Nuclear Instruments and Methods in Physics Research A 735 (2014) 260–266

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Intercomparison of gamma ray scattering and transmission techniques for gas volume fraction measurements in two phase pipe flow

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ARTICLE INFO

Article history:
Received 25 May 2013
Received in revised form
6 September 2013
Accepted 19 September 2013
Available online 27 September 2013

Keywords:
Void fraction
Gamma-rays
Scattering
Transmission

ABSTRACT

Void fraction simulating stratified air–water flow in cylindrical tubes of different radii was measured using transmission and scattering of gamma rays. A simple experimental set-up using ^{137}Cs γ-ray point source of 10 μCi and NaI(Tl) detector was used. The void fractions determined from Compton–Compton scattering and transmission peaks were found in good agreement with the real void fractions. However, deviations were noticed between the results obtained from traditional Compton scattered gamma rays and real void fraction. It was shown that sensitivity of gamma ray scattering is better than the transmission measurements. The set-up used in the present work is simpler than those existing in literature and radiation safety and shielding requirements are minimized.

1. Introduction

Gas volume fraction (GVF), simply void fraction is an important parameter in describing gas–liquid two-phase flows, since it is required to predict e.g., pressure drop, heat transfer or the occurrence of critical two-phase flow. A quantitative knowledge of such effects is needed for example in oil industry and to design industrial reactors. Several methods can be applied to measure GVF. Reviews of these measuring techniques can be found in [1–4]. The methods commonly used are based on weight, electromagnetic signals, optical signals or radiation attenuation. Radiation attenuation methods as gamma-densitometry determine the GVF of two-phase systems non-intrusively. Among the techniques based on radiation attenuation (neutron, γ and X-rays), γ-densitometry has several advantages: it is less expensive than neutron-densitometry and it offers – contrary to X-ray attenuation techniques – mono-energetic rays without intensity fluctuations.

Gamma-ray densitometers usually consist of a γ-source and a γ-ray detector. The detector is positioned to record transmitted and/or scattered γ-rays. Johnasen and Jackson [5] measured GVF in gas/oil/water pipe flows independent of salinity of water component using the so-called dual mode densitometry (DMD). The DMD is based on recording both transmitted and scattered γ-rays using two separate γ-ray detectors. The 59.6 keV line from a ^{241}Am γ-ray source (30 mCi) was used. Wide collimation for the incident γ-ray beam was used, however, narrow collimation of the detectors measuring transmission and scattering radiation were used. Tjugum et al. [6] used a compact low-energy multi-beam γ-ray densitometer for oil/water/gas pipe-flow measurement. They used ^{241}Am source (150 mCi) and three detectors, all collimated and embedded in the pipe wall. Two of the detectors measured transmitted γ-rays and the third measured scattered radiations at 90°. The tests of this system showed that an increase accuracy of the GVF measurements compared to a one-beam geometry, and that the multi-beam geometry and DMD measurements principles yielded flow-regime information and information on the salinity of water fraction. Park and Chung [7] utilized a single-beam γ-densitometer to measure the average void fraction in a small diameter stainless steel pipe under critical flow conditions. They used ^{60}Co source (30 mCi) and a single NaI(Tl) detector and the measurements were based on transmission geometry. Abro and Johansen [8] have shown that a multi-beam γ-ray densitometer with four detector can be used to determine GVF accurately and independent of the flow regime. They used the 59.6 keV line from a ^{241}Am γ-ray source of 14 mCi activity. Wide collimation for the incident γ-ray beam was used, however, narrow collimation of the detectors measuring transmission and scattering radiation were used. The void fraction in the liquid hydrogen used for the moderator of the HANARO cold neutron source was measured by using a γ-densitometer technique based on transmission [9]. They used HPGe detector and a ^{241}Am γ-ray source. Fine geometry for both source and detector was used. Kumara et al. [10]) applied a single-beam γ-densitometer to investigate oil–water flow in horizontal and slightly inclined pipes. They used ^{241}Am γ-ray source (45 mCi) and NaI(Tl) detector. Stahl and von Rohr [11] measured the GVF using a single-beam γ-densitometry based on

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0168-9002/$ - see front matter
http://dx.doi.org/10.1016/j.nima.2013.09.047

transmission. They used ^{125}I and NaI(Tl) detector. The detector was coupled to a counter for registering counts. LI Zhi-biao et al. [12]) used a dual-energy γ-ray system that was composed of radioactive isotopes of ^{241}Am and ^{137}Cs to measure GVF in oil–water–gas multiphase flow. Bruvik et al. [13]) applied γ-ray tomography for two phase flow of oil and water. They determined the average void fraction and visualized distribution of gas. Khorsandi [14] showed that γ-ray transmission is more sensitive than γ-ray scattering in determining density variation for petroleum products. A γ-scattering scanning technique for fluid–fluid and fluid–air interface level and density measurement and inter-comparison with transmission technique were reported [15]. The obtained accuracies and resolution of the level of detections and density measurements are higher in case of the γ-scattering method compared to the transmission method. Yin et al. [16] measured the liquid holdup in a large scale packed column. Boyer and Fanget [17] measured the liquid flow distribution in a large diameter trickle bed reactor. Chan and Banerjee [18] suggested a design procedure for a single-beam γ-densitometer and designed two densitometers for refilling and rewetting experiments and flow boiling experiments, which are both transient experiments. Jiang and Rezkallah [19] performed an experimental study of the suitability of using a γ-densitometer for void fraction measurements in a gas–liquid flow in a small diameter tube. Chu and Song [20] applied the γ-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.

In Compton scattering experiment, recorded γ-rays spectra are from single as well as multiple collisions. The component resulting from single collisions provides useful information about the investigated sample while that resulting from multiple collisions reduces the contrast and sensitivity of the results. The prime source of error in scattering method is multiple scattering and often it is underestimated or overlooked principally because it is a complex, highly geometry dependent problem [24].

The gamma transmission technique requires less time than scattering technique for same statistical accuracy, but not feasible when both sided access is restricted. The presence of multiple scattering is manifested in transmission measurements by a build-up factor. The transmission method is more efficient when the transmission properties of the sample differ sufficiently. But there are many situations in medicine, industry, agriculture and food processing where there is a need of differentiating materials having nearby densities and composition consisting of elements which are neighbors in periodic table. In Compton scattering experiments, some reduction in multiple scattered components can be achieved by selecting a small energy width around the Compton peak and by using a high resolution detector and proper collimation. The multiple scattering interactions depends on the thickness of the sample and hence on the number of scattering centers in the interaction volume and photon attenuation coefficient. The multiple scattering and self-absorption factors have opposite effects on scattered intensity, i.e. the multiple scattering enhances and self absorption decreases the scattered intensity [25].

To the best knowledge of the author, double Compton scattering peak shown in the scattered γ-ray spectra was not used before to determine void fraction for two phase flow in pipes. Therefore, this work aims at determining void fraction in tubes of different radii from the double Compton scattering peak and comparing these results with those obtained from scattered peaks resulting from single and multiple scattering and from transmission measurements. Moreover, and according to the surveyed method above, high activity sources – in the mCi range – are usually used in GVF measurements. In this work a simple experimental set-up geometry based on a low activity γ-ray source (~10 μCi ^{137}Cs) was used for measuring transmitted and scattered γ-rays.

2. Theoretical background

The attenuation of a γ-ray beam passing through a thin homogeneous absorbing medium of uniform thickness is given by Lambert–Beers law, as follows (Eq. (1))

$$I = I_0 e^{-\mu\rho L} \tag{1}$$

where I_0 is the intensity of the incident beam, I the intensity of emerging beam, μ the mass absorption coefficient, ρ the medium density, and L is the thickness of the absorbing medium.

When the γ-ray passes through the gas liquid mixture in a tube, its attenuation varies with difference in the gas and liquid. If the attenuation of column wall is not taken into account, the attenuation of the beam through a tube full of gas and liquid and with two-phase flow is given by the following expressions (Eqs. (2)–(4)):

$$I_l = I_0 e^{-\mu_l \rho_l L} \tag{2}$$

$$I_g = I_0 e^{-\mu_g \rho_g L} \tag{3}$$

$$I_\varepsilon = I_0 \exp(-\mu_l \rho_l (1-\varepsilon_g) L - \mu_g \rho_g \varepsilon_g L) \tag{4}$$

where I_l, and I_g and I_ε the intensities of γ-rays for the liquid, gas and void phases, respectively. Integration of Eqs. (2)–(4) yields the calculation of gas holdup (void fraction), as follows (Eq. (5)):

$$\varepsilon_g = (\ln I_\varepsilon - \ln I_l)/(\ln I_g - \ln I_l) = \ln(I_\varepsilon/I_l)/\ln(I_g/I_l) \tag{5}$$

According to Eq. (5), the void fraction can be determined experimentally from the knowledge of the transmitted γ-rays from a tube full of liquid, empty and containing both liquid and gas. In addition, the real void fraction can be calculated from the known amount of liquid inside the tube and its volume. There is no relation to determine the void fraction from scattered γ-rays.

3. Experimental details

The measurement system consists of a 10 μCi ^{137}Cs γ-source and a sodium iodide (NaI(Tl)) of 3"by 3". The output signal from the detector is coupled to a preamplifier, amplifier, and then fed to 2048 multi-channel analyzer (MCA). The preamplifier, amplifier and MCA altogether with a high voltage power supply providing the detector necessary operating voltage are contained in a single unit (USC-2000). Data acquisition and analysis are controlled by a software (USC-2000) which is installed in Pc. Fan beam geometry of the γ-ray source is used for both transmission and scattering measurements. For the transmission arrangement (Fig. 1A), the center of the source was adjusted to be in the middle of the detector which was fixed above the source and test tube. Four test tubes with internal diameters of 4.3 cm, 5.2 cm, 8.2 cm and 10.1 cm having a length of 70 cm were used in this work. The test tubes were hanged above the source and nearly touching the detector head. The detector was shielded with lead from all sides except its head. This geometry allows γ-rays emitted from the source penetrate test tubes perpendicularly. Namely, γ-rays are passing perpendicular to the liquid–air interface. The divergence of beam was enough to cover all test tubes used in this work. For scattering arrangement (Fig. 1B), the position of the detector was changed such that the center axis of the detector is perpendicular to the central axis of the tubes. Also, in this arrangement, incident γ-ray beam is perpendicular to water–air interface.

Transmitted as well as scattered γ-rays are recorded in the transmission geometry. Namely, build up was not avoided in this study. For the scattering geometry, the detector records γ-rays scattered around 90° from the tube under investigation. Both single