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Development of Multiphase Meter Using Gamma Densitometer Concept

Ibrahim M. M. Babelli
King Abdulaziz City for Science and Technology
PO Box 6086, Riyadh - 11442, Saudi Arabia
Tel: (+966-1) 481-3637, Fax: (+966-1) 481-3887
e-mail: ibabelli@kacst.edu.sa

Abstract

The ability to accurately predict the void fraction of the different phases flowing in a conduit is of extreme importance to the nuclear and oil industries, among others. Some of the major obstacles in performing accurate measurements result directly from the operating conditions of the system involved. The case study in this paper will focus on the issue of predicting the volumetric fraction in oil transport pipelines.

Gamma densitometer utilizes the concept of gamma attenuation in matter where the magnitude of attenuation is directly related to the density of the material through which the gamma ray passes, and to the intensity of the ray itself. By calibrating the gamma ray with a variety of known flow geometries, one can extrapolate the findings to cover all ranges of flow regimes present in a large horizontal pipe, typical of an oil transport pipeline.

The advantage of using gamma densitometers is that it is a non-intrusive technique, relatively inexpensive and portable. Its main disadvantage is that the collimated beam of the gamma ray will produce a line averaged value and local information can not be obtained. Another disadvantage has to do with the necessity to increase the strength of the gamma source with increase in the thickness and/or density of the pipe wall which will require increased radiation protection and reduces portability.

Introduction

Void fraction is one of the most important parameters characterizing multiphase flow. The prediction of the performance of any system operating with more than single phase relies on our knowledge and ability to measure void fraction. Several techniques have been devised to measure void fraction which include: volumetric, electrical, optical, ultrasonic and radiation methods. Void fraction measurements can be divided into local, average and global measurements. Average void fraction measurement usually indicates averaging over cord length, area or volume whereas time averaging is usually implicitly included in the measurement. Most of the reported void fraction measurements are for steady flows. Excellent reviews on the subject are available in Schrock (1969), Hewitt and Lovegrove (1976), Hewitt (1978) and Eberle et al. (1992).

The gamma-ray attenuation technique, a radiation measurement principle, has been widely used for void fraction measurements. This technique has been used since the mid 50s to measure void fraction in simple adiabatic air-water flows and in high pressure boiling flows. Some of the advantages of the gamma-ray attenuation technique are listed below:

1. Non-intrusive
2. Relatively inexpensive
3. Generally reliable
4. Applicable to a wide range of systems due to availability of different gamma-ray energies suitable for different test section material and test fluids
5. Relatively simple
6. Usually portable
7. May be used with two- and three-phase flows
8. Depending on the size of the conduit, it can give average volume, average are, or average cord length measurements
9. Use of one-shot or traverse measurements are both feasible
10. The use of single- or multi-beam configuration, single- or dual-energy sources is feasible

Some of the disadvantages of using the gamma-ray attenuation technique are listed below:

1. Radioactive source
2. Increasing shielding requirement with increase in the source strength needed for transient measurement resulting in increased weight and size of the instrument and becoming less portable
3. Decrease in the gamma-beam sensitivity to water content in the test section with increase in the gamma-ray energy whereas a low energy gamma-ray will experience heavy attenuation and a very intense source will be needed to compensate
4. Relatively long decay constants for the scintillators with high conversion efficiencies, and conversely a low conversion efficiency for the scintillators with relatively short decay constant resulting in a practical limit on the maximum count rate of the scintillator detector
5. If the scintillator is operated in the current mode, as the case was in the early stages of the utilization of this technique, then output signal will suffer from drift
6. For one-shot gamma-ray attenuation technique used with a conduit that has a hydraulic diameter larger than the size of the beam, the phasic flow structure is needed to be known a priori in order to provide meaningful results

Literature survey

Single beam

Cook and Rhodes (1955) and Cook (1956) conducted a series of mock-up studies using Lucite to simulate a number of varied flow regimes and void distribution profiles. Lucite is used due to its close linear attenuation coefficient to that of water. The analysis covered the effects of void distribution with respect to source and

detector locations as well as channel dimensions. Similar experiment was performed by Egen et al. (1957) using rectangular test section at high pressure and a Tm-170 source. Table 1 shows some of the isotopes used for gamma densitometry, reproduced from Chan and Banerjee (1981). A traversing point-by-point chord average measurement was performed. The authors studied the effect of void distribution on the measurement and noted that it is one of the most important factors.

Petrick (1958) and Petrick and Swanson (1958, 1959) studied adiabatic two-phase flow in rectangular channels and in expanding and contracting flow geometries. A comparative study of the one-shot versus the traversing method using Lucite mock-ups was performed. The authors concluded that the measurement error increases with increase in the channel size for the one-shot technique which was in agreement with the results of Cook and Rhodes (1955). All the above measurements were for vertical upward flow. Richardson (1959) measured the void fraction in horizontal two-phase flow. He evaluated the one-shot and the traversing techniques using Lucite mock-ups for both rectangular and circular flow fields and studied the effect of the detector's collimator size on the accuracy of void fraction. Isbin et al. (1957, 1959) used two different sources, namely Se-75 and Tm-170, to measure void fraction in horizontal steam-water systems.

Measurements in tubes

The driving force behind developing void fraction measurement by using gamma-ray attenuation technique was the need to understand complex behavior thermal-hydraulic behavior in nuclear systems. Consequently, most of the published data on this topic focused on two-phase single component media. The majority of the published work reported measurements made using a vertical tube. Hewitt (1978) cited a group of studies from mid 50s to late 70s that were published on gamma-ray attenuation technique measurements in vertical tubes.

Yano (1983, 1984) measured the void fraction caused by flash vaporization of high-pressure and temperature water under an instantaneous 6" pipe break accident of a boiling water reactor using a fast response gamma densitometer. A calibration test was performed by dropping acrylic void simulators and measuring the void fraction. The author reported that a cone slit method is very useful in increasing measurement accuracy.

Kawaji (1984) used a narrow beam gamma densitometer to measure void fraction during reflood of a hot vertical tube, 14.3 mm inside diameter. Kachnik et al. (1986) measured the void fraction during condensation under microgravity conditions using a gamma densitometer. Spindler et al. (1988) measured the void fraction in steady-state and transient two-phase flow of Freon-12. The authors used a 500 mCi Am-241 source. Ralph et al. (1989) developed an axially traversing one-shot gamma densitometer to obtain axial void fraction profiles downstream of the quench front during bottom reflooding of hot tube where the quench front location was controlled by the hot-patch technique.

Jiang and Rezkallah (1993) measured the void fraction in a small vertical tube during upward and downward flow of an adiabatic two-phase mixture. They utilized a

Cs-137 source and an NaI detector in the count mode. The void fraction measurements were calibrated against readings from a quick-closing valves. The results indicated that there is no significant influence of the tube diameter on the results obtained using the gamma densitometry measuring technique.

A single beam gamma densitometer was used for axial void fraction profile measurements and interfacial area concentration in low pressure subcooled flow boiling by Zeitoun et al. (1994) and by Zeitoun and Shoukri (1995, 1997). The authors used a 75 mCi Co-57 sealed line source and a cubic NaI(Tl) scintillator operating in the count mode. The beam was collimated as a thin beam wide enough to cover the entire cross-section for measuring the area-averaged void fraction. The densitometer was calibrated using a Lucite mock-up of the subcooled flow boiling regime.

Measurements in other geometries

Evangelisti and Lupoli (1969) measured the void fraction in annular channel at atmospheric pressure using gamma-ray attenuation technique using Tm-170 as the gamma-ray source. The authors studied the effect of void distribution during subcooled boiling on the void fraction measurement using Lucite mock-ups. Both the one-shot method and the traversing method were evaluated and the authors concluded that the traversing method produces more accurate results. Other measurements using gamma-ray attenuation technique in annular geometry were reported by Zakharova et al. (1970), Staengl and Mayinger (1989) and by Zuzhi et al. (1990).

Gustafsson and Kjellen (1971), Felde (1982), Bukhari (1985) and Kumamaru et al. (1994) reported using gamma-ray attenuation technique in void fraction measurement in rod bundle geometry.

Vorgin (1963), Hammit et al. (1964) and Smith et al. (1964) reported measurements of void fraction in converging-diverging nozzles using the gamma-ray attenuation technique. Gamma densitometry was used to measure void fraction in small nozzles operating at high pressure (4.5-15.0 MPa) by Lin et al. (1980). Honan and Lahey (1978) reported using gamma densitometry to study phase separation in wyes and tees by measuring chordal averaged void fraction in the junction.

Multi-beam measurements

Multi-beam gamma absorption devices are reported by Heidrick et al. (1975), Ybarrando (1975), Lassahn (1975, 1977), Wesley (1977), Franger et al. (1977), Reimann and John (1978), Loeffel (1982), Sonneck (1983) and by Adam et al. (1987). Heidrick et al. (1975) developed a single source and three detector system to measure void fraction of a steam-water mixture flow in a 3" pipe using a 25 Ci Cs-137 source. A computational procedure was used to verify the steady state capability of this 3-beam gamma densitometer. The computational procedure was compared to measurements using Lucite mock-ups inserted in the pipe. The accuracy of the measurement degraded to about 30% for low void fraction values in the flat stratified flow regimes. John et al. (1979) used a 5-beam gamma densitometer to measure void fraction in a steam-water mixture inside a 50 mm pipe at 150 bar. All five beam were collimated from a single source and the result was compared with measurement made

using a 3-beam and a traversing densitometers. An additional reference beam was used in conjunction with the 5-beam densitometer to correct for the system electronic drifts.

The multi-beam system used in the LOFT blowdown experiment to measure void fraction and delineate the flow pattern in a horizontal tube during blowdown using a 30 Ci Cs-137 source. Using a single source, a collimator was used to divided the gamma-ray into three collimated beams and the response was measured using three detectors. The response of the system was used to infer the density distribution inside the 14" Sc. 160 pipe during blowdown simulation. Details of this work may be found in Lassahn (1977) and Wesley (1977).

Design considerations

Inherent to the void fraction measurement using gamma-ray attenuation technique are measurement errors due to geometry, flow regimes and count rate statistics. A detailed discussion of the errors arising in radiation-attenuation void measurements is given by Piper (1974). He derived an expression for the required strength of a source to produce a given accuracy.

In order to minimize the measurement error, efforts were focused on the design optimization of the densitometer. Ferrell and McGee (1966) concluded that for the one-shot technique, the measurement should be dependent on the void distribution of the flow regime, whereas the traversing method should be independent. The authors developed an optimization technique that reduced the error of a one-shot technique to that of the traversing technique by assuming that the detector response and the count rate for both techniques are equal. Next, the void fraction measured from the traversing technique was equated to the void fraction measured from the one-shot technique and the collimator profile design was obtained. The authors concluded that their analysis was applicable if the attenuation fraction was small. The above analysis was further studied and evaluated by Gardner and Ely (1967) and by Gardner et al. (1970). Gardner et al. (1970) assumed a mono-energetic source and thus Am-241 was used instead of Tm-170.

Schrock (1969) discussed the design of a gamma densitometer and evaluated the impact of the following parameters on a good geometry design of the gamma densitometer:

1. Effect of void distribution
2. Effect of collimation
3. Effect of photon energy
4. Type of detection system used
5. Statistical error
6. Source selection

Shipp (1979) reported a comparison between the performance of ionization chamber detectors, plastic scintillation detectors and NaI scintillation detectors. The author reported that the plastic scintillation detector is the most suitable for use with fast transients. Chan and Banerjee (1981) have shown that when a high atomic number element is introduced in the plastic material, a much higher efficiency results without

affecting the time properties of the plastic scintillator. The authors reported ~50% conversion efficiency for a 10% lead loaded plastic scintillator. Table 2 shows some of the scintillators used for gamma densitometry, reproduced from Chan and Banerjee (1981).

Chan and Banerjee (1981) developed a criterion for the optimum design of a single shot gamma densitometer for use with small tubes. The authors concluded that there is no single optimum design for the gamma densitometer but it is rather dictated by the system under investigation. The design procedures proposed by the authors to select the most suitable gamma densitometer are as follows:

1. Specify the test section geometry and material
2. Choose the gamma-ray energy (isotope) with reference to item 1 above
3. Calculate the required source strength
4. Estimate the shielding requirements
5. Choose the scintillator and counting system with reference to item 3 above

Herschthal et al. (1983) developed a narrow beam gamma densitometer for measuring void profiles during reflooding experiments using the traversing technique. The design procedure for this gamma densitometer consisted of five steps:

1. Specify the test section geometry and fluid and the radioactive source
2. Specify the desired fraction error in the void fraction measurement and the minimum void fraction of interest
3. Choose the detector area, counting time, and photon transmission distance through media
4. Calculate the required source strength
5. Iterate on item 3 above along with source type to achieve economical shielding

After careful consideration one may add three other steps to the steps mentioned above to complete the selection process, namely:

1. Select the number of gamma-ray beams according to number of phases
2. Decide on the method of operation, i.e., one-shot or the traversing method
3. Design the source and detector collimators

Liu and Wang (1991) developed an implicit and iterative analysis for improving the one-shot technique by applying a Monte Carlo simulation of the source, flow field and detector configuration using MCNP. L. Pan et al. (1993) developed a gamma densitometry using dual-energy gamma-beam and discussed the principle of using dual-energy gamma densitometry for measurement of three-phase void fraction and reported the design procedure. Eberle et al. (1994) generalized the approach of Chan and Banerjee (1981) to develop an optimization criterion for the one-shot technique for narrow pipes. The authors used pressure drop measurements, conductivity probe measurements and Lucite mock-ups to evaluate the accuracy of the gamma densitometer measurements and reported good agreement.

The errors caused by the dynamic effects of voids were theoretically evaluated by Levert and Helminski (1973) for two energies provided from two isotopes. Harms

et al. (1971, 1973) and Laratta et al. (1974) studied the dynamic effects and the dynamic bias in two-phase flow measurements using radiation techniques. The main concern was the inability to differentiate down-scattered photons from the lower energy photons. Elias et al. (1976) attempted to resolve the above mentioned problem by measuring the scattered flux as opposed to the unperturbed flux. The authors investigated the response function for the scattered flux theoretically using Monte Carlo simulation and two ranges of energy, namely, 640-680 KeV and 100-220 KeV.

Zielke et al. (1975) measured the 90° scattered flux of a traversing measurement across a fuel bundle using a Cs-137 source. Kennet et al. (1976) used highly energetic photons scattered through 20°. The investigation of average bias in the scattered flux measurement clearly indicated a decrease in dynamic error as the photon energy increased.

Oil measurements

The use of gamma-ray attenuation technique in the oil industry has been reported by several authors. Ryabov et al. (1976) used gamma densitometry to study flooding intervals in a borehole in order to enhance the efficiency of well logging.

Abouelwafa and Kendall (1980) applied the dual-energy gamma densitometry technique to the measurement of the phase fractions of air-oil-water mixtures and claimed accurate chordal phase fractions obtained. Tomada et al. (1987), Rafe et al. (1989) and Rafe (1989) reported the development of three-phase flow meter using dual-energy gamma densitometry. Nuland et al. (1991) used dual-gamma energies from Ba-133 to measure the phase fractions in air-oil-water flow. They showed the time-series of chordal phase fractions and compared the measured phase fractions with those measured using quick-closing valves. The comparison was not satisfactory especially at high air flow rates which may be attributed to method of data interpretation.

Robgetz et al. (1991) showed numerically that good measurement accuracy can be obtained for the chordal phase fractions in air-oil-water flow using dual energy gamma densitometry. The authors reported that by adding NaCl or KCl to the water phase, the measurement accuracy can be improved. The measured phase fraction reported by the authors, however, were much less accurate than what the analysis predicted.

Bishop and James (1993) introduced the concept of neural network technique to aid in the phase configuration and phase fraction recognition. The raw signals are obtained from dual energy multiple-beam gamma densitometer. This work was conducted to measure the void fraction and flow pattern in a mixture of oil, water and gas in oil pipelines.

Fischer (1994) reported the development of a technique for the continuous measurement of the total mass flow and composition of oil/salt water/gas mixtures using a combination of a venturi tube, a capacitor and a single-beam gamma

densitometer. The author suggested that the measurement is valid only if the mixture is virtually homogeneous throughout the flow with oil or air forming a continuous phase.

Pan and Hewitt (1995) demonstrated theoretically and experimentally that the cross sectional phase fractions in air-oil-water flow can be measured using a dual-energy gamma-densitometer. The authors reported a 3% average uncertainty in the measurements.

Roach et al. (1995) and Hartley et al. (1995) reported the measurements of a multiphase meter using two gamma-ray transmission gauges mounted on a pipe carrying the full flow of oil, water and gas. Van Santen and Kolar (1995) showed that a third photon energy can be used to greatly reduce the systematic errors in the watercut resulting form spatial and temporal variations in the oil-water-gas mixture composition when measured with a dual-energy gamma densitometer.

The available research on void fraction measurement in the multiphase flow in the oil pipelines using gamma densitometry is limited in number and in nature. The majority of the published work deals with relatively small tubes and the extrapolation from the small scale to the large scale has not been carried out rigorously. The wide range of flow patterns and void fraction profiles in oil transport pipeline range from stratified in the large size shipping pipelines to the highly mixed highly agitated homogeneous flow exiting the well. These variations call for the development of an accurate gamma densitometer that is calibrated in situ for each application. The rigorous experimental extrapolation from the small scale measurements to the large scale application must be validated both analytically and experimentally.

Chordal void fraction measurement

The basic principle for the gamma-ray attenuation technique is the experimentally observed fact that the intensity of the collimated beam decreases exponentially as it passes through matter. Mathematically, the attenuated flux passing through two-phases in a conduit of height H, is given by:

$$I = I_0 \cdot \exp(-\gamma_1 x_1 - \gamma_2 x_2)$$

where $$x_1 + x_2 = H\,.$$

From the above two equations, the void fraction is calculated as:

$$\alpha = \frac{x_1}{H} = \frac{L/H + \gamma_2}{\gamma_2 - \gamma_1}$$

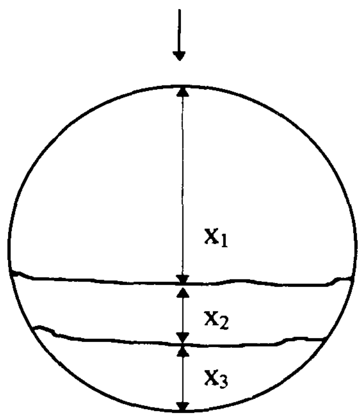
where $$L = \ln\left(\frac{I}{I_0}\right).$$

The above is true for a chordal average value of the void fraction across the conduit. Generalizing the above relation to three-phase flow and by using dual-energy

gamma beam, and by looking at the figure below, we can express the attenuated flux of both beams, A and B as follows:

$$I_A = I_{0A} \cdot \exp(-\gamma_{1A}x_1 - \gamma_{2A}x_2 - \gamma_{3A}x_3)$$
$$I_B = I_{0B} \cdot \exp(-\gamma_{1B}x_1 - \gamma_{2B}x_2 - \gamma_{3B}x_3)$$
$$x_1 + x_2 + x_3 = H$$

Gamma rays A and B



Stratified three-phase flow in a large pipe

From the above equations, we can derive the void fractions:

$$\alpha_1 = \frac{-\gamma_{2A}\gamma_{3B} - \gamma_{2A}L_B/H + \gamma_{3A}L_B/H + \gamma_{3A}\gamma_{2B} + \gamma_{2B}L_A/H - \gamma_{3B}L_A/H}{\gamma_{2A}\gamma_{1B} - \gamma_{2A}\gamma_{3B} - \gamma_{3A}\gamma_{1B} - \gamma_{1A}\gamma_{2B} + \gamma_{1A}\gamma_{3B} + \gamma_{3A}\gamma_{2B}}$$

$$\alpha_2 = \frac{-\gamma_{3A}\gamma_{1B} - \gamma_{1B}L_A/H + \gamma_{3B}L_A/H + \gamma_{1A}\gamma_{3B} + \gamma_{1A}L_B/H - \gamma_{3A}L_B/H}{\gamma_{2A}\gamma_{1B} - \gamma_{2A}\gamma_{3B} - \gamma_{3A}\gamma_{1B} - \gamma_{1A}\gamma_{2B} + \gamma_{1A}\gamma_{3B} + \gamma_{3A}\gamma_{2B}}$$

$$\alpha_3 = 1 - \alpha_1 - \alpha_2$$

where $L_A = \ln\left(\frac{I_A}{I_{0A}}\right)$ and $L_B = \ln\left(\frac{I_B}{I_{0B}}\right)$

The error analysis in the void fraction measurement of three-phase flow reported here will be limited to the statistical error in the measurements assuming ideal experimental conditions. The analysis follows on the footsteps of the work published by Pan and Hewitt (1995). The errors in a measured void fraction are given by:

$$(\delta\alpha)^2 = \left(\frac{\partial\alpha}{\partial L_A}\delta L_A\right)^2 + \left(\frac{\partial\alpha}{\partial L_B}\delta L_B\right)^2$$

where $$\delta L_A = \frac{1}{\sqrt{C_A t}}$$

Then for each void fraction, the error is given by:

$$\delta\alpha_1 = \left[\frac{(\gamma_{3B}-\gamma_{2B})^2}{C_A} + \frac{(\gamma_{3A}-\gamma_{2A})^2}{C_B}\right]^{1/2} \frac{1}{DH\sqrt{t}}$$

$$\delta\alpha_2 = \left[\frac{(\gamma_{1B}-\gamma_{3B})^2}{C_A} + \frac{(\gamma_{1A}-\gamma_{3A})^2}{C_B}\right]^{1/2} \frac{1}{DH\sqrt{t}}$$

$$\delta\alpha_3 = \left[\frac{(\gamma_{2B}-\gamma_{1B})^2}{C_A} + \frac{(\gamma_{2A}-\gamma_{1A})^2}{C_B}\right]^{1/2} \frac{1}{DH\sqrt{t}}$$

where $$D = \gamma_{2A}\gamma_{1B} - \gamma_{2A}\gamma_{3B} - \gamma_{3A}\gamma_{1B} - \gamma_{1A}\gamma_{2B} + \gamma_{1A}\gamma_{3B} + \gamma_{3A}\gamma_{2B}$$

Minimizing the error in the measurements depends on a group of five parameters:

1. Count rates
2. Measurement time
3. Cord length
4. Mass attenuation coefficients
5. Gamma source energies

The selection of gamma energies was the focus of the optimization effort of Pan and Hewitt (1995). The authors reported a theoretical study for the selection of best pairs of gamma energies for the specific geometry and composition. For a stainless steel 3" pipe , Ba-133 with energies of 31 Kev and 81 KeV and a strength of 20 mCi was selected and gave a measurement error of 3%. The authors used 8-points traversing measurements covering half of the pipe cross section - assuming symmetry- and a scintillation detector operating in the count mode.

One of the important conclusions of the authors was that the smaller the energy of the lower gamma beam the better the statistical error. A tradeoff between minimum error and shielding requirement due to increase in source strength needed to overcome absorption must be struck for each experimental setup.

Conclusions

In order to accurately measure the cross sectional void fraction in a three-phase flow of oil, water and gas, it is recommended that the dual-gamma energies be

optimized for the specific geometry and mixture flow rate. The traversing method is judged to be the most suitable for oil-water-gas chordal void fraction measurements, in agreement with Pan and Hewitt (1995), provided the measurement location is precisely repeatable.

It is concluded that detailed measurements of the cross sectional or single-shot average void fraction of oil-water-gas flow in large pipes, typical of oil transporting pipelines, should be carried on to validate the use of gamma densitometry for this type of measurements.

It is further concluded that there is a need to document a large data bank of flow rate, void fraction and flow pattern measurements of oil-water-gas flows in large pipe such that any future measurements may be calibrated against this data.

Table 1

Isotope	Half-life	Principal photon energy (KeV)	Emission + (%)
Americium-241	433 y	11.9-22.3 59.5	~40 35.3
Barium-133	10.8 y	30-36 80-81 276.0 303.0 356.0 384.0	~123 36.2 7.1 18.7 61.5 8.9
Cadmium-109	453 d	22.1-26.0 88.0	102.3 3.6
Cesium-137	30.1 y	32.0-38.0 662.0	8.0 85.1
Cobalt-57	270.5 d	6.4-7.0 14.4 122.0 136.5	~55 9.4 85.2 11.1
Cobalt-60	5.27 y	1173.0 1333.0	99.86 99.98
Curium-244	17.8 y	12.1-23.0	~8
Gadolinium-153	241.5 d	41.3-47.3 69.7 97.4 103.2	~110 2.6 30 20
Iodine-129	1.57×10^7 y	30-35 40.0	~69 7.5
Lead-210	22.3 y	9.42-16.4 46.5 *	~21 ~4
Mangnese-54	312.5 d	835.0	100
Plutonium-238	87.75 y	11.6-21.7	~13
Tellurium-123m	119.7 d	27.4-31.1 159.0	~50 83.5
Thullium-170	128 d	50.0-59.7 84.3 *	~5 3.4

* In addition to Bremmstrahlung radiation.
+ Emission ratio is defined as the number of gammas of a particular energy emitted per 100 disintegration of the radionuclide.

Table 2

Scintillator	Decay constant (μs)	Density (gm/cm^3)	Conversion efficiency (%)
NaI(Tl)	0.23	3.67	100
CsI(Na)	0.63	4.51	85
CsI(Tl)	1.0	4.51	45
CsF	.005	4.11	3
^{6}LiI(Eu)	1.4	4.08	35
CaF_2(Eu)	0.9	3.19	50
BaF_2	0.63	4.88	10
KI(Tl)	0.24/2.5	3.13	24
Ps	~0.002	1.05	<5

Nomenclature

C	Gamma-ray count rate (photons/s)
H	Conduit height (m)
I	Gamma-ray intensity ($photons/m^2/s$)
t	Counting time (s)
x	Thickness of the phase (m)
α	Chordal void fraction
γ	Linear attenuation coefficient (m^{-1})

Subscripts

0	Incident gamma-ray beam
A, B	Lower and upper gamma-ray energies
1, 2, 3	Mixture phases

List of References

M.S.A. Abouelwafa and E.J.M. Kendall, "The measurement of component ratios in multiphase systems", J. Phys. E: Sci. Instrum., v 13, 1980, p 341.

E. Adam, J. Sydow and J. Wolff, "Applying a 6-channel gamma-ray densitometer to measure the density of a two-phase flow", Energietechnik, 1987, v 37, p 163-168.

C.M. Bishop, and G.D. James, "Analysis of multiphase flows using dual-energy gamma densitometry and neural networks", Nuclear Instruments & Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, v A327, n 2-3, 1993, p 580-593.

Bukhari, K.M., "Phase separation and distribution phenomena in a two-dimensional test section", Ph.D. Thesis, Rensselaer Polytechnic Inst., 1985.

A.M.C. Chan and S. Banerjee, "Design aspects of gamma densitometers for void fraction measurements in small scale two-phase flows", Nuclear Instruments and Methods in Physics Research, v 190, 1981, p 135-148.

W.H. Cook and R.R. Rhode, "Effect of Preferred Void Distribution on Void Measurements", Argonne National Laboratory Report, ANL-5462, 1955.

W.H. Cook, Boiling Density in Vertical Rectangular Multichannel Sections with Natural Circulation", Argonne National Laboratory Report, ANL-5621, 1956.

C.S. Eberle, M. Ishii and S.T. Revankar, "A review of gamma densitometer designs and measurements in two-phase flows", Purdue University Report, PU/NE-92-3, 1992.

C.S. Eberle, W.H. Leung, M. Ishii and S.T. Revankar, "Optimization of a one-shot gamma densitometer for measuring area-averaged void fractions of gas-liquid flows in narrow pipelines", Measurement Science and Technology, v 5, 1994, p 1146-1158.

R.A. Egen, D.A. Dingee and J.W. Chastain, "Vapor Formation and Behavior in Boiling Heat Transfer", ASME 57-A-74, also see Battelle Memorial Institute Report BMI-1163, 1957.

E. Elias, Y. Segal and A. Notea, "Dual Gaugeing Utilizing Penetrating and Scattered Photon Fluxes", Nucl. Tech., v 33, 1976, p 305-313.

R. Evangelisti and P. Lupoli, "The Void Fraction in An Annular Channel at Atmospheric Pressure", International Journal of Heat Mass Transfer, v 12, 1969, p 699-705.

D.K. Felde, "Design concept and testing of an in-bundle gamma densitometer for subchannel void fraction measurements in the THTF electrically heated rod bundle. PWR", NUREG/CR-2545, 1982.

J.K. Ferrell and J.W. McGee, "An Accurate One-Shot Gamma Attenuation Technique for Measuring Void Fractions", Chem. Eng. Prog. Sym., v 62, 1966, p 112-120.

C. Fischer, "Development of a metering system for total mass flow and compositional measurements of multiphase/multicomponent flows such as oil/water/air mixtures", Flow Measurement and Instrumentation, v 5, n 1, 1994, p 31-42.

U. Frangar, R. Pepelnik and W. Michaelis, "Determination of conveyor-flow parameters by gamma-ray transmission analysis", Proc. Nuclear Techniques and Mineral Resources, IAEA, Vienna, 1977, p 539.

R.P. Gardner and R.L. Ely Jr., Radioisotope Measurement Applications in Engineering, Reinhold Pub. Co., New York, Chapter 12, 1967, p 325-369.

R.P. Gardner, R.H. Bean and J.K. Ferrell, "On the Gamma-ray One-Shot Collimator Measurement of Two-Phase Flow Void Fractions", Nucl. Appl. Tech. V 8, 1970, 88-94.

B. Gustafsson and B. Kjellen, "Two-phase flow in a 9 rod bundle with inclined power distribution", Paper A5, Proceedings of the European Two-Phase Flow Group Meeting, RISO Denmark, June 1971.

F.C. Hammitt, W. Smith, I.E.B. Lauchlan, R.D. Iyany and M.J. Robinson, "Void fraction measurements in a cavitating mercury venturi", ANS Transactions, v 7, n 1, 1964, p 189-193.

A.A. Harms and C.F. Forrest, "Dynamic Effect in Radiation Diagnosis of Fluctuating Voids", Nucl. Sci. Eng., v 46, 1971, p 408-413.

A.A. Harms and F.A.R. Laratta, "The Dynamic-Bias in Radiation Interrogation of Two-Phase Flow", Int. J. Heat Mass Transfer, v 16, 1973, p 1459-1465.

P.E. Hartley, G.J. Roach, D. Stewart, J.S. Watt, H.W. Zastawny and W.K.Ellis, "Trial of a gamma-ray multiphase flow meter on the West Kingfish oil platform", Nuclear Geophysics, v 9, n 6, 1995, p 533-552.

T.R. Heidrick, J.R. Saltvold and S. Banerjee, "Application of a 3-beam gamma densitometer to two-phase flow regime and density measurements", CONF-760816, AIChE Symposium Series, v 73, n 164, National heat transfer conference, St. Louis, MO, 8 - 11 Aug 1976, p 248-255.

M. Herschthal, M. Kawaji and S. Banerjee, "Design and Testing of a Laboratory Gamma-Densitometer for Two-Phase Flow", Electrical Power Research Institute Report EPRI-NP-2819, 1983.

G.F. Hewitt, Measurement of Two Phase Flow Parameters, Academic Press, 1978.

G.F. Hewitt and P.C. Lovegrove, "Experimental Methods in Two-Phase Flow Studies", Electrical Power Research Institute Report, EPRI-NP-118, 1976.

T.J. Honan and R.T. Lahey, Jr., "Measurement of phase separation in wyes and tees", NUREG/CR-0557, 1978.

H.S. Isbin, N.C. Sher and K.C. Eddy, "Void Fraction in Two-Phase Steam-Water Flow", AIChE. Journal, v 3, 1957, 136-142.

H.S. Isbin, H.A. Rodriguez, H.C. Larson and D.B. Pattie, "Void Fraction in Two-Phase Flow", AIChE Journal, v 5, 1959, 427-432.

Y. Jiang and K.S. Rezkallah, "An experimental study of the suitability of using a gamma densitometer for void fraction measurements in gas-liquid flow in a small diameter tube", Measurement Science and Technology, v 4, 1993, p 496-505.

H. John, J. Reimann, H. Alsmeyer, H. Hahn, and A. Megerle, "Serial 5-beam gamma densitometer for measuring of two-phase flow density", KFK-2783, 1979.

M.L. Kachnik, M. Gaeta, J. Terrell, F. Best and N. Faget, "Design and test program for a micro-gravity convective condensation experiment", Transactions of the symposia on space nuclear power systems, M.S. El-Genk and M.D. Hoover, eds., CONF-860102—Summs, Symposium on space nuclear power systems, Albuquerque, NM, 13-16 Jan. 1986, p TM-10.1-TM-10.3.

M. Kawaji, "Transi non-equilibrium two-phase flow: reflooding of a vertical flow channel", Ph.D. Thes fornia Univ., Berkeley, 1984.

T.J. Kennett, W.V. Prestwich and A. Robertson, "Dynamic Density Measurement By High Energy Photon Scattering", Int. J. A. Rad., v 27, 1976, p 529-532.

H. Kumamaru, M. Kondo, H. Murata and Y. Kukita, "Void-fraction distribution under high-pressure boil-off conditions in rod bundle geometry", Nuclear Engineering and Design, 1994, v 150, p 95-105.

F.A.R. Laratta and A.A. Harms, "A Reduced Formula for the Dynamic Base in Radiation Interrogation of Two-Phase Flow", Int. J. Heat Mass Transfer, v 17, 1974, p 464.

G.D. Lassahn, "Mathematical analysis of a two-beam gamma densitometer", ANCR-1201, 1975.

G.D. Lasssahn, "LOFT three-beam densitometer data interpretation", TREE-NUREG-1111, 1977.

F.E. Levert and E. Helminski, "A Dual-Energy Method for Measuring Void Fractions in Flowing Mediums", Nucl. Tech., v 19,1973, p 58-60.

J.C. Lin, G.E. Gruen and W.J. Quapp, "Critical flow in small nozzles for saturated and subcooled water at high pressure", CONF-801102-10, ASME winter annual meeting, Chicago, IL, 16 - 21 Nov.,1980.

H. Liu and T. Wang, "A Modified One-Shot Photon-Attenuation Method for Void Fraction Determination in Two-Phase Flow Systems", Appl. Radiat. Isot., v 42, 1991, p 25-30.

R. Loeffel, "Two-phase flow measurements using a 6-beam-gamma-densitometer", IAEA-CN--40/31P, Proceedings of the International conference on industrial application of radioisotopes and radiation technology, Grenoble, France, 28 Sep. - 2 Oct. 1981, p 459.

S. Nuland, K. Skarsvag, G. Sather and P. Fuchs, Phase fraction in three-phase gas-oil-water flow, Elsevier Science Publishers, 1991.

L. Pan and G.F. Hewitt, "Precise measurement of cross sectional phase fractions in three-phase flow using a dual-energy gamma densitometer", HTC-Vol. 8, ANS Proceedings of the 1995 National Heat Transfer Conference, Portland, Or., August 5-9, 1995, p 71-78.

L. Pan, M.A. Mendes-Tatsis and G.F. Hewitt, "Development of dual-energy gamma densitometer-Principle and design considerations", Report-MFS/33-WASP/04, Chem. Eng. Dept., Imperial College, London, 1993.

M. Petrick, "Two-Phase Air Water Flow Phenomena", Argonne National Laboratory Report ANL-5787, 1958.

M. Petrick and B.S. Swanson, "Radiation Attenuation Method of Measuring Density of a Two-Phase Fluid", Rev. Sci. Inst., v 29, 1958, p 1079-1085.

M. Petrick and B.S. Swanson, "Expansion and Contraction of an Air-Water Mixture in Vertical Flow", AIChE Journal, v 5, 1959, p 440-445.

T.C. Piper, "Dynamic gamma attenuation density measurements", Aerojet Nuclear Company, ANCR-1160, 1974.

K.G. Rafe, "Dual-energy gamma-ray compositional measurement for oil/water/gas systems", Proc. Symp. Multiphase Flow-Technology and Consequences for Field Development, Norwegian Petroleum Society, Stavanger, Norway, May 8-9, 1989.

K.G. Rafe, T. Tomada and R. Ridley, "Flow loop and field testing of a gamma-ray compositional meter", ASME paper 89-pet-7, Proc. Energy Sources Technology and Exhibitions, ASME, Houston, Texas, Jan. 22-25, 1989.

J.C. Ralph, D.P. Frankum, C.D. Wade and P.S. Black, "Post dryout heat transfer and void fraction measurements relevant to a reactor reflooding", Thermal non equilibrium in two phase flow, INIS-mf—11484, Proceedings of the 7th Eurotherm seminar, Rome, Italy, 23-24 Mar. 1989, p 147-156.

M.D. Rebgetz, J.S. Watt and H.W. Zastawny, "Determination of the volume fractions of oil/water/gas by dual energy gamma-ray transmission", Nucl. Geophys., Int. J. Radiat. Appl. Instrum. Part E, v 5, 1991, p 479.

J. Reimann and H. John, "Measurements of the phase distribution in horizontal air-water and steam-water flow", Proceedings of the CNSI Meeting on Transient Two-Phase Flow, Paris, June 1978.

B.L. Richardson, "Some Problems in Horizontal Two-Phase Two-Component Flow", Ph.D. Thesis, Purdue University, West Lafayette, Indiana; also see Argonne National Laboratory Report ANL-5949, 1959.

G.J. Roach, J.S. Watt, H.W. Zastawny, P.E. Hartley, and W.K. Ellis, "Field trial of a gamma-ray multiphase flow meter on Thevenard Island", Nuclear Geophysics, v 9, n 1, 1995, p 1-17.

B.M. Ryabov, V.V. Trufanov, A.G. Gajnanshin and V.G. Dvoretskij, "Ways for enhancing efficiency of well logging of low-discharge borehole-pump well", Well logging for oil field exploitation, n 6, 1976, p 66-71.

V.E. Schrock, "Radiation Attenuation Techniques in Two-Phase Flow Measurements", Eleventh ASME/AICHE Heat Transfer Conference, Minneapolis, 1969, p 24-35.

R.L. Shipp, "Comparison of gamma densitometer detectors used in loss of coolant studies", CONF-791037-28, Proceedings of the IEEE nuclear science symposium. San Francisco, CA, 17 - 19 Oct. 1979.

W. Smith, G.L. Atkinson and F.G. Hammitt, "Void fraction measurement in a cavitating venturi", Journal of Basic Engineering, 1964, p 265-274.

G. Sonneck, "On the computation of the density of a two-phase mixture using data from a three-beam gamma densitometer", OEFZS-4206, 1983.

K. Spindler, E. Hahne and R. Loeffel, "Gamma densitometer for void fraction measurements in two-phase flows", Tech. Mess. TM., 1988, v 55, p 228-233.

G. Staengl and F. Mayinger, "Void fraction and pressure drop in subcooled forced convective boiling with refrigerant 12", Thermal non equilibrium in two phase flow, INIS-mf—11484, Proceedings of the 7th Eurotherm seminar, Rome, Italy, 23-24 Mar. 1989, p 83-97.

T. Tomada, M. Komaru, S. Badono, K. Tsumagari and D. Exall, "Development of gamma-ray oil/water/gas fraction meter for crude oil production system", Proc. Int. Conf. Industrial Flow Measurement On-shore and Off-shore, London, 1987.

H. Van Santen and Z.I. Kolar, "Using a third photon energy for gamma-and/or X-ray composition measurements in oil-water-gas mixtures", Nuclear Geophysics, v 9, n 5, Oct. 1995, p 413-423.

J.A. Vorgin, "An experimental investigation of two-phase, two-component flow in a horizontal converging-diverging nozzle", Argonne National Laboratory Report, ANL-6754, 1963.

R.D. Wesley, "Performance of drag-disc turbine and gamma densitometer in LOFT", Paper No. I.5, Proceedings of Meeting of Review Group on Two-Phase Flow Instrumentation, NUREG-0375, 1977.

T. Yano, "Development of gamma-ray densitometer and measurement of void fraction in instantaneous pipe rupture under BWR LOCA condition", JAERI-M-83-192, 1983.

T. Yano, "Void fraction measurement by a gamma-ray densitometer under instantaneous pipe rupture", Nuclear Engineering and Design, v 79, 1984, p 101-113.

L. Yberrando, "Dynamic analysis of pressure transducer and two-phase flow instrumentation ", Third Water Reactor Safety Research Information Meeting, Washington DC, 1975.

E.A. Zakharova, B.A. Kolchugin and I.P. Korniukhin, "Vapor void-fraction in annular channels at separated and joint heat supplied", Paper B 5.5, 4th International Heat Transfer Conference, Paris, 1970.

O. Zeitoun, M. Shoukri and V. Chatoorgoon, "Measurement of interfacial area concentration in subcooled liquid-vapor flow.", Nuclear Engineering and Design, 1994, v. 152, p 243-255.

O. Zeitoun and M. Shoukri, "Bubble behavior and mean diameter in subcooled flow boiling", NUREG/CP-0142, Proceedings of the 7th International Meeting on Nuclear Reactor Thermal-Hydraulics NURETH-7, Saratoga, NY, 10-15 Sep. 1995, v 4, p 3175-3196.

O. Zeitoun and M. Shoukri, "Axial void fraction profile in low pressure subcooled flow boiling", International Journal of Heat and Mass Transfer, v 40, n 4, 1997, p 869-879.

L.A. Zielke, C.G. Howard, R.L. Currie and C.D. Morgan, "Rod Bundle Subchannel Void Fraction by Gamma Scattering", Trans. Am. Nucl. Soc., v 21, 1975, p 412-413.

L. Zuzhi, Z. Dingsheng and J. Liangfu, "Experimental study of steam-water two phase flow void fraction measured by gamma-ray densitometer under low pressure and low velocity", Nuclear Power Engineering, 1990, v 11, p 35-43.