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Determination of void fraction in horizontal air-water two-phase flow using gamma ray attenuation technique

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ABSTRACT

Gamma ray attenuation method is widely used non-intrusively for measuring void fraction in gas–liquid two-phase flow systems. In this study, single-energy gamma rays of activity 30mCi from caesium-137 were used to measure void fraction in a horizontal air-water two-phase flow system at ambient temperature. The study was done on a test rig made of PVC pipe of diameter 2.54cm. The gamma ray counts for the static calibrations and air-water two-phase flow mixture at various water flow rates were measured using thallium-activated NaI scintillation detector and the void fraction calculated. The trend of the results obtained compared well with existing trends. When the water flow rate was varied from 6L/min to 16L/min, at a constant air flow rate, the void fraction varied from 0.141 to 0.102 respectively. The experimental results were compared with those obtained from the use of the model of Chisholm to obtain the mean deviations. The error margins were in the range of 0.3% – 4.2%.

KEYWORDS

Gamma rays;
Void fraction;
Horizontal flow.

INTRODUCTION

Two-phase flow occurs in a wide range of industrial plants. Typically, vapour and water flow together in heat transfer equipment like boilers, heat exchangers and nuclear reactor cooling systems[1]. From a practical engineering point of view, one of the major design difficulties in dealing with two-phase flow is that the mass, momentum, and energy transfer rates and processes are usually sensitive to the geometric distribution of the phase components within the flow field. A particular type of geometric distribution of the phases in a two-phase flow is called 'flow pattern' or 'flow regime'. Accurate assessment of the actual flow regimes when gas and liquid flow together in a pipe is a challenging problem in two-phase fluid dynamics. This is due to the complexity of the flow regimes as well as the rates of change of the phase geometries. Among the parameters that characterize two-phase flow, void fraction is of particular importance[2].

Void fraction

It is the ratio of the gas flow area to the total flow area. Knowledge about void fraction is required in setting safety limits of important operating parameters such as pressure drop, heat transfer coefficient and two-phase flow mixture density in some process plants including nuclear power reactors in which two-phase flow occur. Water moderated reactors, for instance, can be made inherently safer by ensuring that the core reactivity decreases with increasing void fraction and decreasing water density. A quantitative knowledge of void fraction would therefore ensure the optimization of such process plants with regards to economics and safety issues[3].

Among the techniques based on radiation application in measuring void fraction, gamma ray attenuation technique has a number of advantages. It is simple and easy to operate. It is less expensive, in terms of shielding, than neutron attenuation techniques. It also provides single-energy gamma rays without intensity fluctuations which cannot be obtained with x-ray application technique [1]. The method of application of radiation, especially beta, gamma and x-ray in void fraction measurement is more often referred to as densitometry[4, 5]. Gama densitometry has been used by many researchers including Abro and Johansen[6], Kern[7], Zhibiaoe, Yingxiang and Donghui[8], and Stahl and von Rohr[5] for measuring void fraction. In this study, gamma rays from caesium-137 and sodium iodide detector were used to measure void fraction in horizontal air-water two-phase flow system at ambient temperature as a feasibility study on the rig used in the study. The purpose is to assess whether it is possible to modify the rig into a dual-purpose facility, capable of being used, for studying void fraction in horizontal air-water two-phase flow and still maintain its current function. Currently, the test rig is used mainly as Residence Time Distribution studying facility, in the National Nuclear Research Institute of Ghana Atomic Energy Commission.

Void fraction models

Determining the phase distribution from input conditions for a given pipe in two-phase flow is complicated. Due to its complexity and inadequate understanding of the basic underlying physics of two-phase flow systems, majority of the analyses were more inclined towards empirical correlations. Many void fraction models were developed analytically or correlated under various flow conditions and phase configurations and are presented in literature. Some of those void fraction models relevant to this study were used to verify the experimental result. Notable among those that apply well to horizontal air-water two-phase flow systems at ambient temperature are those of Chisholm[9, 10], Franca et al and Zhibiaoe et al.[8]. For Chisholm;

$$\alpha_{Ch} = \frac{1}{1+\frac{\rho_G}{\rho_L}\left(\frac{1-x}{x}\right)\left[1-x(1-\frac{\rho_L}{\rho_G})\right]^{\frac{1}{2}}} \qquad (1)$$

ρ_G and ρ_L are gas and liquid phase densities respectively

The flow quality, *x*, is the ratio of mass flow rate of the gas to the total mass flow rate.

For Franca et al; $\alpha_{Fr} = \frac{u_{SG}}{0.16+0.98U}$ (2)

u_{SG} is the gas phase superficial velocity.

U is the sum of the individual phase superficial velocities.

For Zhibiaoe et al; $\alpha_{Zb} = \frac{1}{1+\left[0.2+0.98574(\frac{u_{SL}}{u_{SG}})\right]}$ (3)

u_{SL} is the liquid phase superficial velocity.

It is noted from Equations (4) to (6) that it is not possible to measure the void fraction directly. At best, the flow quality, the mean phase velocities as well as the phase densities (which depend on the void fraction itself) of the fluid must be known before the void fraction can be found. Hence experimental determination of void fraction is done by inferences made from the measurement of other quantities.

Measurement principle

Gamma ray attenuation technique for measuring void fraction employs gamma densitometer as the measuring equipment. Gamma densitometer consists of gamma source and a detector. The source is a radioisotope, which emits gamma radiations. The source is shielded with a collimator and usually has only one opening to form a narrow gamma-beam.

The attenuation of gamma rays in solids is higher than that in liquids which is also higher than that in gases. The intensity of the emanating radiation as it traverses matter is therefore a means to conclude on the phase of the matter. The measured intensity can be represented by the count rates registered by the detector since the intensity of single-energy gamma rays is directly proportional to the photon counts per unit time[4]. Attenuation of gamma rays depend upon the density, composition and thickness of the material. The attenuation of a narrow beam of single-energy gamma photons penetrating a homogeneous material of good geometry follows Lambert-Beer's exponential attenuation law[5].

$$I = I_o \exp(-\mu x) \qquad (4)$$

I_o = initial intensity of the gamma-ray incident on a target material(γ/cm^2s)

x = thickness of target material (cm)

μ = linear attenuation coefficient of target material (cm^{-1})

I = intensity of gamma ray that passes through the target material (γ/cm^2s).

When Equation (4) is applied to the situations where the pipe contains only air (I_G), only water (I_W), and the two-phase flow mixture (both water and air in the pipe) (I_{tp}), Equation (5) can be obtained which could be used to calculate the void fraction (α).

$$\alpha = \frac{\mathrm{In}\left(\frac{I_{tp}}{I_w}\right)}{\mathrm{In}\left(\frac{I_G}{I_w}\right)} \qquad (5)$$

THE EXPERIMENTAL SYSTEM

The experimental facility

The study was carried out using an experimental facility in the Radiotracer Laboratory of National Nuclear Research Institute of Ghana Atomic Energy Commission.

The experimental facility is made of polyvinylchloride pipe of internal diameter of 2.54cm. The test section was made of transparent tubing to aid visual monitoring. The loop of the rig used in the study has a total length of about 7.5m. The water flow rate through the facility was measured with a flow meter which could also regulate the flow rate from a minimum of 2L/min to a maximum of 26L/min. As the rig is primarily designed for studying Residence Time Distribution, it has no provision for air inlet

Data acquisition system

Figure 1 shows the equipment used in the data collection. The radiation detector used was thallium-activated sodium iodide scintillation detector. It is commonly used for counting transmitted gamma-rays due to its good detection efficiency[11].

Experimental procedure

Figure 2 shows the gamma source and NaI(Tl) detector mounted on the test section.

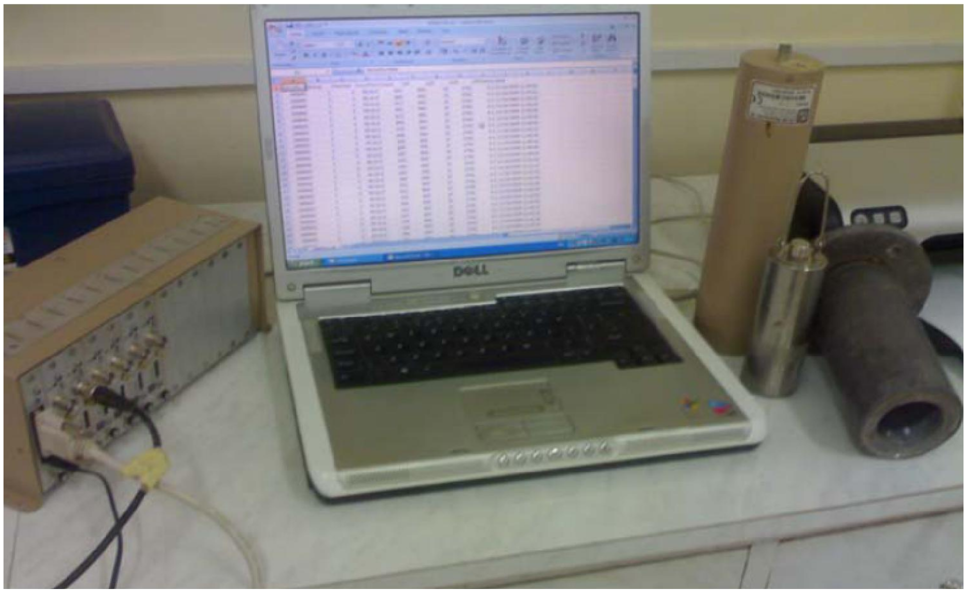

Figure 1: Equipment used for data collection

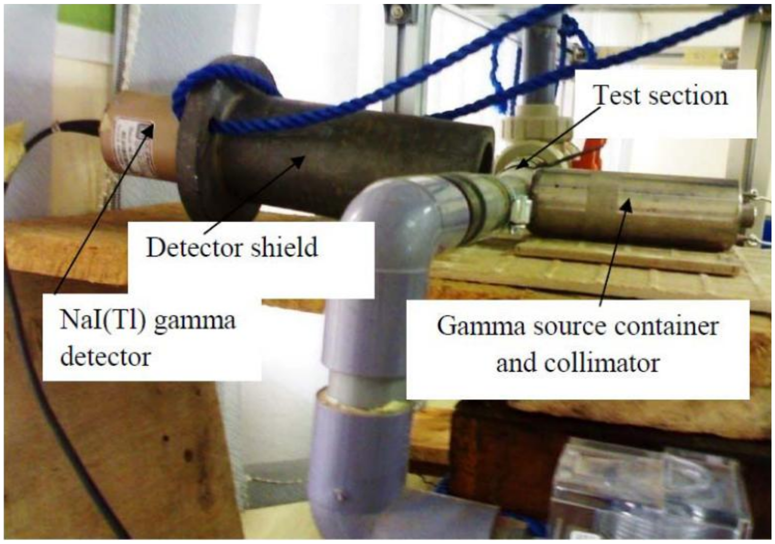

Figure 2 : Gamma source and NaI(Tl) detector mounted on the test section

The background radiation was measured before the radiation source was brought into the laboratory for taking the experimental data. The radiation source was mounted at the test section directly opposite to the detector. The power source of the pump was then turned on for the water to circulate through the test rig. The water was allowed to run for some time for it to get stabilized before the first flow rate of 6L/min was set. The data acquisition system was then operated for five minutes with recycling time of 10seconds to record the radiation counts. The same procedure was used in determining the radiation counts for the other flow rates.

Experimental void fraction

The average value for the background counts, I_B, was first calculated from the 30 data points obtained for the background counts. Similarly, the average values for the static calibration counts for air only in the pipe, I_G, and water only in the pipe, I_W, were also separately computed. The average background count was then used to make background correction for the counts obtained for each flow rate. Background corrections were also made for the static calibration counts, I_G, and I_W. The corrected counts were then used in Equation (3) to calculate 30 void fraction values (α) from the 30 data points obtained for each of the six (6) flow rates used. The average void fraction was then computed for each flow rate to obtain six (6) average void fraction values corresponding to the six (6) different flow rates used.

Theoretical (analytical or correlated) void fraction

The enabling input parameters used in evaluation of the theoretical (analytical or correlated) void fraction models are presented in TABLE 1.

The water flow rates were converted to velocities and used in the theoretical void fraction models. This was done to obtain void fraction values which could serve as reference against which the experimental void fractions could be compared in order to have a good idea of the performance of the rig being assessed. Every void fraction model relies on the flow rates or velocities of each phase as its simplest input data to compute the void fraction. However, the test facility used in this study was primarily designed for studying Resident Time Distribution and has no provision for air inlet. The amount of air that naturally circulated with the water during the experiment was therefore estimated. Some amount of air was actually collected by the pump and circulated with the water during the experiment, as is usually the case when liquid is pumped through pipe; hence air-water two-phase flow was created during the experiment. As such all the air velocities used in these void fraction models were estimated at 5%, 10%, 25% and 40% of the minimum water velocity. The amount of air that circulated with the water during the experiment was expected to be the same for each flow rate setting.

Only one value of the air velocity is required for the evaluation of the theoretical void fraction models

TABLE 1 : Input parameters

PARAMETERS		
CONSTANTS (Temperature range: 20^{o}C – 25^{o}C)		**VALUE**
Density of water (kg/m^3)		998.5
Density of air (kg/m^3)		1.2928
MEASURED	**CALCULATED**	**ESTIMATED**
Water flow rate (L/min)	Water velocity, u_{SL}(m/s)	Air velocity, u_{SG} (m/s). Estimated at 5%, 10%, 25% and 40% of 0.19733
6.0	0.19733	0.00987, 0.01973, 0.04933, 0.07893
8.0	0.26310	
10.0	0.32888	
12.0	0.39465	
14.0	0.46043	
16.0	0.52621	
Pipe diameter = 25.4mm		

but estimating one value might result in under or over estimation hence it was necessary to get at least three estimates. The best estimate used in the validation of the experimental results was determined from the graphs of experimental and theoretical void fractions that were plotted. Equations (1), (2) and (3) were used to calculate the theoretical void fractions.

RESULTS AND DISCUSSION

The graphs for the results were plotted at varying water velocities and constant air velocities as indicated on each graph. Except the curve for the experimental void fraction the others depend on the estimated air velocities. Figure 3 shows the graph for estimated air velocity of 0.00987m/s (that is 5% of the minimum water velocity).

In order to fairly assess the experimental void fraction, it was necessary to use at least two different theoretical void fraction models. Using void fraction values calculated from one theoretical model would be misleading because the void fraction models which were supposed to be “standards” do not agree well among themselves. This might be because they were derived based on different sets of assumptions. The trend depicted by the experimental void fraction in Figure 3 appears to follow those of Chisholm and Zhibiao et al more closely than that of Franca et al. However the experimental void fraction values were higher than those obtained using the theoretical models. This is an indication that the amount of air estimated and used for the models in the plot of Figure 3 might be smaller than the one which actually circulated with the water. This is because the greater the amount of air in the system the higher is the void fraction. Therefore if the estimated amount of air were close to its actual value, the theoretical void fraction curves and the experimental void fraction curve would have been closer.

It could be said from Figure 4 that the trend of the curve for the experimental void fraction relative to those for the theoretical void fraction was not different from that observed for Figure 3. However, the curves for the theoretical void fraction models gave higher void fraction values and were closer to the curve for the experimental void fraction. This is because the air velocity (and hence the amount of air) used in plotting the graph of Figure 4 was more than that used for Figure 3.

Figure 5 shows the graph for estimated air velocity at 0.04933ms^{-1} (that is at 25% of the minimum water velocity). The values of the experimental void fractions compare more favourably with those of the theoretical void fractions in Figure 5 than those of Figures 4 and 3. The curves for the theoretical void fractions are also closer to that of the experimental void fraction. This is an indication that the value of the air velocity used for computing the theoretical void fractions was close to that which circulated with the water during the experiment.

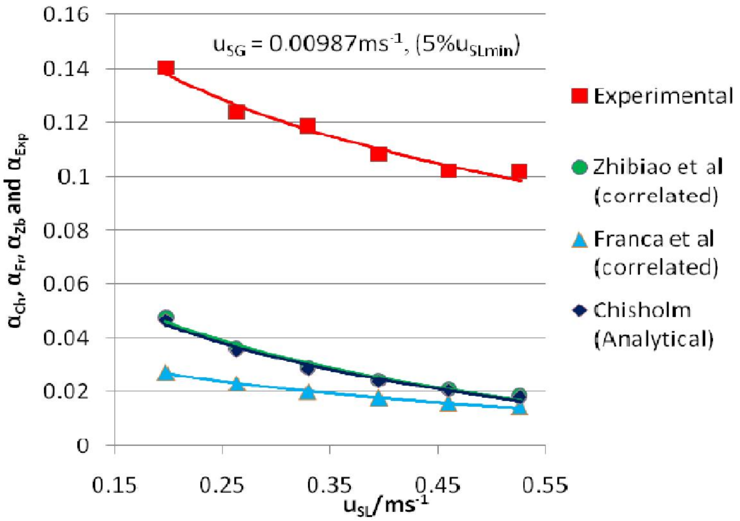

Figure 3 : Void fraction against water velocity (I)

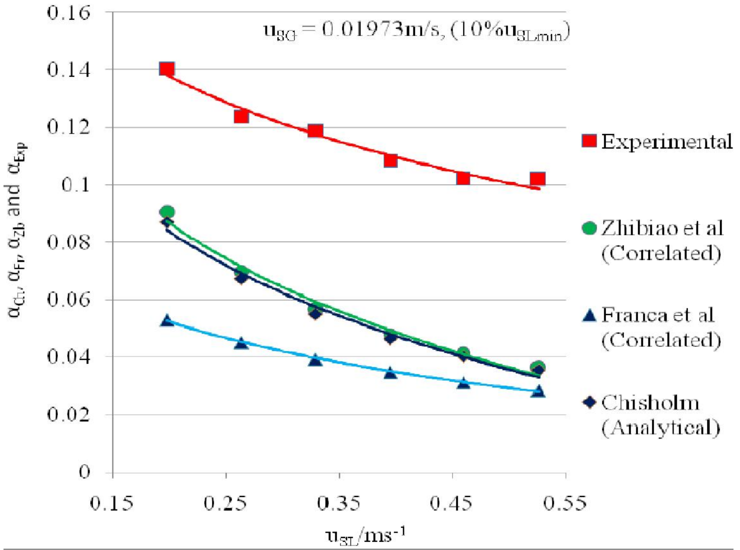

Figure 4 : Void fraction against water velocity (II)

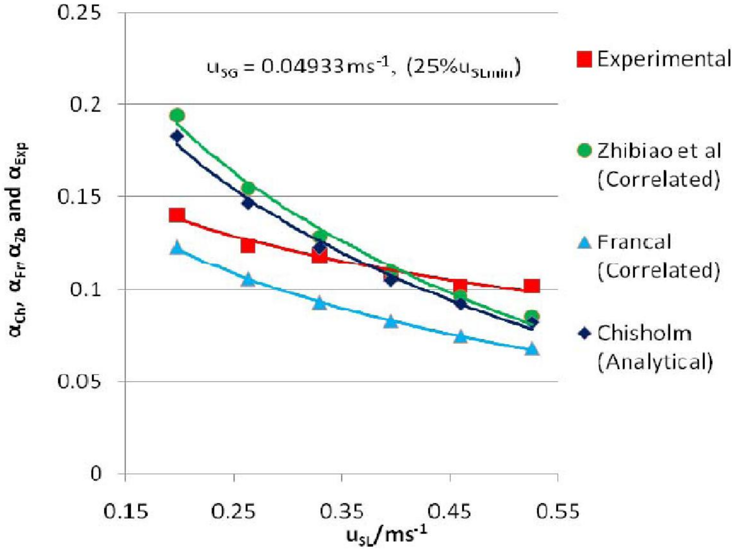

Figure 5 : Void fraction against water velocity (III)

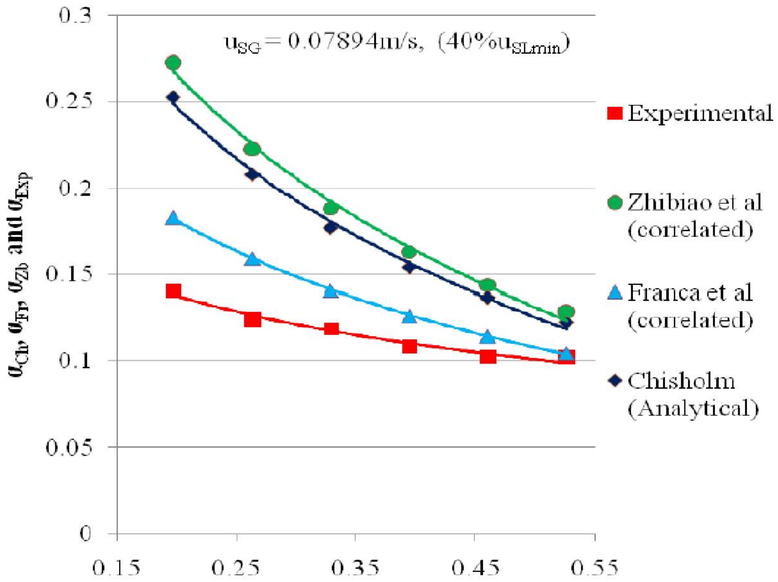

Figure 6 : Void fraction against water velocity (IV)

Figure 6 presents the graph for the estimated air velocity of 0.07894m/s (that is at 40% of the minimum water velocity).

The trend of the curve for the experimental void fraction is not different from those of the graphs for lower air velocities. However, the theoretical void fraction values are higher than those of the experimental values, indicating higher estimated air velocity than that which actually circulated with the water during the experiment. It is important to mention that the curves for all the graphs appear to follow existing trends in literature even though they are not parallel to one another at every point. This may be due to the fact that not all the assumptions underlying the derivation of these equations are the same. Some of the uncertainties with the experimental results were determined through error analysis in order to establish the accuracy and reliability of the results.

Error analysis

Two statistical parameters, the mean deviation ($\overline{D}_{ev}$) and standard deviation (SD) were used to test, verify and validate the experimental result against the theoretical ones. The theoretical results were obtained from the use of Chisholm model (Eqn. (1)) at the estimated air velocity of 0.04933ms^{-1} (that is 25% of the minimum value of the water flow rate). The smaller the value of these statistical indicators, the better is the experimental result[12, 13]. Values of mean deviation reported in the literature were in the range of 1% - 2.5% but it is possible to achieve better results with proper planning and careful experimental design[14]. The summary of the values of these statistical indicators are presented in TABLE 2.

$$\overline{\mathbf{D}}_{ev} = \frac{\mathbf{1}}{\mathbf{N}}\sum_{1}^{N}\left|\alpha_{Exp} - \alpha_{Std}\right| \quad \mathbf{(7)}$$

$$\mathbf{SD} = \frac{\mathbf{1}}{\mathbf{N-1}}\sum\left[\left(\alpha_{Exp} - \alpha_{Std}\right)^{2}\right]^{\frac{1}{2}} \quad \mathbf{(8)}$$

α_{Exp}= experimental void fraction

α_{Std} = void fraction obtained from the model equation used as the standard

N= number of data points obtained for each flow rate

The choice of the Chisholm model as the standard at the estimated air velocity of 0.04933ms^{-1} was due to the fact that the experimental void fractions compare more favourably with those of Chisholm model in Figure (6).

TABLE 2 : Error margins for the experimental void fraction

WFLR (L/min)	$\overline{D}_{ev}$ %	SD %
6	-4.2240	4.2999
8	-2.2834	2.3291
10	-0.3731	0.4212
12	+0.3085	0.3727
14	+0.9756	1.0085
16	+1.9664	2.0036

CONCLUSIONS

Void fraction was successfully measured on the test facility, using gamma ray attenuation technique in air-water horizontal two-phase flow at ambient temperature. The experimental results and their trends compare well with those reported in literature. The experimental void fraction compare well with those obtained using the model of Chisholm. The mean deviations of the experimental void fractions from those obtained from the use of the Chisholm model ranged from 0.3% for the water flow rate of 12L/min to 4.2% for water flow rate of 6L/min. The standard deviations also ranged from 0.3% to 4.3% for water flow rates of 12L/min and 6L/min respectively. If the values of statistical parameters are means to make judgements and conclusions, then the test facility is worth considering for modification for studying void fraction in horizontal air-water two-phase flow system. This is because the values of the statistical parameters gave good accounts of the performance of the test facility as potentially suitable for consideration for modification for studying void fraction.

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