli (L-M) [12]	0.98–3.18
Chisholm[13]	1.84
Lin [14]	1.46–1.86
Jia-Cai [15]	1.42–1.80
Reference	1.69–2.05

Note: The reference slip ratio is calculated by Eq. (5), based on the line-average void fraction obtained by gamma system and the equal-diameter double-circle interface model.

$$I = I_0 e^{-\mu_r d} \tag{10}$$

where μ_r is the mean linear absorption coefficient of the sample, d is the sample thickness, and I_0 is the initial gamma ray intensity.

Since the gamma rays are collimated before passing through the throat, the gamma rays do not cover the entire cross section of the channel but only a wedge-shaped segment as shown in Fig. 5. For homogeneous flow, the void fraction measured by the gamma ray attenuation method is independent of the measuring angle, θ. However, most industrial wet gas flows are not homogeneous, so the gamma ray attenuation varies with the measuring angle.

When the gamma ray beam is well collimated, the measurement can be regarded as the average void fraction along the line at the measuring angle. Thus, the void fraction measured in Fig. 5 is referred to as the line-averaged void fraction, α_{line}, which varies with the measuring angle and can be calculated as

$$\alpha_{\mathrm{line}}(\theta) = \frac{\ln(I/I_{\mathrm{L}})}{\ln(I_{\mathrm{G}}/I_{\mathrm{L}})} \tag{11}$$

where I is the transmitted intensity and depends on the fractions of gas and liquid in the flow. Subscripts L and G refer to the channel being filled with single-phase liquid and gas, respectively.

Similarly, the line-averaged liquid holdup, $\varepsilon_{\mathrm{L,line}}$, can be calculated as:

$$\varepsilon_{\mathrm{L,line}}(\theta) = 1{-}\alpha(\theta) \tag{12}$$

4. Slip ratio model evaluation and selection

Lockhart-Martinelli model [12] and Hamersma-Hart model [9] are both in the form of

$$\varepsilon_{\mathrm{L}} = \left[1 + a\left(\frac{u_{\mathrm{G}}}{u_{\mathrm{L}}}\right)^{b}\left(\frac{\rho_{\mathrm{G}}}{\rho_{\mathrm{L}}}\right)^{c}\left(\frac{\mu_{\mathrm{L}}}{\mu_{\mathrm{G}}}\right)^{d}\right]^{-1} \tag{13}$$

where a, b, c and d are the empirical coefficients determined from experimental data. Both correlations show that the slip ratio increases with the gas volume fraction, and that the slip ratio tends to infinity as

Table 2
Measurement uncertainties (95% confidence).

Source	Manufacturer	Calibration range	Expanded uncertainty estimate (%)
Gas mass flow rate	SICK Mailhak FLOWSIC600 Quattro UFM	$0.15–13 \times 10^6$ (Reynolds number)	0.3
Liquid mass flow rate	EMO Ltd 3-bladed 3-inch turbine flow meter/EMO Ltd 3-bladed 1-inch turbine flow meter (switched by the metering manifold)	14.3–93.2 m^3/h/1.48–19.5 m^3/h	0.2
Pressure	Yokogawa Transmitter: Type EJA430A	0–7 MPa	0.10
Temperature	Sensing Devices Ltd RTD: Type 4-wire PRT	5–55 °C	0.05

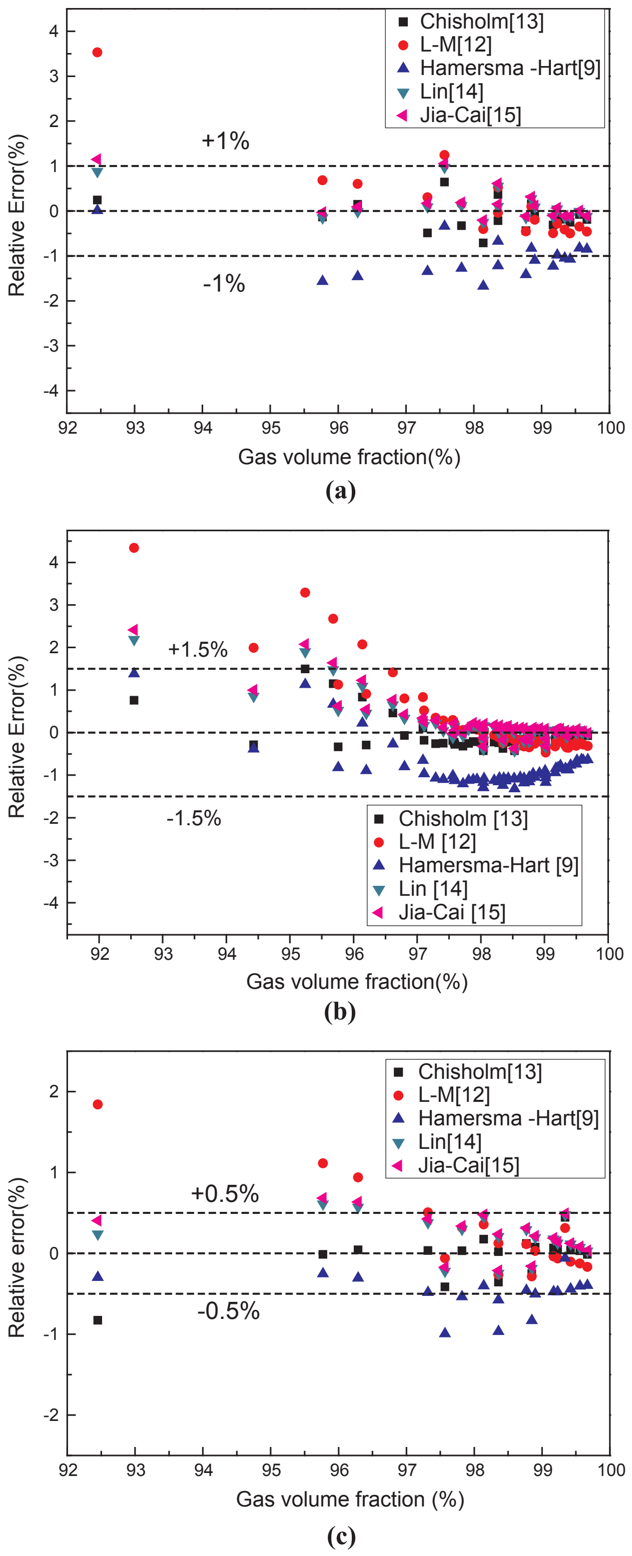


Fig. 6. Relative errors in the predicted line-averaged void fractions at 30°, 45°, 60°. The case of 30°. (b) The case of 45°. (c) The case of 60°.

Table 4
Average errors and RMSE of each model at 30°.

Models	Lockhart-Martinelli [12]	Hamersma-Hart [9]	Lin [4]	Jia-Cai [15]	Chisholm [13]
Average error (%)	0.60	1.05	0.23	0.26	0.28
RMSE	0.009646	0.01128	0.003583	0.004170	0.003359

Table 5
Average errors and RMSE of each model at 45°.

Models	Lockhart-Martinelli [12]	Hamersma-Hart [9]	Lin [14]	Jia-Cai [15]	Chisholm [13]
Average error (%)	0.51	0.97	0.24	0.28	0.23
RMSE	0.9383	0.9944	0.4885	0.5424	0.3557

Table 6
Average errors and RMSE of each model at 60°.

Models	Lockhart-Martinelli [12]	Hamersma-Hart [9]	Lin [4]	Jia-Cai [15]	Chisholm [13]
Average error (%)	0.38	0.49	0.27	0.30	0.17
RMSE	0.005928	0.005429	0.003156	0.003474	0.002700

the gas volume fraction approaches 100%. These results are only reasonable with the separated flow model. However, if the entrainment effect is taken into account, the droplet entrainment increases gradually with the gas volume fraction. For gas concentrations close to 100%, the liquid phase mainly exists as entrained drops in the gas phase. Consequently, the slip ratio approaches a certain value rather than infinity. Thus, with droplet entrainment, the slip ratios predicted by Lockhart-Martinelli model [12] and Hamersma-Hart model [9] are much larger than the actual values for high gas concentrations.

Jia-Cai model [15] was developed from Lin model [14] which was derived for high-pressure steam-water flow. Both models have the form:

$$S = 1 + \frac{m + n\alpha^2}{\sqrt{u_{sl}}}\left(1-\frac{P}{22.1}\right) \tag{14}$$

where the constant 22.1 MPa refers to the critical pressure of water, and m and n are the empirical coefficients. These probably do not apply to nitrogen-kerosene two-phase flow, since Eq. (14) was derived for steam-water-oil three-phase flows. However, note that Jia-Cai model [15] was calibrated using data for multiphase flow metering at void fractions greater than 80%, with a Venturi throat diameter of 43.08 mm, and a diameter ratio of 0.65. The geometrical sizes are all similar to the present case, so the experimental data in Jia and Cai [15] is referable for the present work to some extent.

As for Chisholm model [13], since the Lockhart-Martinelli parameter in the current experimental conditions is always less than 1, only the influence of the liquid-gas density ratio needs to be considered according to Eq. (9). The calculated slip ratio of Chisholm [13], Lin [14], and Jia-Cai [15] models are listed in Table 3. In addition, the reference slip ratio is also calculated by the Eq. (5), based on the line-average void fraction obtained by gamma system and the equal-diameter double-circle interface model.

The most suitable correlation was found by using each model to predict the line-averaged void fraction at 30°, 45°, and 60° together with the equal-diameter double-circle model. The predictions of each correlation are compared with the gamma ray attenuation measurements as shown in Fig. 6. Lin [14], Jia-Cai [15] and Chisholm [13] models all agree well with the experimental data. The average errors and the root-mean-square errors (RMSE) for each model are listed in Tables 4–6:

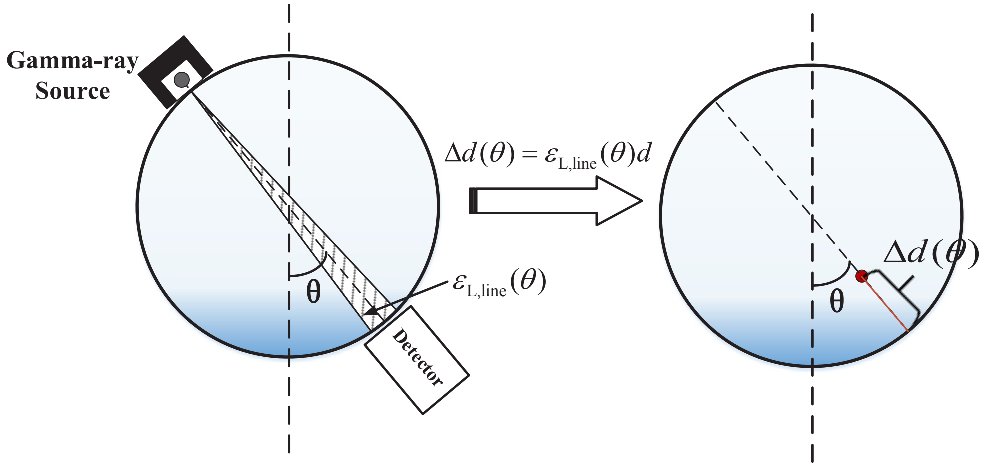
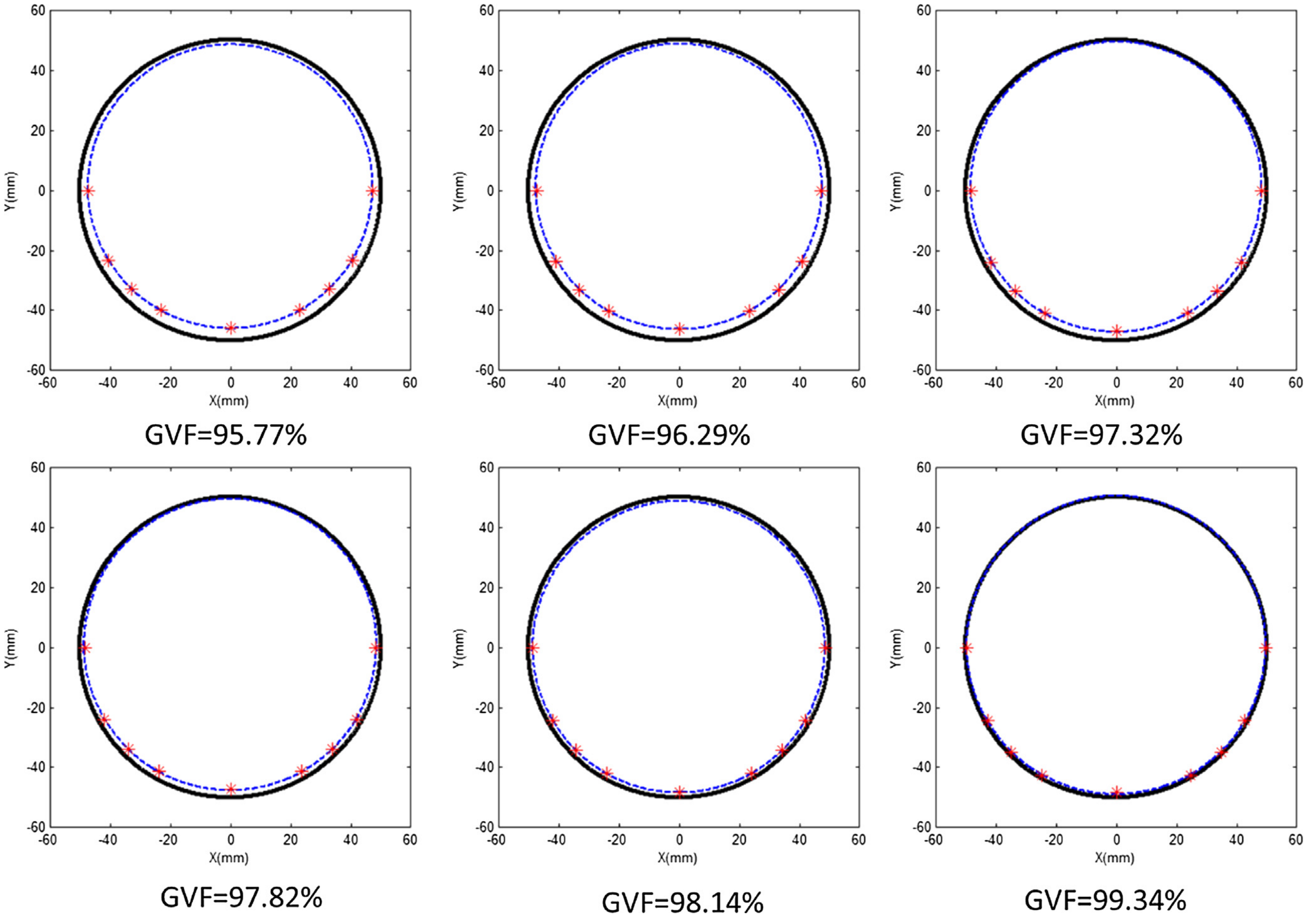


Fig. 7. Relation between line-averaged liquid holdup and the radial distance from the pipe wall.



GVF=95.77%
GVF=96.29%
GVF=97.32%
GVF=97.82%
GVF=98.14%
GVF=99.34%

Fig. 8. Schematic of the gas-liquid interface obtained multiple gamma ray measurements at various gas volume fraction (GVF).

Table 7
Diameter ratios for the various gas volume fractions.

Gas volume fraction (%)	95.77	96.29	97.32	97.82	98.14	99.34
Diameter ratio	0.945	0.950	0.965	0.970	0.971	0.993

Note: the diameter ratio is defined as the ratio of the fitting-circle diameter to the pipe inner diameter.

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\alpha_{\mathrm{line,predicted}}(i)-\alpha_{\mathrm{line,reference}}(i)}{\alpha_{\mathrm{line,reference}}(i)}\right)^2} \tag{15}$$

where N is the total number of the test data points, $\alpha_{\mathrm{line,prediction}}$ is the line-averaged void fraction predicted by the model, and $\alpha_{\mathrm{line,reference}}$ is the value measured by the gamma ray attenuation system. Among these models, Chisholm model [13] gives the best results for most cases, so it is chosen to predict the slip ratio for the equal-diameter double-circle model.

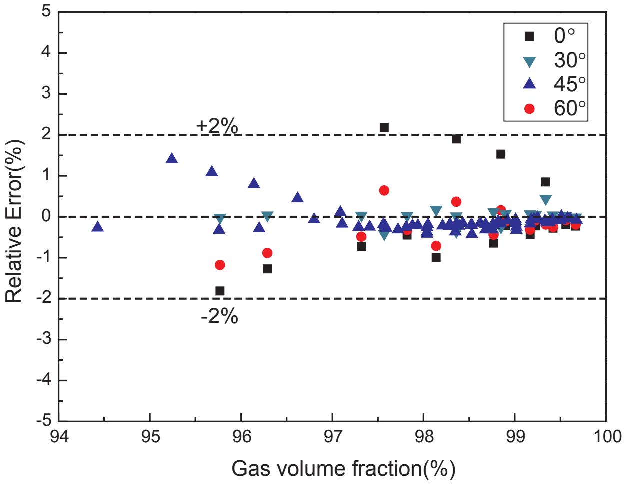


Fig. 9. Relative errors in the predicted gas volume fractions at different angles.

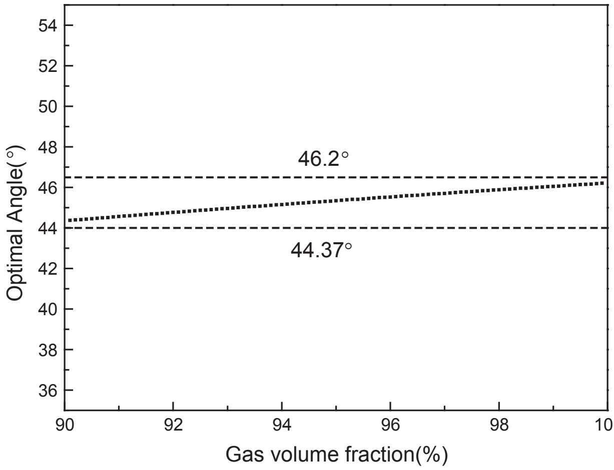


Fig. 10. Optimal measurement angles predicted by the equal diameter double circle model.

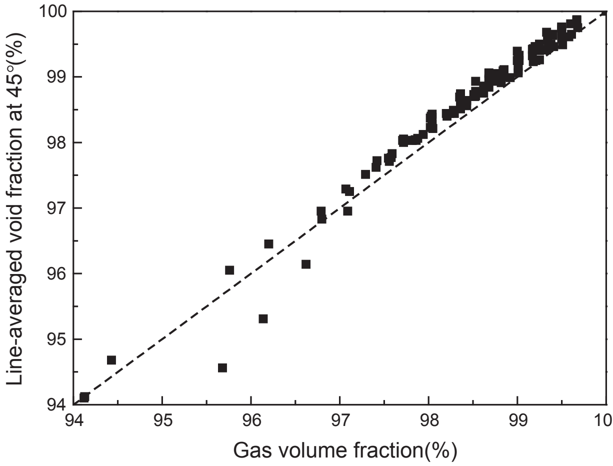


Fig. 11. Comparison of the measured line-averaged void fractions at 45° with the actual gas volume fractions.

5. Model validation

This section verifies the double-circle equal-diameter assumption and slip ratio correlation against the experimental data. The model is then used to find the optimal measuring angle.

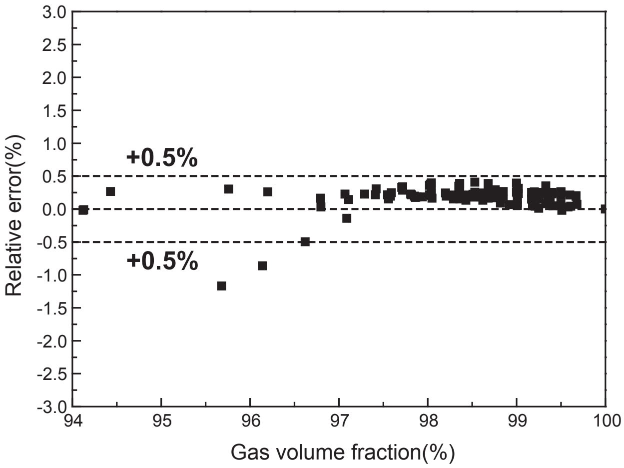


Fig. 12. Relative errors between the measured line-averaged void fractions at 45° and the actual gas volume fractions.

5.1. Verification of equal-diameter assumption

The line-averaged liquid holdup was measured by the gamma ray attenuation system for various gas volume fractions at various angles. The gas-liquid interface was then identified by converting the line-averaged liquid holdup into the radial distance from the pipe wall, Δd, as shown in Fig. 7:

$$\Delta d(\theta) = \varepsilon_{L,\text{line}}(\theta)d \tag{16}$$

where d is the pipe diameter and $\varepsilon_{L,\text{line}}(\theta)$ is the line-averaged liquid holdup at θ.

The dots in Fig. 8 represent the converted Δd at 0°, 30°, 45°, 60°, and 90°, which refer to the line-averaged liquid holdups at each angle correspondingly. These points are then fitted to a circle to determine the gas-liquid interface marked by the dotted line in Fig. 8.

Table 7 lists the diameter ratios for each gas volume fraction. The diameter ratio is defined here as the ratio of the fitting-circle diameter to the pipe inner diameter. The results indicate that for gas volume fractions more than 95%, the fitting-circle diameter is almost equal to the pipe inner diameter. Thus, for high-pressure wet gas flows, the gas-liquid interface could be modeled as a portion of an eccentric circle with the same diameter as the inner pipe diameter. In all cases, the differences were less than 5.5%.

5.2. Verification of the slip ratio based equal-diameter double-circle model

The slip ratio based model was verified for high-pressure wet gas flows using the algorithm as follows: First, the actual gas volume fraction was determined from the separate gas and liquid single-phase flow rate measurements. Then, the slip ratio based model was used to calculate the line-averaged void fraction at various angles. Finally, the predicted line-averaged void fractions were compared with the actual results measured by the gamma ray attenuation system. The line-averaged void fractions measured by the gamma ray attenuation system depend on the measurement angle including 0°, 30°, 45°, and 60°.

Fig. 9 shows the relative errors between the model predictions and the measurements. The relative errors are almost all within $\pm 2\%$. Furthermore, the relative errors at 30° and 45° are all within $\pm 1\%$. Thus, the slip ratio based model can accurately predict the line-averaged void fraction and describe the gas-liquid interface for high-pressure wet gas conditions.

5.3. Prediction of the optimal measuring angle based on the equal-diameter double-circle model

The gas volume fraction is one of the key parameters for wet gas flow metering. Industries commonly use the gamma ray attenuation technique to measure the void fraction and the gas volume fraction. Generally speaking, the costs and the limitations of the gamma ray collimation result in only 1 or 2 gamma ray detectors used in industrial applications, so the line-averaged void fractions are only measured at 1 or 2 angles. However, the measured line-averaged void fraction may not be equal to the actual gas volume fraction.

When the wet gas flows through a horizontal pipe, the liquid film thickness over a cross section is not uniform. The angle at which the measurement result is closest to the gas volume fraction for the given working conditions is defined here as the optimal measurement angle. The measured line-averaged void fraction at this angle is then theoretically equal to the actual gas volume fraction within small relative error range.

As shown in Section 5.2, the slip ratio based model can accurately describe the gas-liquid interface. This model can also be used to predict the optimal measurement angle to tell the best installation position and measurement angle for the gamma ray attenuation system. The results in Fig. 10 show that for gas volume fractions between 90% and 99.9%, the predicted optimal angle varies from 44.37° to 46.2°, which are all close to 45°. Thus, for engineering convenience, the measurement angle can be set at 45° with the measured line-averaged void fraction being very close to the gas volume fraction for the present experimental conditions.

The gas volume fractions measured by the gamma ray attenuation system at 45° are compared with the actual gas volume fractions in Fig. 11.

Fig. 12 shows the relative errors between the line-averaged void fractions at 45° measured by the gamma ray attenuation system and the actual gas volume fractions. For gas volume fractions greater than 95%, the measured line-averaged void fractions at 45° are in good agreement with the actual gas volume fractions with relative errors within ± 1.2%. The average relative error is about 0.2% and the RMSE is 0.0026. In addition, for gas volume fractions greater than 96.5%, the relative error is within ± 0.5%.

The experimental data points are the averages of 10-min duration for each measurement. The duration is so long as to neglect the influence of flow fluctuation. The results show that the model can be applied to industrial wet gas flow measurements.

6. Conclusion

A slip ratio based equal-diameter double-circle model has been developed for high-pressure wet gas flow measurements. A series of gas-liquid two-phase flow measurements are used to validate the model. The following conclusions can be made.

(1) The slip ratio based model can accurately predict the line-averaged void fraction with relative errors within ± 2%, so the model can accurately predict the gas-liquid interface for high-pressure wet gas flows.
(2) By comparing of the five existing slip ratio models, Chisholm model [13] is proven to give the best predictions for the current working conditions. Thus, this model is used to predict the slip ratio.
(3) The slip ratio based model can be used to predict the optimal measurement angle for the gamma ray attenuation measurement system. The calculation shows that the line-averaged void fractions along 45° are closest to the actual gas volume fractions for the current working conditions. Further experiments show that the measured line-averaged void fractions at 45° match with the actual volume fractions with relative errors within ± 1.2%, an average relative error of about ± 0.2% and an RMSE of 0.0026. For gas volume fractions greater than 96.5%, the relative errors are within ± 0.5%.

Acknowledgements

We appreciate the support provided by National Engineering Laboratory, UK, in the supply of equipment for these experiments. This work was financially supported by the high-tech ship research project, subordinate to the Ministry of industry information technology: the development of the underwater two-phase wet gas flow device, with the project approval number: [2014] 497.

References

[1] International Organization for Standards, Measurement of Wet Gas Flow by Means of Pressure Differential Devices Inserted in Circular Cross-section Conduits, ISO, 2012.
[2] D. He, B. Bai, Y. Xu, X. Li, A new model for the V-Cone meter in low pressure wet gas metering, Meas. Sci. Technol. 23 (12) (2012) 125305.
[3] C. Wang, N. Zhao, L. Fang, T. Zhang, Y. Feng, Void fraction measurement using NIR technology for horizontal wet-gas annular flow, Exp. Therm. Fluid Sci. 76 (2016) 98–108.
[4] S. Huang, B. Zhang, J. Lu, D. Wang, Study on flow pattern maps in hilly-terrain air–water–oil three-phase flows, Exp. Therm. Fluid Sci. 47 (2013) 158–171.
[5] M.A. Woldesemayata, A.J. Ghajar, Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes, Int. J. Multiph. Flow 33 (4) (2007) 347–370.
[6] R. Thorn, G.A. Johansen, E.A. Hammer, Recent developments in three-phase flow measurement, Meas. Sci. Technol. 8 (7) (1997) 691–701.
[7] S.F. Huang, Parameter Measurements and Tomography in Two-Phase Flows by Wire-Mesh Capacitance Probes, PhD Thesis Xi'an Jiaotong University, 2008, p. 2 (in Chinese).
[8] D. He, B. Bai, J. Zhang, et al., Online measurement of gas and liquid flow rate in wet gas through one V-Cone throttle device, Exp. Therm. Fluid Sci. 75 (2016) 129–136.
[9] P.J. Hamersma, J. Hart, A pressure drop correlation for gas/liquid pipe flow with a small liquid holdup, Chem. Eng. Sci. 42 (5) (1987) 1187–1196.
[10] J. Hart, P.J. Hamersma, J.M.H. Fortuin, Correlations predicting frictional pressure drop and liquid holdup during horizontal gas-liquid pipe flow with a small liquid holdup, Int. J. Multiph. Flow 15 (6) (1989) 947–964.
[11] M.A. Rahman, A. Amirfazli, T. Heidrick, B.A. Fleck, A review on advanced two-phase gas/liquid flow measurement techniques, in: Proceedings of the International Conference on Mechanical Engineering 2007 (ICME2007), 29–31 December 2007, Dhaka, Bangladesh.
[12] R.W. Lockhart, R.C. Martinelli, Proposed correlation of data for isothermal two-phase, two-component flow in pipes, Chem. Eng. Prog. 45 (1949) 39–48.
[13] D. Chisholm, Two-phase flow in heat exchangers and pipelines, Heat Transfer Eng. 6 (2) (1985) 48–57.
[14] Z.H. Lin, S.Z. Wang, D. Wang, Gas-liquid Two-phase Flow and Boiling Heat Transfer, Xian Jiaotong University Press, Xi'an, 2003, pp. 106–131 (in Chinese).
[15] Z.H. Jia, X.S. Cai, Investigation of the oil-gas-water multiphase flow rate model with high void fraction, J. Eng. Thermophys. 31 (5) (2010) 789–792 (in Chinese).
[16] J.M. Quibén, Experimental and analytical study of two-phase pressure drops during evaporation in horizontal tubes, PhD Thesis Pierre and Marie Curie University, 2005.
[17] M.P. Dudukovic, J. Chaouki, F. Larachi, Non-Invasive Monitoring of Multiphase Flows, 1997.
[18] G.A. Hughmark, B.S. Pressburg, Holdup and pressure drop with gas-liquid flow in a vertical pipe, AICHE J. 7 (4) (1961) 677–682.
[19] A.E. Dukler, M.W. Iii, R.G. Cleveland, Frictional pressure drop in two-phase flow: a comparison of existing correlations for pressure loss and holdup, AICHE J. 10 (1) (1964) 38–43.
[20] D. Butterworth, A comparison of some void-fraction relationships for co-current gas-liquid flow, Int. J. Multiph. Flow 1 (6) (1975) 845–850.
[21] H.Q. Zhang, Q. Wang, C. Sarica, et al., Unified model for gas-liquid pipe flow via slug dynamics: part 1—model development, J. Energy Res. Technol. 125 (4) (2003) 811–820.
[22] Y. Fan, An Investigation of Low Liquid Loading Gas-liquid Stratified Flow in Near-horizontal Pipes, The University of Tulsa, 2005, p. 3.
[23] Z. Zhou, Studies on the Models for the Low-liquid-loading Gas-oil-water Three Phase Flow in Near-horizontal Pipes, Master's Thesis China University of Petroleum (East China), 2011, p. 5 (in Chinese).
[24] Y.P. Liu, Study on the Flow Regime Transition in Horizontal Gas-oil Flow and the Characteristics of Gas-liquid Interface, PhD Thesis Shanghai Jiao Tong University, 2008, p. 15 (in Chinese).
[25] N. Brauner, J. Rovinsky, D.M. Maron, Determination of the interface curvature in stratified two-phase systems by energy considerations, Int. J. Multiph. Flow 22 (6) (1996) 1167–1185.
[26] Y. Taitel, A.E. Dukler, A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow, AICHE J. 22 (1) (1976) 47–55.
[27] X.T. Chen, X.D. Cal, J.P. Brill, Gas-liquid stratified-wavy flow in horizontal pipelines, J. Energy Res. Technol. 119 (4) (1997) 209–216.

[28] E. Grolman, J.M.H. Fortuin, Gas-liquid flow in slightly inclined pipes, Chem. Eng. Sci. 52 (24) (1997) 4461–4471.
[29] H. Dong, H.Q. Zhang, C. Sarica, An experimental study of low liquid loading gas-oil-water flow in horizontal pipes, Proc. Hum. Fact. Ergon. Soc. Ann. Meet. 25 (149) (2009) 193–197.
[30] S. Cadalen, M. Lance, A mechanics approach for wet gas flow metering, theory and application to flow loop tests, Int. J. Multiph. Flow 37 (3) (2011) 260–267.
[31] A. Banafi, M.R. Talaei, M.J. Ghafoori, A comprehensive comparison of the performance of several popular models to predict pressure drop in stratified gas–liquid flow with low liquid loading, J. Nat. Gas Sci. Eng. 21 (21) (2014) 433–441.
[32] E. Nazemi, S.A.H. Feghhi, G.H. Roshani, R.G. Peyvandi, S. Setayeshi, Precise void fraction measurement in two-phase flows independent of the flow regime using gamma-ray attenuation, Nucl. Eng. Technol. 48 (1) (2016) 64–71.
[33] Z.B. Li, Y.X. Wu, D.H. Li, Gamma-ray attenuation technique for measuring void fraction in horizontal gas-liquid two-phase flow, Nucl. Sci. Tech. 18 (2) (2007) 73–76.
[34] C. Wang, N. Zhao, L. Fang, et al., Void fraction measurement using NIR technology for horizontal wet-gas annular flow, Exp. Therm. Fluid Sci. 76 (2016) 98–108.
[35] M.S.A. Abouelwafa, E.J.M. Kendall, The measurement of component ratios in multiphase systems using alpha-ray attenuation, J. Phys. E: Sci. Instrum. 13 (3) (1980) 341.
[36] E. Åbro, G.A. Johansen, Improved void fraction determination by means of multibeam gamma-ray attenuation measurements, Flow Meas. Instrum. 10 (2) (1999) 99–108.
[37] A. Tesi, Multiphase Flow Measurement Using Gamma-based Techniques, PhD Thesis Cranfield University, 2011.
[38] R. Hanus, Application of the Hilbert Transform to measurements of liquid–gas flow using gamma ray densitometry, Int. J. Multiph. Flow 2015 (72) (2015) 210–217.
[39] E. Nazemi, S.A.H. Feghhi, G.H. Roshani, et al., Precise void fraction measurement in two-phase flows independent of the flow regime using gamma-ray attenuation, Nucl. Eng. Technol. 48 (1) (2016) 64–71.
[40] S.V. Paras, N.A. Vlachos, A.J. Karabelas, Liquid layer characteristics in stratified—atomization flow, Int. J. Multiph. Flow 20 (5) (1994) 939–956.
[41] F.S. Silva, P. Andreussi, P.D. Marco, Total mass flowrate measurement in multiphase flow by means of a Venturi meter, V International Conference on Multiphase Production, Cannes June 19–21, 1991.
[42] International Organization for Standards: Measurement of Fluid Flow by Means of Pressure Differential Devices Inserted in Circular cross-section Conduits Running Full, Part 4: Venturi Tubes, ISO 5169-4-2003.