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STUDY OF LOCAL PHASE FRACTION IN STRATIFIED DENSE-GAS-LIQUID PIPE FLOW USING GAMMA-RAY DENSITOMETRY

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Abstract. The gamma-ray technique is frequently used in multiphase-flow experiments and also in onshore and offshore pipelines for volumetric-fraction measurements. In this work we propose to study the gamma ray technique in a static situation and then discuss the necessary improvements for more precise application. The experiments were performed in a stainless steel pipe with 108.45 mm i.d., maintained in a horizontal position. The gamma densitometer system is composed by a radioactive isotope source of Cs-137 with intermediate emission energy (661.6 keV) and a scintillation detector of Sodium Iodide (Na). A high precision actuator for positioning was designed to allow accurate movements in the vertical direction. The first data was acquired to a static case using a tube with 50% of water and 50% of air. The results have shown a good agreement with the expected and a great potential for the next experiments. We also realize that the commercial (standard) collimator has not a good enough resolution. We need a much more narrowed beam to achieve the precision in the results expected for the larger facilities which are going to study dense gas-liquid flow. We intend to use oil and SF₆ (sulfur hexafluoride) as working fluids to allow mimicking the pre-salt production condition where a liquid-gas flow with density ratio smaller than 10 between the phases is observed.

Keywords: Gamma-ray densitometry, two-phase flow, gas-liquid flow, dense gas, stratified flow

1. INTRODUCTION

Multiphase pipe flows in the oil and gas industry have motivated a large number of research works for the last decades. An important characteristics of a gas-liquid flow in a pipe is the flow pattern, which is how the phases are geometrically distributed (Elseth, 2001). Despite the attention paid to gas-liquid pipe flow, there are few studies in the literature about the case of gas-liquid flow at high pressures in horizontal or almost horizontal pipes, where there is low density ratio between fluids.

Tzotzi (2011) argues that the gas density has influence on the transition from stratified smooth to stratified wavy, using phases with maximum density ratio of 10. Even though there is a number of studied focused on flow patterns, the density ratio between the phases has not been deeply studied, i.e. the effects of density and pressure on flow behavior.

Measurement techniques based on radiation attenuation have been extensively used in multiphase flow applications. The high penetration capacity and low fluctuation intensity of gamma-rays are proper for measuring phase fractions with high precision (Jayanti and Hewitt, 1991). The spatial resolution has also been studied, mostly for medical applications, providing necessary concepts for its improvement (Bishop and Abookazeni, 1979; Valda, *et al.*, 2005).

In this work we are going to study the gamma-ray technique for a static flow, first to acquire the necessary expertise on the technique and later to understand its precision and resolution limitations. The spatial resolution of the technique is a major point to our future works, where we expect to study phase-fraction distribution and the flow patterns in dense-gas-liquid flow, with fluids having low density ratio, using the gamma-ray technology.

2. THEORY

The principle of the gamma-ray attenuation technique is based on the fact that electromagnetic radiation is attenuated as it passes through matter. This attenuation is due to the interaction of the beam (generated from the gamma-ray photons), with the matter, i.e. the material will absorb a fraction of the photons energy. The attenuation of the beam depends on the characteristics of the material, like density and elemental composition and the distance traveled. The capability of a material to absorb gamma radiation is defined by its mass absorption coefficient (μ). We can define the linear attenuation coefficient (γ) as the product of mass absorption coefficient and the density of absorbing material. So, the law of attenuation, also known as Lambert-Beers is represented by (Kumara et al., 2009):

$$I = I_0 \exp(-\mu\rho x) = I_0 \exp(-\gamma x) \quad (1)$$

where I is the local intensity of the beam, I_0 is the incident intensity and x is the absorber thickness and represents the distance traveled by beam. We can also express the mass absorption coefficient as a function of atomic mass number A_M from the material, and the atomic absorption cross section σ_A :

$$\gamma = \left(\frac{N_A}{A_M}\right)\rho\sigma_A \quad (2)$$

and N_A is the Avogadro number. In the case of an air-water two-phase flow, material properties and geometric distribution from both materials should be considered (Amundsen, 2011). The water volume fraction ε_w can be defined by

$$x = x_w + x_a \quad (3)$$

$$\varepsilon_w = \frac{x_w}{x_w + x_a} = \frac{x_w}{x} \quad (4)$$

where the subscripts w and a denote respectively the water and air phases. Substituting the equations (3) and (4) in Eq. (1) we have:

$$I = I_0 \exp [x(-\gamma_w \varepsilon_w - \gamma_a(1 - \varepsilon_w))] \quad (5)$$

or:

$$\varepsilon_w = \frac{1}{\gamma_w - \gamma_a} \left[\left(\frac{\ln(I_a)}{x} \right) - \gamma_a \right] \quad (6)$$

To obtain the linear attenuation coefficients it is necessary to run calibration scans with single-phase flow. Applying Eq. (1) for each phase, the results will be, for water:

$$I_w = I_0 \exp(-\gamma_w x) \quad (7)$$

Analogous for air:

$$I_a = I_0 \exp(-\gamma_a x) \quad (8)$$

Finally, combining the calibration equations (7) and (8) we obtain the logarithmic relation for the water volume fraction:

$$\varepsilon_w = \frac{\ln\left(\frac{I}{I_a}\right)}{\ln\left(\frac{I_w}{I_a}\right)} \quad (9)$$

where I is the intensity measured for the air-water flow, I_a the measured intensity for air calibration scan and I_w the measured intensity for the water calibration scan.

2.1 COLLIMATOR

The gamma-ray system includes two collimators, one in the emitting source and one in the detection component. Each of them performs different functions. The first collimator is usually cylindrical (round-hole type) and must be placed right after the radiation source, in order to narrow the beam. This is necessary since the beam is emitted spherically which results in a dispersion angle. This dispersion may be seen as a problem for the spatial resolution,

especially in the interfaces, since the minimum step possible is limited by the beam width as it passes through the tube. It is possible to see the beam path in the Fig 1.

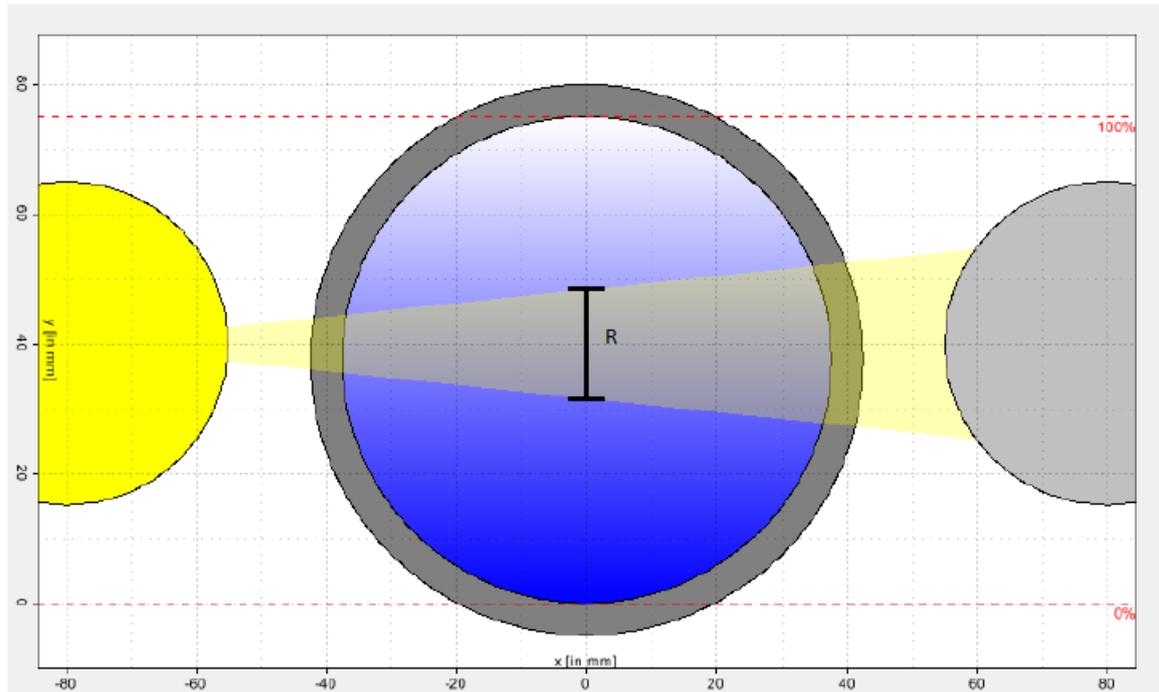


Figure 1: Example of a beam dispersion from an industrial gamma-ray densitometer. Values provided by Vika Controls.

The second collimator usually has the form of parallel plates (parallel-hole type). Because of the complex interaction of radiation and matter, the intensity measured by the detector is not easily distinguished by its nature. For the case of an isotope emitting radiation with an intermediate energy level (for example 661.6 keV), the effects of Compton scattering (single and multiple) and also a secondary radiation must be considered. These two effects work as a noise inducer in the receptor. The second collimator has the function to filter this radiation.

Both collimators work with a trade-off about the total available energy (or sensitivity) and the spatial resolution. A pair of collimators with small aperture may improve the spatial resolution but will certainly decrease the total energy available in the experiment. So, the main problem is about to work with the geometrical dimensions of the collimator to obtain the desirable resolution. A mathematical expression for the resolution is discussed by Valda, *et al.*, (2005) and is given by:

$$R = d \left(1 + \frac{L}{\epsilon} \right) \quad (10)$$

where d is the collimator diameter, L is the distance between the collimator face and the point where we want to calculate de resolution and ϵ is the collimator thickness.

3. EXPERIMENTAL METHOD

3.1 Experimental apparatus

The gamma-ray densitometry technique was applied in an experiment using static fluids in a tube. The experiments were performed in the Industrial Multiphase Flow Laboratory (LEMI) of the University of São Paulo (USP), São Carlos Campus. The test line is composed of a 108.45 mm diameter stainless steel pipe and has a system for its vertical movement. The gamma densitometer system is basically composed by a radioactive source, a detector and a signal processing system. For the present measurements the radioactive isotope source used is the Cs-137. The Cs-137 source has an intermediate radiation energy of 661.6 keV and an average half-life of 30.2 years. For detection we use a scintillation detector of Sodium Iodide (NaI). The working fluids in this first experiment were water and air. Fig 2 shows the used experimental apparatus.



Figure 2: Apparatus for operating the gamma-ray densitometer, with vertical movement

To achieve measurements of phase fraction distribution with milimetric resolution we need first be able to take very small steps in the vertical direction. For this, we developed an actuator for positioning. The mechanical adjustment system allows micrometric vertical movements covering the entire pipe section.

The second necessary point is a pair of collimators, one in the source of radiation and another in the receptor. The first collimator is built to narrow the gamma-radiation beam. The minimum vertical step is related to the beam dispersion. Since makes no sense a movement smaller than the area covered by the beam, we want a very narrowed beam. The second collimator is placed on the receptor. This is necessary since we have Compton scattering and a secondary radiation due to the interaction of gamma ray and the absorber matter, which may cause some peaks of intensity and loss of resolution. Therefore, the collimator must allow only gamma rays traveling parallel to a specified direction to pass through. In this experiment we used the commercial (standard) collimator that came with the system and are the most used in the industry application.

In the first measurements we used water and air as working fluids in static experiment. The main goal here was to develop the expertise in the gamma ray technique and figure out what are going to be the principal challenges to use the technique in a larger facility. Since the thermodynamics properties of air and water are very well known for the ambient temperature (approximately 25 C in this case) they were perfect suitable for this study.

3.2 Experimental procedure

The water phase fraction should be obtained by the Eq.(9). So, we first need the calibrations curves for water and air. With the empty tube we measured the intensity in 9 points at the radial direction, obtaining the calibration curve for the air. The figure 3 shows an image of a sectional area indicating where the points are going to be taken. First we take a point at the upper boundary of the tube and the next is taking subsequent steps of 13 mm down the tube. The same procedure was done with the tube full of water, getting the water curve. The values obtained get stored in the density meter LB 444 which is the electronic device connected to the receptor.

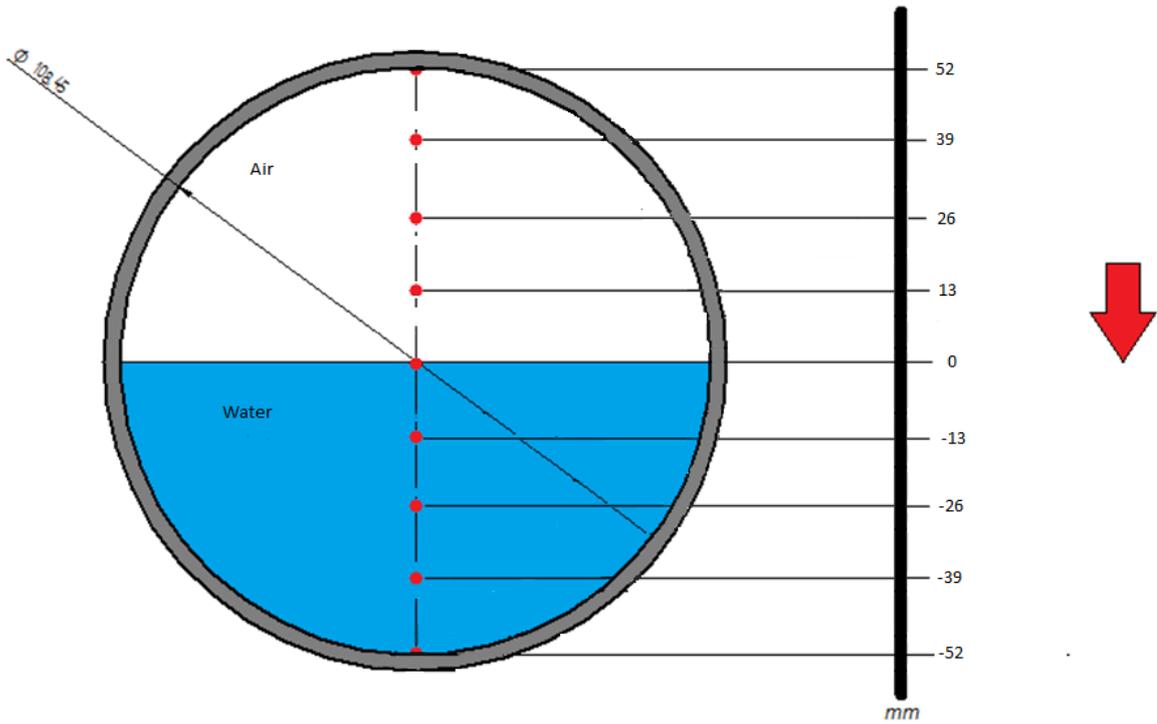


Figure 3: Schematic measurement distribution in a sectional area

After the calibration curves got stored in the electronic meter we drained out the water from the tube and started to add enough water until it is approximately 50% water and 50% air. With a known volume and after waiting for the water become fully static we started the scan measurement at the same point as before, as shown in fig.3. The meter LB 444 gives us the intensity for each point in a sectional area.

4. RESULTS AND DISCUSSIONS

Using the data from the calibration curves and the measurement scan we can use the Eq.(9) to obtain the water phase fraction. We plotted the phase fraction as a function of dimensionless distance (the source height, h , divided by the tube internal radius, R). Result can be seen in the Fig 4

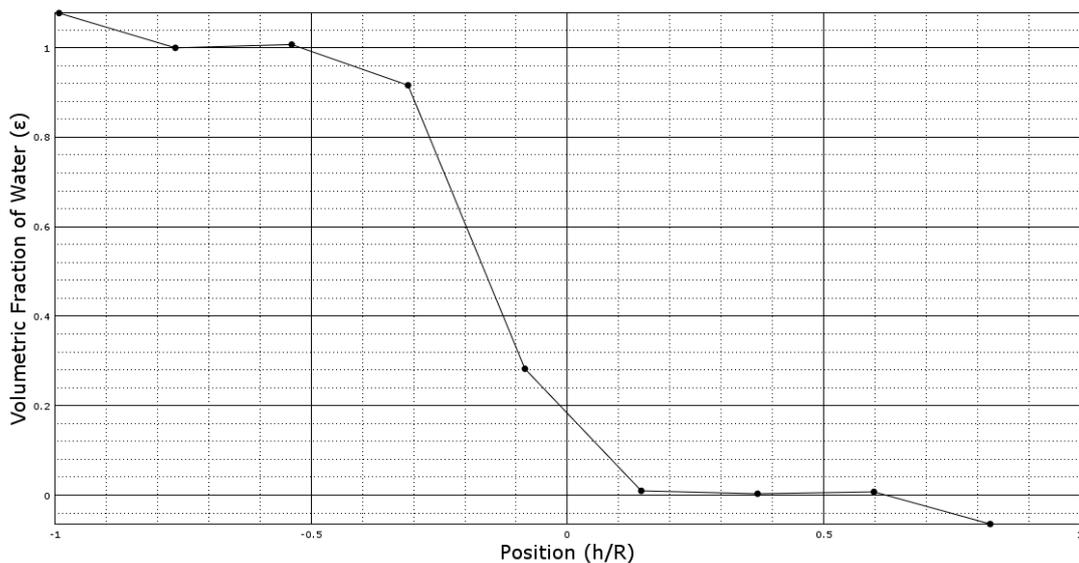


Figure 4: Water Phase Fraction as function of the dimensionless position

As we can see in the Fig. 4, it indicates zero water phase fraction at the end of the points (upper boundary). It agrees with our expectations since there is only air at the top of the tube. Then an sharp increase of the water phase fraction as it passes through the center (from the position at 0.25 to -0.25), until it reaches 1 (only water phase). Even though the transition is not exactly on the center, probably because the center of the tube is not perfectly aligned with the center of the source of radiation, the increase was surely expected, since in the interface it turns from air to water, until it is only water at the bottom of the tube.

Even though the technique has shown effectiveness and gave a result aligned with the expected from the theory, the precision achieved using the standard collimator is not good enough. It can be seen analyzing the upper and lower borders and also the interface. The first point is lower than expected probably because the measurement is taking matter from inside the tube and also from outside. Since the beam is divergent, so it has some thickness, part of the beam is passing inside the tube and part is passing outside the tube. This same explanation applies to the other cases. At the bottom of the tube the beam is probably measuring the water inside and air outside the tube. And in the interface, part of the beam is being attenuated by one phase and part by the other phase.

5. CONCLUSIONS

So we can conclude that the technique is powerful and the results agree with the expected but the standard configuration for the collimators are not good enough for the desired precision and so must be improved. For future works, we aim to apply the gamma-ray technique to obtain a database of local phase-fraction distribution for stratified dense-gas-liquid flow in an horizontal pipe, using oil and SF₆ (sulfur hexafluoride) as working fluids. To achieve a higher resolution we are going to develop a new collimator to narrow the beam until a defined precision.

6. REFERENCES

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