Applied Thermal Engineering 60 (2013) 398–410

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Recognition and measurement in the flow pattern and void fraction of gas–liquid two-phase flow in vertical upward pipes using the gamma densitometer

Yu Zhao, Qincheng Bi*, Richa Hu

State key Lab. of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, No. 28 Xianning West Road, Xi'an 710049, China

HIGHLIGHTS

- We propose a new method to study flow patterns in vertical upward pipes.
- Visual observation of two-phase flow patterns during upward flow.
- Void fraction is calibrated with the quick-closing valve method.
- Good agreement with experimental results and predicted model.

ARTICLE INFO

Article history:
Received 5 June 2013
Accepted 4 July 2013
Available online 22 July 2013

Keywords:
Two-phase flow
Vertical upward flow
Flow pattern recognition
Void fraction measurement
Gamma densitometer

ABSTRACT

An experiment has recently been carried out to recognize the flow pattern and to measure the void fraction of gas–liquid two-phase flow in vertical upward pipes at Xi'an Jiaotong University (XJTU). The test fluid in this experiment is the air and water. The experimental system includes a closed water loop, an open air loop, inlet and outlet header, vertical upward parallel pipes, a high speed camera system and a gamma densitometer system. The inlet header, outlet header and vertical upward pipes are made of transparent glass and acrylic fabric, and the purpose is for bubbly flow, slug flow and annular flow patterns visualization. In this present study, firstly, the flow patterns of the two-phase flow are identified by the high speed camera system and gamma densitometer system. Secondly, the void fraction of the two-phase flow is measured by the gamma densitometer, and the results are compared with the quick-closing valve measurement. Thirdly, the variations of the flow patterns with the void fraction are also discussed in the present study. Finally, the experimental results in present study are compared with some calculated (predicted) correlations.

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]. Comparing with the single-phase flow, a lot of difficulties for measuring direct and indirect parameters accurately in gas–liquid two-phase flow are still a vital problem. In the scientific and industrial investigation process, the recognition and measurement in the flow pattern and void fraction are the most important investigations in the gas–liquid two-phase flow. Commonly the investigation methods in gas–liquid two-phase flow are intrusive and low accurate. By comparing with the conventional investigation, the gamma densitometer system is an accurate, reliable, online, continuous and non-intrusive method which means doesn't disturb the flow pattern and increase the accuracy.

Flow pattern recognition in gas–liquid two-phase flow is usually obtained by visual observation. The designation of flow pattern has not yet been accurately standardized and depends largely upon individual interpretation of visual observations, therefore a variety of classifications exist. The major difficulty of visual observation, even using high speed camera system, is that the picture is often confusing and difficult to interpret, especially when dealing with high velocity flows. In addition, there are systems which are opaque where flow visualization is impossible [2]. A large number of experimental works of gas–liquid two-phase flow has been performed, however, still not accepted by everyone in the development for the flow pattern classification. Hsu et al. [3] utilized a hot wire anemometry technique for measuring void distribution for

* Corresponding author. Tel.: +86 29 8266 5287; fax: +86 29 8266 9033.
E-mail addresses: qcbi@mail.xjtu.edu.cn, qcbi@sohu.com (Q. Bi).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.07.006

Nomenclature

A	pipe cross-section area (m^2)
D	diameter of pipe (m)
E	photon energy of gamma source (J)
I	gamma photon count (s^{-1})
I_0	original incident energy of gamma source (s^{-1})
I_a	gamma photon count for an empty pipe (s^{-1})
I_w	gamma photon count for a full pipe (s^{-1})
U_{sg}	actual mean gas velocity (m s^{-1})
U_{sl}	superficial liquid velocity (m s^{-1})
U_g	gas volumetric flow rate (l s^{-1})
U_l	actual mean liquid velocity (m s^{-1})
Q_g	gas volumetric flow rate (l s^{-1})
Q_l	liquid volumetric flow rate (m^3 h^{-1})
Q_m	mixture volumetric flow rate (m^3 h^{-1})
S	slip ratio (u_g/u_l)
X	quality
CR	Count Rate

Greek letters

α	void fraction
β	volumetric flow fraction
μ	material energy absorption coefficient
ρ_g	density of gas phase (kg m^{-3})
ρ_l	density of liquid phase (kg m^{-3})

Subscripts

l	liquid phase
g	gas phase
sl	superficial liquid
sg	superficial gas
in	inlet of pipe
Out	outlet of pipe
M	mixture of two-phase
SCA	single-channel analysis
MCA	multi-channel analysis
B	bubbly flow
S	slug flow
A	annular flow

vertical flow and also used the signal output for flow pattern characterization. Jones and Delhaye [4] reviewed and summarized a variety of measuring techniques used in two-phase flow of which only few are used directly for flow pattern characterization. Jones and Zuber [5] developed an X-ray void measurement system for obtaining statistical measurements in vertical air–water two-phase flow in a rectangular channel. Dvora Barnea et al. [2] utilized an improved system conductance probes to identify the flow patterns in two-phase horizontal, near horizontal and upward flows. César Marques Salgado et al. [6] used an approach is based on gamma-ray pulse height distributions (PHDS) pattern recognition by means the artificial neural networks (ANNS). Stephen and Hoi [7] classified the multiphase mixture's flow pattern through the analysis of the probability distributions from the gamma densitometer data and self-organizing feature maps. For these investigations above mentioned, a common problem is lack of the contrast between the flow pattern visualization and the non-intrusive gamma densitometer. In this study, an improved technique which comparing the visualization with the intensity of gamma rays measurement at every flow condition is proposed. Special efforts were made to design the gamma densitometer system to detect flow pattern differences as dictated by the basic definitions of the flow patterns.

The void fraction (α) is one of the most important parameters in characterizing gas–liquid two-phase flow, and a lot of efforts to be devoted to measure it accurately. Void fraction is a key physical parameter for determining other two-phase parameters, namely, two-phase mixture density, frictional pressure drop and two-phase real velocities. In addition, void fraction plays an important role in the modeling of flow pattern transition and heat transfer. In industrial applications, for example, the boiling water reactor (BWR) uses light water as a neutron moderator and coolant, and the void fraction is significant in estimating the reactivity of the nuclear reactor. Traditional techniques to measure the void fraction are the volumetric, electrical, optical, ultrasonic and radiation methods. In these methods, radiation methods are widely utilized and developed in many applications comparing with other techniques as a result of the reliable and non-intrusive. 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 densitometer 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 [8]. 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 [9]. The gamma-ray densitometer 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. A.M.C Chan and Banerjee [10] suggested 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 were obtained for relatively fast transients. Jiang and Rezkallah [11] performed 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 [12] applied 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.

2. Experimental facility and methods

2.1. Air–water two-phase flow loop

The experiments were performed in the air–water two-phase flow facility at Xi'an Jiaotong University, China. A simplified flow principle diagram of the experimental equipment is shown in Fig. 1. The experiments were carried out to use the air and water at room temperature and atmospheric outlet pressure. The physical properties of the test fluid are shown in Table 1. The water was stored in the tank and the air was generated using the air compressor. The air–water two-phase flow system consisted of a closed water loop, an open air loop, and a data recording and an acquisition system. The closed water loop used the circulated volumetric pump to move the water into the liquid experimental line, where an electromagnetic meter was used to measure the water flow rate. The water then entered the air–water mixer. The air from the compressor flowed through a pressure regulator and a surge tank, which was used to adjust the air pressure and flow rate, and then went through a set of air filter. The air flow rate was measured and controlled by a Corilis mass