Experimental Thermal and Fluid Science 79 (2016) 213–221

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Application of multi-slot sampling method for gas-liquid two-phase flow rate measurement

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A R T I C L E I N F O

Article history:
Received 25 February 2016
Received in revised form 16 May 2016
Accepted 9 July 2016
Available online 11 July 2016

Keywords:
Two-phase flow
Flow rate metering
Sample
Flow pattern

A B S T R A C T

A novel approach to measure the individual mass flow rates of gas-liquid two-phase flow was proposed. Gas-liquid two-phase flow was divided into eighteen equal parts by a specially designed sampler and three parts were applied as sample fluid. The total gas and liquid flow rates are determined according to the flow rates of sampled fluid and the extraction ratio. The correlation of extraction ratio is deduced from the relation of resistance between the main loop and the division loop. Experiments were carried out in an air-water two-phase flow loop and the gas quality ranged from 0.008 to 0.66. The observed flow pattern included stratified smooth, stratified wavy, annular and slug flows. It was found that the gas and liquid extraction ratios are very close to the theoretical value (0.167) and independent of inlet flow pattern, gas and liquid velocities. The error of gas and liquid mass flow rates measurements was less than ±5.0%.

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1. Introduction

Accurate measurement of individual flow rate of multiphase mixture is of great importance in various modern engineering fields, such as nuclear, petroleum industry, chemical engineering processes and advanced heat transfer systems [1]. During the past several decades, significant efforts have been made to develop reliable flow rate measurement techniques and instruments. Millington [2], Falcone et al. [3] and Thorn et al. [4] reviewed the multiphase flow metering methods. In general, multiphase flow rate measurement instruments can be classified into two major categories: on-line and separation multiphase flow meter.

On-line multiphase flow meter measures the gas and liquid flow rates independently and simultaneously. One of the on-line multiphase flow meter is Coriolis mass flow meter, which can measure both mass flow rate and fluid density. Previous study showed that Coriolis flow meter has been successfully applied in oil-water two-phase flow metering [5]. However, experimental study also showed that great measurement error or even complete failure would occur under high gas fraction conditions [5,6].

The second idea of on-line multiphase flow meter is to measure the gas and liquid velocities coupled with the measurement of phase fraction [2]. The gas and liquid velocities are often determined by taking cross-correlation of two adjacent signals. The widely used phase fraction measurement techniques are gamma energy absorption, capacitance (or conductivity) method and tomography method. Hoffmann reported the measurement of phase distribution in high pressure three-phase flow using gamma densitometry [7]. Costigan and Whalley designed a conductivity probe to measure the void fraction of air-water two-phase flow [8]. Bieberle measured the void fraction using gamma-ray computed tomography [9]. Xu et al. [10] obtained the distribution of bubbles in liquid using transmission-mode ultrasound computerized tomography (UCT). Dong et al. [11] proposed a dual-plane Electrical Resistance Tomography (ERT) system for gas–liquid flows in vertical upward pipe. The void fraction was measured by ERT sensors and the velocity of each phase was determined by taking cross-correlation of void fraction signals. Warsito and Fan [12] and Huang et al. [13] measured the void fraction using Electrical Capacitance Tomography (ECT). Unfortunately, ERT and ECT often require the pipe wall to be insulator, which limits their application in metal pipe. Recently, the wire mesh tomography technology has been proposed for gas-liquid two-phase flow rate measurement. The wire mesh sensor consists of two perpendicular arrays of electrodes that form a grid of conductivity-sensing nodes, which allows the measurement of gas–liquid distribution in the cross-sectional area of the pipe without reconstruction calculation [14,15]. Nuclear Magnetic Resonance (NMR) and Pulsed Neutron Activation (PNA) technologies have also been reported to measure phase fraction and velocities directly [16,17]. However, both NMR and PNA are technically complicated and expensive.

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http://dx.doi.org/10.1016/j.expthermflusci.2016.07.014
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Nomenclature

A	pipe cross sectional area
C	discharge coefficient
Err	measurement error
K	extraction ratio
M	mass flow rates of two phase flow
N	number of slot
ΔP	pressure loss
U_{SL}	superficial liquid velocity
U_{SG}	superficial gas velocity
X	gas quality

Greek symbols

ρ	density
β	diameter ratio
ψ	thermal correction factor
θ	modification factor

Subscripts

1	inlet pipe
2	main fluid loop
3	sample fluid loop
G	gas
L	liquid

The direct measurement of velocity or phase fraction of each phase in two-phase flow is rather complicated and uneconomical. Since the flow rate and phase fraction can be indirectly obtained by two different flow meters, quite a number of combination methods have been proposed in recently years. Sun utilized a combination of a venturi tube and a vortex flowmeter to meter gas–liquid bubbly flow [18]. Oliveira et al. reported a gas-liquid two-phase flow metering system by a resistive void fraction meter coupled to a venturi or orifice plate [19]. However, Falcone et al. found that this combination multiphase metering method would lead to multiplication of the measurement uncertainty, and limit the achievable accuracy [3]. Wang et al. also pointed out that these combined methods mentioned above can work well within their corresponding metering ranges, however, the measurement error would increase rapidly and the instruments may even fail to work once beyond their narrow ranges of application [20].

Virtual metering is a non-conventional option of multiphase flow measurement, which is characterized by no velocity or void fraction measurement sensor applied. The flow rate of gas-liquid is estimated using pattern-recognition or statistical signal processing of time-variant signal of the existing sensors in the multiphase flow pipeline. In another word, the flow rate of the gas-liquid mixture is inferred by predictive models instead of velocity or void fraction measurement sensor [21,22]. Imperial College developed a virtual flow meter named EMMER for two-phase flow metering [23]. A set of features, which are uniquely related to water and gas flow rate, are extracted from absolute and differential pressure signals. The accuracy of virtual flow meter depends on how realistic the model is. Unfortunately, the model is difficult to develop due to the complexity of two-phase flow.

For on-line multiphase flow metering method, the measurement sensor is directly applied under two-phase flow condition. The measurement accuracy is usually affected by the flow pattern and fluctuation of the gas-liquid interface. In addition, some of the on-line multiphase flow meters are very sensitive to the fluid properties, which may require sophisticated calibration.

Separation multiphase flow meter is characterized by performing a complete separation of the multiphase stream, followed by metering of each phase separately, using corresponding single-phase flow meters [24]. One example is Gas-Liquid Cylindrical Cyclone (GLCC), which has been studied widely in recent years [25]. The advantage of the separation type method is that the two phase metering process is simplified into single phase metering process and the measurement accuracy only depends on the separation efficiency. Although this method is considered to be accurate and reliable, it requires expensive and bulky separation equipment which significantly limits its usability [26].

Flow division and separation multiphase flow meter is a novel instrument of two-phase flow measurement [27]. As shown in Fig. 1, a small fraction of the total multiphase fluid flow is withdrawn from the main stream by a sampler. Then the extracted gas-liquid mixture is separated by a small separator. Then, single phase flow meters are employed to measure the flow rate of the separated gas and liquid respectively. After metering, the extracted fluids mix and return to the main stream. The total mass flow rate of gas (M_{1G}) and the total mass flow rate of liquid (M_{1L}) are determined by using the following equations:

$$M_{1G} = \frac{M_{3G}}{K_G} \tag{1}$$

$$M_{1L} = \frac{M_{3L}}{K_L} \tag{2}$$

where M_{3G} and M_{3L} are the extracted gas and liquid mass flow rates respectively; while K_G and K_L are the gas and liquid extraction ratios respectively.

Since only a small portion of the total flow is sampled, separated and metered, the size of separator can be greatly reduced compared with traditional complete separation type method, in which all of the two-phase mixture is fully separated. Besides, as the metering processes are conducted under single phase environment, the flow rate of each phase can be measured in an easy and extremely precise way by single phase flow meter.

In order to measure the total gas and liquid flow rates accurately, it is crucial to ensure that the bypassed sample flow is representative of the main multiphase flow. For an ideal sampler, K_G and K_L should be identical and remain relatively stable over a wide range. K_G and K_L are determined by the sampler. In the last several years, some special samplers have been developed, which are listed in Table 1.

Andreussi [28] proposed a sample system in which the two-phase mixture was mixed by a nozzle before the sample fluid was drawn through three probes fixed in the flow channel. Wang and Lin [29] invented a rotational drum type sampler from which about 20% of the two-phase mixture was drawn from the main stream. Later, Wang et al. [20] proposed a wheel type sampler to switch the total flow to the sample loop periodically and the extraction ratio was as small as 5%. However, neither the rotation drum sampler nor the wheel type sampler is easy to fabricate. In addition, the rotation drum and wheel will keep rotating during working, which reduces their reliability and increases maintenance cost if they are used in harsh environment. Liang et al. [30] reported a swirling type distributor for gas-liquid two-phase flow metering. The sample fluid was extracted from eight holes placed

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