Flow Measurement and Instrumentation 49 (2016) 18–30

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

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

Void fraction measurement in steam–water two-phase flow using the gamma ray attenuation under high pressure and high temperature evaporating conditions

Yu Zhao [a,*], Qincheng Bi [b], Yuejin Yuan [a], Haicai Lv [b]

[a] The school of Mechanical and Electrical Engineering, Shaanxi University of Science and Technology, 6 Xuefu Road, Weiyang District, Xi'an, Shaanxi 710021, China

[b] State Key Lab. of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, No. 28 Xianning West Road, Xi'an 710019, China

ARTICLE INFO

Article history:
Received 9 September 2015
Received in revised form
13 February 2016
Accepted 9 March 2016
Available online 17 March 2016

Keywords:
Gamma ray attenuation
Void fraction
Steam–water two-phase flow
Evaporating flow condition

ABSTRACT

The void fraction is one of the most important parameters used to characterize gas–liquid two-phase flow, and a myriad of researchers have investigated it under the adiabatic flow conditions. The gamma ray attenuation is a frequently used non-intrusive method for measuring component volume fraction in gas–liquid two-phase flow system. In this paper, firstly, the influence of the various parameters and test conditions on the gamma ray attenuation have been completely examined, such as the calibration of Count Rate for pure gas and liquid phases, the influences of fluid temperature, phase changing point and fluid mass velocity, distance between gamma ray attenuation measuring instrument and experimental section etc. Secondly, the measurement of void fraction was taken in the vertically upward pipes under high pressure and high temperature evaporating conditions. The experimental results of void fraction were compared with the data in reference literature for measurement, the results from the gamma ray attenuation show good agreement with the literature for air–water two-phase flows, but for the evaporating conditions, a small number of compared data beyond the statistical approach for 90% of confidence interval due to some reasons, such as heat flux, the diameter of Taylor-bubbles, longitude of slugs etc. Finally, six predicted correlations from four groups were selected for comparing with the experimental data. The most of compared data were within the statistical approach for 85% of confidence interval. In general, the void fraction was rarely investigated and the available data was limited under high temperature and high pressure evaporating conditions. The investigations of present study are helpful to resolve the difficulties of measuring for gas–liquid two-phase flows concerning to the heated evaporating condition.

1. Introduction

It is well known that gas–liquid two-phase flow is frequently encountered in a lot of industrial applications, such as boilers, core and steam generators in nuclear reactors, petroleum transportation, electronic cooling and various types of chemical reactors [1]. The cross sectional void fraction α (simply referred to as the void fraction in what follows) is one of the most important parameters used to characterize gas–liquid two-phase flow [2], which represents the fraction of the flow channel cross sectional area occupied by the gas phase. As well, the variational range of void fraction is from 0 to 1. The numeric 0 means the single-phase liquid flow in pipe, and the numeric 1 means the single-phase gas flow in pipe. Void fraction is an also key physical parameter for determining other numerous key two-phase parameters on account of as an input data, including the two-phase flow density, the two-phase flow viscosity and the average velocities of the two phases [3]. Moreover, the void fraction plays an important role in the modeling of two-phase flow regime transitions, heat transfer and pressure drop. The knowledge of the void fraction is also crucial in many thermal-hydraulic simulations, such as coupled neutronics-thermal hydraulic calculations and two-phase natural circulation loop flow rates and heat transport rates predictions [4].

Traditional techniques to measure the void fraction are the volumetric, electrical, optical, ultrasonic and radiation methods. In these methods, radiation method is widely utilized and developed in many applications comparing with other techniques as a result of the reliable and non-intrusive. For example, the volumetric and optical measurement methods are usually utilized, however, because of the influences of fluid pressure and temperature, these

* Corresponding author.
E-mail address: yuzhao4827@163.com (Y. Zhao).

http://dx.doi.org/10.1016/j.flowmeasinst.2016.03.002
0955-5986/

Nomenclature

A	pipe cross-section area (m^2)
D	diameter of pipe (m)
E	photon energy of gamma source (J)
G	mass velocity ($kg \cdot m^{-2} \cdot s^{-1}$)
q	heat flux ($kW \cdot m^{-2}$)
I	gamma photon count (s^{-1})
I_0	original incident energy of gamma source (s^{-1})
I_a	gamma photon counts for superheated steam flowing in pipe (s^{-1})
I_w	gamma photon counts for subcooled water flowing in pipe (s^{-1})
x	quality or dryness
CR	Count Rate

Greek letters

α	void fraction
β	volumetric flow fraction
μ	material energy absorption coefficient
ρ_G	density of gas phase ($kg \cdot m^{-3}$)
ρ_L	density of liquid phase ($kg \cdot m^{-3}$)

Subscripts

SCA	single-channel analysis
MCA	mluti-channel analysis

two methods can not be used directly. And two problems of electrical methods are always occurred in the process of measuring. One problem is accuracy of measurement would be reduced on account of fluid temperature, the other is to disturb the flow pattern, especially influencing on annual flow. For these reasons, the gamma ray attenuation would be selected to investigate the void fraction under high pressure and high temperature conditions. The radiation attenuation techniques include neutron, X-ray and gamma-ray methods serve as the basis of on-line measurement. By comparing with other measurement methods, the gamma ray attenuation method has some advantages, such as the higher penetration. The higher penetration capabilities of gamma densitometer in comparison to neutron beams make it deal system for measuring the phase fractions in large industrial systems [5]. In addition, it is less expensive compared with the neutron densitometry. The gamma-ray attenuation systems produce mono-energetic rays without intensity fluctuations contrary to X-ray attenuation techniques [6]. The gamma ray attenuation method is a non-intrusive technique that does not disturb the flow under investigation. The technique has been utilized widely in a variety of multiphase flow in energy power and nuclear energy. Chan and Banerjee [7] suggest a design procedure for a single-beam gamma densitometer and designed two densitometers for refilling and rewetting experiments and flow boiling experiments, which are both transient experiments. Good average void fraction measurements are obtained for relatively fast transients. Jiang and Rezkallah [8] perform an experimental study of the suitability of using a gamma densitometer for void fraction measurements in a gas–liquid flow in a small diameter tube. Finding the performance of the gamma densitometer is good during adiabatic upward and downward two-phase flows. Chu and Song [9] apply the gamma ray attenuation technique to measure the void fraction of a steam–water mixture flowing downward in a down-comer annulus in a direct vessel-injection experiment.

For the design of gamma densitometry, Chaouki et al. [5] have written a comprehensive summary of the existing gamma densitometry methods. In general, the basic design of a gamma-ray attenuation measuring instrument contains a radioactive source, detector and signal processing system. The “heart” of the instrument is the radioactive source providing gamma radiation at a constant intensity. The radioactive gamma ray passes the experimental fluid to the detector, then into the signal processing system for the optical signal is converted into electrical signal. The energy attenuation of radioactive source by a set narrow rays is the function of the gamma radioactive source photon's energy and the density of the absorbing material [10]. With the development of on-line measurement technology in gas–liquid two-phase flow, it is can be calibrated to measure the component fractions in the volume covered by the gamma rays. According to the previous relevant research [11], the changed regions of void fraction are strongly dependent on the flow regimes of gas–liquid two-phase flow. But in the actual flow, the transition of the flow regimes is always little-known or mathematically not exactly describable, the flow regime dependence is usually neglected for purpose of calculating void fraction from gamma-ray attenuation data [8,11,12]. The multi-ray or multi-source is utilized as the more accurate measurement method in order to improve the accuracy of void fraction in two-phase flow. The reason is that multi-path interrogation enables to calculate the phase fractions of two-phase flow systems without the need to characterize the flow pattern.

The research of void fraction includes two important contents, one content is the measurement and the other is prediction. The background of measurement has been discussed in the above section. For the prediction of void fraction, numerous methods have been proposed so far and several assessments of prediction methods have been published due to its importance, which includes the recent contributions by Vijayan et al. [13]., Woldesemayat and Ghajar [14] and Godbole et al. [15]. According to Vijayan et al., in particular, these available prediction methods could be classified into four groups, namely slip ratio correlations, $K\varepsilon_H$ correlations, drift flux correlations and general void fraction correlations. The first group is given by slip ratio correlations which are a general expression for this type of correlation is put forward by Butterworth [16] as a function of the ratios between wetness fraction $(1-x)$ and x the “quality” or dryness fraction, where x is defined as the ratio of gas mass flow rate to the two-phase total mass flow rate; the ratios of densities of the gas and liquid phase (ρ_G and ρ_L); and the ratios of the viscosities of the gas and liquid (μ_G and μ_L). The second group is given by $K\varepsilon_H$ models that predict the void fraction by multiplying the homogeneous model void fraction ε_H with an empirically derived correction factor K. Then, the third group is given by drift-flux correlations which are an expression which characterizes the distribution parameter C_0 and drift velocity (U_{GM}), defined as the difference between the gas phase velocity (U_G) and the two-phase mixture velocity (U_M). Finally, the fourth group is given by general void fraction correlations which are mostly in nature with the basic underlying physical principles incorporated into the different physical parameters when developing them.

From the above literatures, the measurement and prediction of void fraction are very important in gas–liquid two-phase flow, these are investigated mostly under the adiabatic conditions and the test fluids are air and water. However, for the most actual scientific conditions, most of gas–liquid two-phase flows are