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TIME SERIES ANALYSIS OF GAMMA DENSITOMETRY SIGNALS

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Single, narrow-beam densitometry has been developed as a method for determining the flow regime and void fraction for industrial liquid–gas experiments at high pressures and temperatures in a vertical, thick-walled, steel vessel. To develop suitable techniques, the experimental conditions were simulated using a transparant air/water column. In the transition region from bubbly to slug flow, a time sequence of four regimes, viz. annular flow, partially developed annular flow, coalescing bubble flow and bubbly flow were visually identified in a given cross section. Gamma rays were used to interrogate a column diameter, and digital time series analysis methods were applied. Amplitude spectral densities were used to determine any periodicity in the gas phase flow. The average void fraction for periodic gas flows was obtained by analysis of probability density distributions (PDD). The time sequence of the flow regimes was obtained from the signal magnitude of the diametral void fractions and the time spent in each regime was measured by the associated probability. The results compared well with those obtained from other methods. In the bubbly flow region, the standard deviation of the PDD exceeded that expected for nuclear counting. This bubble noise was assessed with respect to bubble properties.

1. Introduction

Chemical reaction rates between two fluids, one gaseous and one liquid, will depend, among other things, on the contact surface between them. In a set of high-temperature, high-pressure industrial experiments where the two fluids are both flowing up a vertical cylindrical reaction vessel, the flow regime and the void fraction of the mixture are important process parameters. Since invasive techniques were inappropriate for these experiments, non-invasive methods were sought to identify the flow regime, to measure the frequency spectrum of any periodic flow, and to measure the time averaged void fraction.

Single, narrow-beam gamma-ray densitometry with digital time series analysis of the signals was developed for this purpose.

2. Background theory

In a vertical pipe containing a slowly moving or stationary column of liquid through which a gas is percolated, the condition at any cross section is relatively simple with a high degree of symmetry about the axis. It will have one of two states (see fig. 1). In

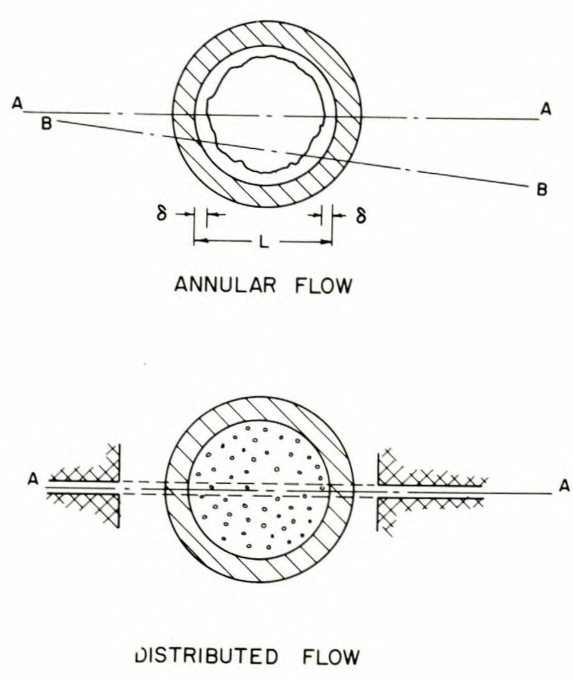

Fig. 1. Schematic illustration of the possible two-phase flow states in a vertical pipe.

distributed or bubbly flow, the gas phase is uniformly distributed throughout the volume in small discrete bubbles. The void fraction, α_d, defined as the fraction of the total volume occupied by gas, is nominally the same in any partial volume such as the beam volume of a densitometer. Thus the void fraction measured along the beam α_1 equals the cross-sectional void fraction α_d.

When the gas flows through a central core, the liquid forms a non-uniform annulus of thickness δ around the inside diameter, L. In this annular flow state, the cross-sectional void fraction, α_a, is not the same as that of a partial volume. For a narrow-beam densitometer aligned on a diameter, the beam void fraction $\alpha_2 = 1 - 2\delta/L$ while $\alpha_a = (1 - 2\delta/L)^2$ so $\alpha_a = \alpha_2^2$. If the flow state is unknown, then single narrow-beam densitometry gives an ambiguous answer.

Of a number of methods developed to overcome this ambiguity, an effective one has been multibeam densitometry where the diametral beam is supplemented by chordal beams. The existence and thickness of liquid annuli can be deduced from the differences between beam void fractions [1,2].

When the void fraction measurement can be made at the expense of flow regime information, a good approximation will be obtained by broad-beam gamma-ray densitometry over the complete range of flow regimes [3].

As the gas flow rate is increased for most gas/liquid combinations, the flow state is bubbly at low flow and annular at high flow. Between these is a transitional range of flow rates where axial asymmetry occurs. The flow state alternates stepwise between the bubbly flow state and annular flow state, as "plugs" of large bubbles flow through the pipe. The plug occupies most of the pipe diameter and is of variable but discrete length.

Thus, in the slug flow regime*, the time-dependent beam void fraction $\alpha_b(t)$ alternates between the annular and distributed flow states.

For the reaction vessel application, the flow regime must be identified and could range from bubbly flow to slug flow, but not continuous annular flow. Also, the densitometer must have a vertical scanning capability. These conditions ruled out broad beam and multi-beam densitometry. We reasoned that the alternating flow states of slug flow would be recognizable with single narrow-beam densitometry, and continuous conditions could be unambiguously interpreted as bubbly flow.

Identification and analysis of time variant phenomena can be done via the method of time series analysis [4,5]. One of these methods is the probability density distribution (PDD) of the sampled time function. Through an iterative process, we determined that the PDD from our process conditions contained discrete features that were well separated by their associated densitometer count rates. Thus the PDD resembled an X-ray spectrum where the statistical noise due to the count rate was analogous to spectrum line broadening due to detector noise.

The resolution of the PDD is related to the count rate by a full width at half maximum

$$\mathrm{fwhm} = 1.66\,(N/T)^{1/2}, \tag{1}$$

when a ratemeter with time constant, T, is used. The useful width of the PDD will range from a count rate N_0 for the liquid filled pipe ($\alpha = 0$), to N_1 for the empty pipe ($\alpha = 1$). If there are m features in the PDD with nominally uniform distribution then the separation between features will be

$$\Delta N \approx \frac{N_1 - N_0}{m - 1}. \tag{2}$$

If we assume that separations of one fwhm can resolve relatively strong features then a requirement for a working count rate N_0 can be established for the experiment by equating ΔN and fwhm.

Spectrum analysis methods can then be used to determine the peak area, A_m, and the mean count rate, N_m, for each feature. The ratio of the peak area to the total area of the PDD, A_p, will give the fraction of time, t_m, spent in the flow state of mth feature. For a medium with absorption coefficient μ, the beam void fraction for the mth feature can be calculated from $\alpha_b = \ln(N_0/N_m)/(\mu L)$ and converted to the cross-sectional void fraction, α_m, by $\alpha_m = \alpha_b$ for distributed flow states and $\alpha_m = \alpha_b^2$ for annular flow states. The overall mean void fraction can then be obtained from

$$\bar{\alpha} = \sum_{m=1}^{n} \alpha_m t_m. \tag{3}$$

One disadvantage of PDD methods is the loss of the frequency information of the signals. Amplitude spectrum analyses were done in parallel to obtain the characteristic frequency spectrum of the flow regimes.

3. Experimental method

Glass tubing, 2.5 cm inside diameter by either 1 or 3 m in length was set up to contain a vertical, static, water column. A gamma-ray beam line, using 6.4 mm diameter collimators, was established across a diameter at the mid elevation of the column. ^{137}Cs (662 keV) gamma rays or ^{241}Am (60 keV) gamma rays were used to obtain different attenuations across the column, and the beam intensity was varied as required by inserting absorbers in the beam line.

* In this paper the term flow state refers to the conditions across a cross section at an instant in time while flow regime refers to the general flow conditions in the pipeline. The slug flow regime describes the condition where "plugs" of gas are separated by "slugs" of liquid.

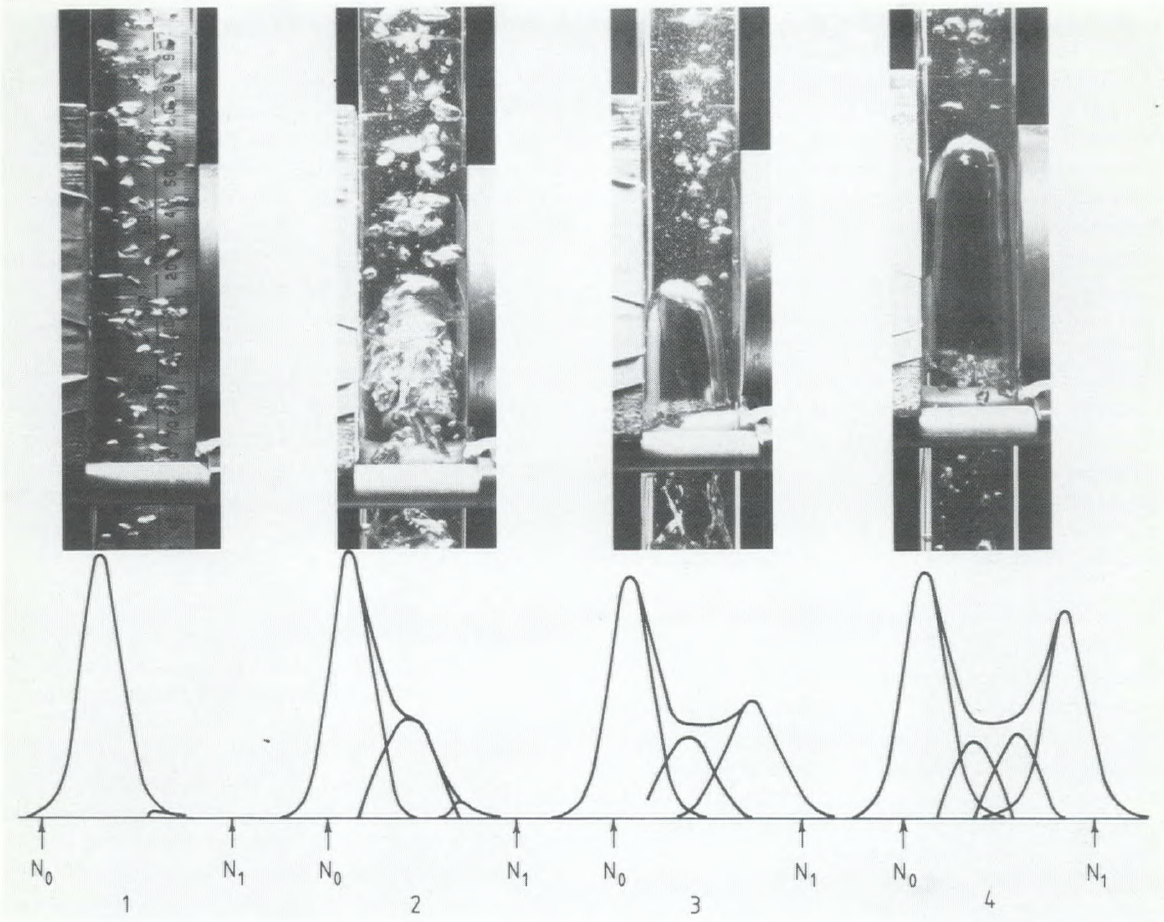

Fig. 2. Representative photographs and probability density distributions of (1) bubbly flow, (2) coalescing bubble flow, (3) initial slug flow, and (4) slug flow.

A 5 cm × 5 cm NaI detector was used with a discriminating amplifier set to reject all but full energy pulses. The pulse train was time-averaged by a linear ratemeter with switchable time constants down to 0.01 s. This ratemeter approach was adopted to give an analog output for processing by the sampling analog-to-digital converter and the computers of the Dynamic Analysis Laboratory at the Chalk River Nuclear Laboratories. Digital time-series-analysis programs were available for these computers.

Air flow was injected into the bottom of the water column, using an orifice as a bubble generator, to generate two-phase flow patterns. Changing the orifice gave different bubble sizes. The rate of air flow was varied to create a range of flow regimes, and the overall average void fraction for each test condition was determined by comparing the height of the static water column to the height with the air flow.

PDD and amplitude spectrum analyses were per-

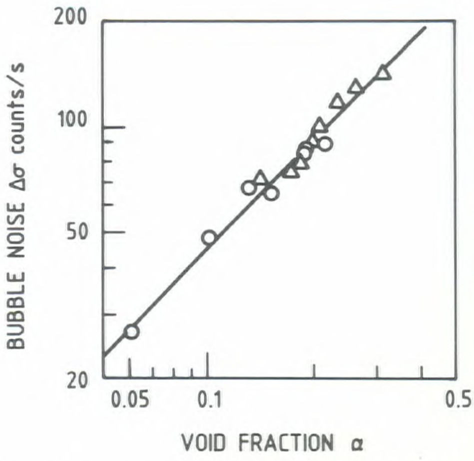

Fig. 3. The contribution of noise to the probability density distribution due to bubble behaviour.

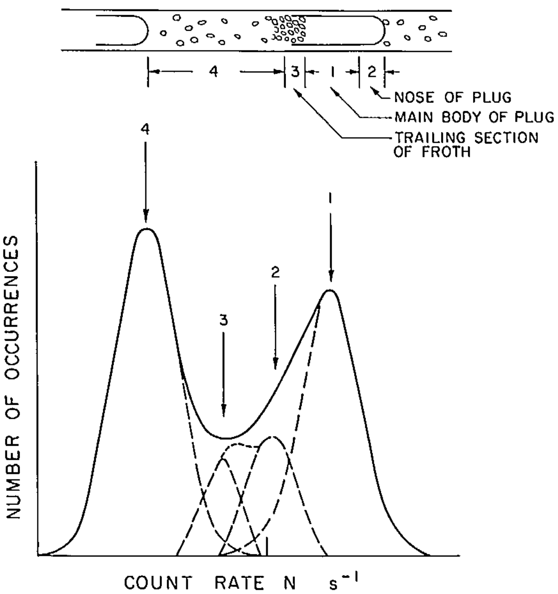

Fig. 4. The identification of the component flow states of the slug flow regime and their appearance in the probability density distribution.

formed on the gamma-ray densitometer signals. We confirmed the resolution relationships with the instrumentation parameters described above, viz.

(a) the sensitive width of the PDD, $N_1 - N_0 = 1 - \exp(-\mu(E)L)$, was altered by changing the attenuation coefficient $\mu(E)$, i.e. by source selection.

(b) beam attenuators varied the base counting rate, N_0, and thereby the fwhm of the PDD, and

(c) different time constants of the ratemeter were selected.

The best approach was to select the shortest available time constant and to size the source energy and beam intensity to the specific application.

4. Results and discussion

The range of two-phase flow regimes generated by progressively increasing the air flow rate had distinctive features, or flow states, visibly identifiable in the column. Representative photographs of these flow regimes along with the corresponding PDDs (see fig. 2) showed features which are discussed below, in order from left to right.

4.1. Bubbly flow

The discrete bubbles were well distributed radially and with only a slight tendency for groupings of bubbles to form in the axial direction. The PDD had only one feature, and the mean count rate increased with increasing voidage or flow rate. In addition, the standard deviation of the PDD peak, σ_m, increased more than that expected for nuclear counting statistics, σ_k as a result of random disturbances caused by bubbles that were comparable in size to the collimator diameter. The empirical relationship between the bubble noise, $\Delta\sigma$, and the void fraction was linear, where $\Delta\sigma = (\sigma_m^2 - \sigma_k^2)^{1/2}$ (see fig. 3). The relationship was apparently not affected by changing the average bubble size by a factor of two as indicated by data symbols, the circles for small bubbles, the triangles for large (see fig. 3).

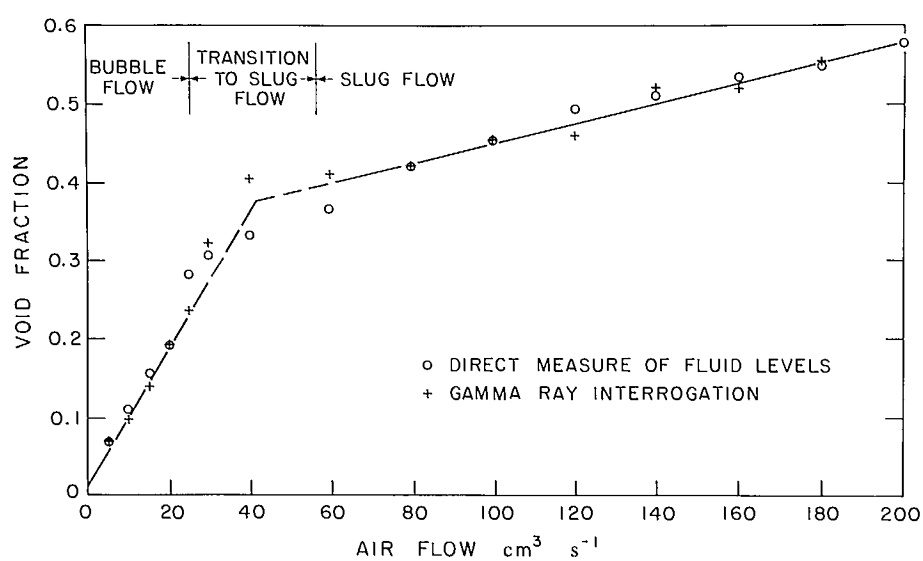

Fig. 5. Experimental measurements of average void fraction by gamma-ray densitometry and by the heights of the static water column and the two-phase flowing column.

Amplitude spectrum analysis showed general noise indistinguishable from the random statistics of nuclear counting.

4.2. *Coalescing bubble flow*

A special periodic form of the distributed flow state formed from simple bubbly flow at high bubble rates. Large groupings of bubbles coalesced into a distinctive new feature. It appeared in the PDD at a higher count rate, indicating a higher local void fraction than the bubbly flow state in the interspaces between the large groupings. The interspatial void fraction dropped to a low value of about 5% void and remained relatively stable as the flow regimes continued to change with increasing air flow.

In amplitude spectra (with the high-frequency filter set at 25 Hz) gathered over periods of 15 min, the periodic behaviour of the bubble groups was indicated by dominant frequencies, (usually 4) in the range from 0.5 to 4 Hz. However, they were not reproduced in successive data sets.

4.3. *Initial slug flow*

The onset of slug flow occurred when the coalesced bubble groups began to form single bullet-shaped bubbles. Cinematography showed them rising with considerable radial motion giving a non-uniform liquid layer around them. Waves were frequently seen on the poorly shaped noses. In the PDD, these incipient annular flow states appeared as the broad third feature at the highest count rate. The coalescent groups of bubbles disappeared as a separate form and its appearance in the PDD indentifies the group of bubbles forming the tail of the plug. As the plugs rose in the column, they overtook slower moving small bubbles and incorporated them into the nose of the plug. However, the turbulence of the passage of the plug generated small bubbles in a group at the tail that were shed to form an equilibrium bubbly flow state in the interspace between plugs.

Short-duration amplitude spectra were similar to those observed for bubble groups, i.e. apparently dominant frequencies that could not be reproduced. However, in a spectrum of long duration, 8 h, there was a broad, relatively smooth distribution of amplitudes rising from the general noise at 0.2 Hz, peaking at 1 Hz and receding back into the noise at 6 Hz. This general spectrum shape was consistently observed at all of the void fractions of the slug flow regime.

4.4. *Slug flow*

Slug flow became fully developed when the plugs had elongated to permit the diameter to expand to form a uniform liquid annulus along the body of the plug. The PDD feature of incipient slug flow separated into two features to give a final form with four features (see fig. 4). The middle two have been attributed to the bubbly tail and the poorly developed annulus of the nose of the plug. These remained relatively constant as air flows and thus void fractions were increased. The lowest count rate was for the bubbly flow interspace while the highest count rate corresponded to the annular flow state along the body of the plug. Increases in air flow or void fractions caused the body of the plug to elongate at the expense of the bubbly flow interspace.

The features of the PDD had now been identified with flow states so that the appropriate conversion from beam void fraction to cross-sectional void fractions could be made. The PDD features were separated by a simple peak extraction method used in gamma-ray spectrometry. It was assumed that the nuclear counting statistics would dominate the two major peaks and that they would be symmetrical. The outer halves of the peaks were folded over and subtracted from the PDD to reveal the inner features. Peak areas, A_m, and mean count rates, N_m, with the associated beam void fractions α_1 or α_2 were calculated. Finally, the average void fraction was calculated using eq. (4), which is an expansion of eq. (3)

$$\bar{\alpha} = \sum_{m=1}^{4} \alpha_m t_m = \sum_{m=1}^{2} \alpha_{1m} \frac{A_m}{A_p} + \sum_{m=3}^{4} \alpha_{2m}^2 \frac{A_m}{A_p}. \qquad (4)$$

The void fraction results thus obtained by densitometry were plotted against air flow, along with the reference void fraction results obtained from the ratio of column heights (see fig. 5). The agreement was acceptable for the proposed application.

5. Conclusions

Single, narrow-beam, gamma-ray densitometry can be used, in conjunction with PDD and amplitude spectrum analyses, to characterize the flow regimes from bubbly flow to slug flow. The PDD gives data on beam void fractions and time fractions for the flow states that comprise the flow regime to permit the determination of average void fractions.

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