Signals features extraction in liquid-gas flow measurements using gamma densitometry. Part 1: time domain

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Abstract. The paper presents an application of the gamma-absorption method to study a gas-liquid two-phase flow in a horizontal pipeline. In the tests on laboratory installation two [241]Am radioactive sources and scintillation probes with NaI(Tl) crystals have been used. The experimental set-up allows recording of stochastic signals, which describe instantaneous content of the stream in the particular cross-section of the flow mixture. The analyses of these signals by statistical methods allow to determine the mean velocity of the gas phase. Meanwhile, the selected features of signals provided by the absorption set, can be applied to recognition of the structure of the flow. In this work such three structures of air-water flow as: plug, bubble, and transitional plug – bubble one were considered. The recorded raw signals were analyzed in time domain and several features were extracted. It was found that following features of signals as the mean, standard deviation, root mean square (RMS), variance and 4th moment are most useful to recognize the structure of the flow.

1 Introduction

Two-phase flow i.e. flow including gas and liquid phase commonly occurs in industry, especially in nuclear, chemical and petrochemical engineering. To fully describe such flow, it is required to determine variation of the velocity or flow rate for each fluid phase, as well as their mixing and distribution between the transported streams. Depending on the liquid phase velocity, viscosity and existence of turbulence, the same volume of gas may be transported in different ways, evolving from bubble up to annular flow. Selected structures in the case of liquid-gas flow in horizontal pipeline are presented in figure 1 [1].

Currently, such flows may be examined by using several methods, such as computer tomography (resistive, capacitive, optical and X-rays), Coriolis flowmeters, optical equipment, PIV, LDA and nuclear techniques [2-12]. These latter are also used by the authors of this article in studies of two-phase flows [13-21].

The nuclear methods are based on application of radiotracers or on a usage of a sealed gamma ray sources for the flow analysis. The last gamma-absorption method is particularly convenient for continuous non-invasive observation of two-phase flows, providing velocity of gas phase as well as a selected information about flow structure. That goal is achieved by statistical analysis of stochastic signals delivered by scintillation probes mounted outside the analysed stream as detectors of the radiation.
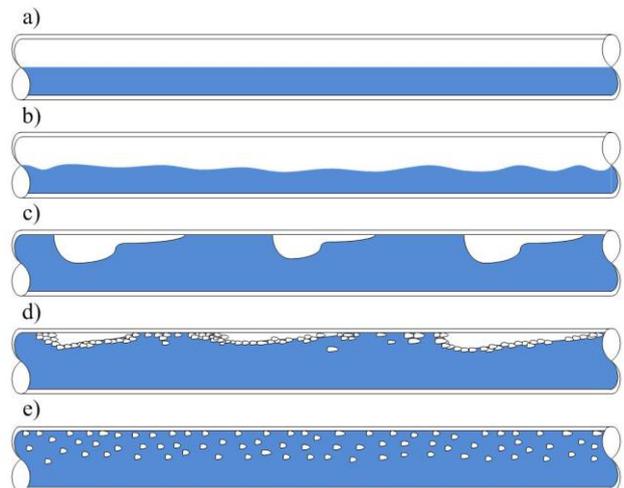

Figure 1. The selected liquid-gas flow patterns in horizontal pipeline: a) stratified smooth, b) stratified wavy, c) plug, d) transitional plug – bubble, e) dispersed bubble.

Flow regimes identification inspires many studies of two-phase flows. A quantitative description of flow regimes can be obtained by the analysis of the signals registered in radioisotope measurements. According to [22-31] the time-series analysis can be made in time domain, frequency domain (spectral analysis) or state-space domain (chaos analysis).

In this work the signals obtained by using gamma-absorption set were analyzed in time domain. Several

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features of signals, e.g., mean, standard deviation, kurtosis, skewness, root mean square (RMS), variance and 4th order moment were extracted. It was examined which features of signals are the most useful to recognize the flow structure.

2 Gamma-absorption in two-phase flow evaluation

The gamma absorption is based on exponential decreasing of a monoenergetic gamma beam in function of composition and geometry of absorbent [9]. The changes of the intensity of radiation are recorded by the scintillation detectors and converted into output electrical impulses [7].

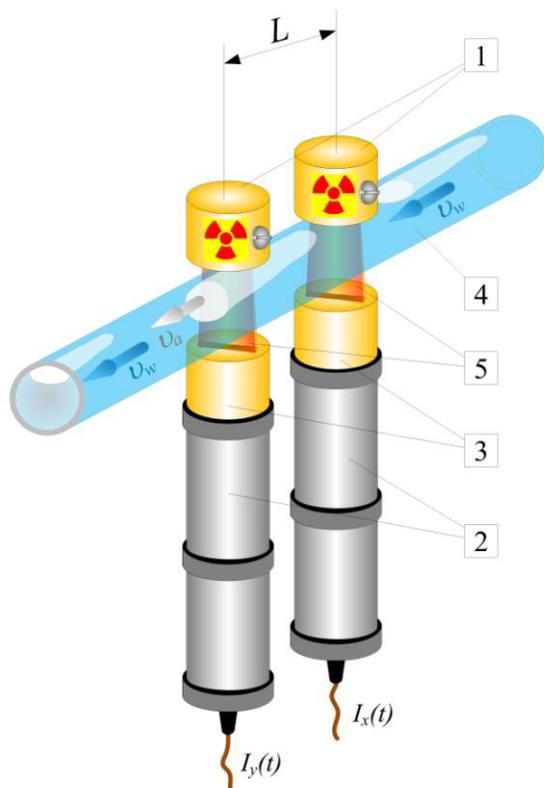The typical gamma-absorption measuring set is presented in figure 2.

Figure 2. The gamma-absorption measuring set: 1 – collimators shaping gamma beam emitted by gamma ray sources, 2 – scintillation probes, 3 – detectors' collimators, 4 – pipeline, 5 – the main beam of gamma rays, v_a – velocity of gas phase, v_W – velocity of water.

Two sealed radioactive sources emit gamma radiation beams shaped by collimators (1). Photons pass through the pipeline with analyzed two-phase flow (air-water mixture) (4) and detector's collimator (3) before achieved scintillation probes (2). In the presented experiment two sets consisting of linear [241]Am sources with an activity of 100 mCi and probes with NaI(Tl) scintillation detectors are placed at a distance of $L = 97$ mm between them. At the outputs of two scintillation probes, count signals $I_x(t)$ and $I_y(t)$ are recorded for the first and second probe respectively.

3 Experimental set-up

The experimental set-up together with measuring equipment described above, was applied in the Industrial Radiometry Laboratory of the AGH University of Science and Technology in Krakow, Poland. Scheme of experimental set-up has been presented in figure 3.
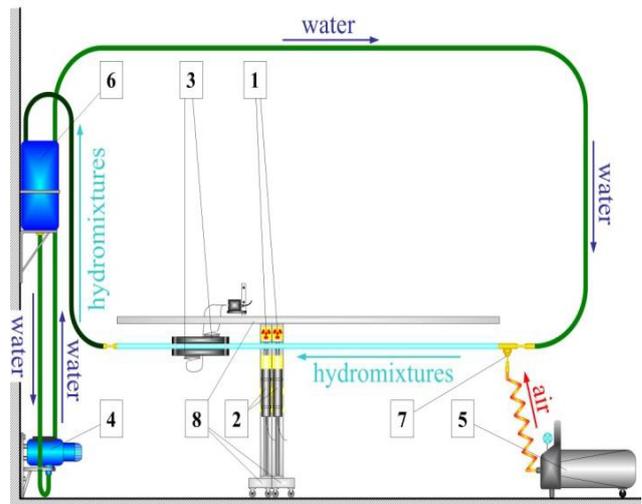

Figure 3. Scheme of experimental set-up: 1 - gamma-ray sealed source, 2 – scintillation probe, 3 – ultrasound flow meter, 4 – pump, 5 – compressor, 6 – air-removing container, 7 – air nozzle, 8 – shifting system of gamma-absorption set.

The test section consists of a transparent acrylic glass pipe with internal diameter of 30 mm and a length of 4.5 m. Water is pumped by a rotary pump (4) and air is provided by the compressor (5) by an injector nozzle (7). Due to this, the controlled mixture of water and air, fills the measuring pipe, and flows up to the air removing tank (6). The measuring system consisting of two γ-radioactive sources (1), two scintillation probes (2) and the system of data acquisition and analysis. The measuring set is mounted on a special trolley (8), which allows to move the set along the pipeline. The water flow rate being continuously measured by Uniflow 990 ultrasonic flowmeter (3). The rotary pump (4) controlled by an inverter enables selection of water velocity in the measuring pipe between 0.5 - 2.5 m / s. The transparent measuring section of the pipeline allows a photographic documentation of the observed two-phase flows [13].

The data acquisition equipment is comprised of PC with the dedicated counters card connected to a USB port. The pulses $I_x(t)$ and $I_y(t)$ obtained from the detectors counted within the sampling time $\Delta t = 1$ ms create stochastic signals $x(t)$ and $y(t)$. The analysis of these signals allows to determine the mean velocity of gas phase v_a, its concentration and void fraction [18-21].

4 Examples of recorded signals

In this work there are three structures of air-water flow in horizontal pipeline, which are being considered: a plug flow, bubble flow, and transitional plug-bubble flow. For these types of flow the measurement signals were recorded in experiments denoted as: BUB6, BUB4,

and BUB1 with a sampling rate of 1000 Hz. Obtained from the first probe data records length on 300,000 samples have been written to files:

- BUB601 - plug flow: $v_W = 0.90$ m / s, $v_a = 0.710$ m / s,
- BUB401 - transitional plug – bubble flow: $v_W = 1.36$ m / s, $v_a = 1.066$ m / s,
- BUB101 - bubble flow: $v_W = 1.92$ m / s, $v_a = 1.446$ m / s,

where v_W – velocity of water measured by ultrasonic flowmeter Uniflow 990. Velocity of gas phase v_a was determined using cross-correlation method [32-34]. Photos of particular types of structures performed in a laboratory and time records of the signals obtained in experiments BUB6, BUB4, and BUB1 are presented in figure 4.

5 Signals features extraction

The data records registered in the experiments BUB6, BUB4, and BUB1were divided into segments containing 10,000 samples. Developed in LabVIEW software allows to use moving average to smooth out short-term fluctuations, and overlapping (0 – 90%) of the segments [35]. Based on the analysis of these segments the following parameters ("features") were calculated for the three types of the flow regimes ("classes"): "plug flow", "transitional plug – bubble flow", and "bubble flow":

- mean value:

$$\mu = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{1}$$

- variance:

$$\sigma^2 = m_2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu)^2 \tag{2}$$

- standard deviation (STD) σ,
- 4th order moment:

$$m_4 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \mu)^4 \tag{3}$$

- root mean square (RMS):

$$RMS = \sqrt{\mu^2 + \sigma^2} \tag{4}$$

- skewness:
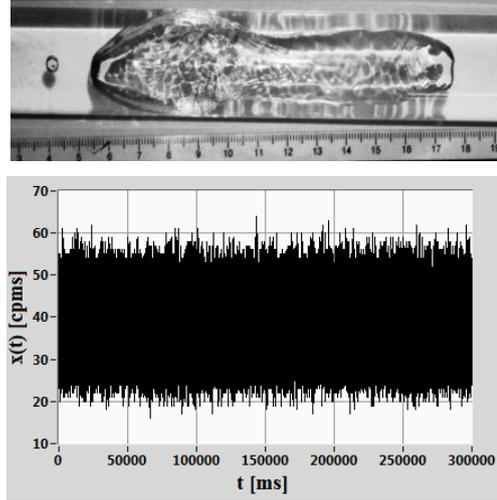
$$g_1 = \frac{m_3}{m_2 \sqrt{m_2}} \tag{5}$$

where

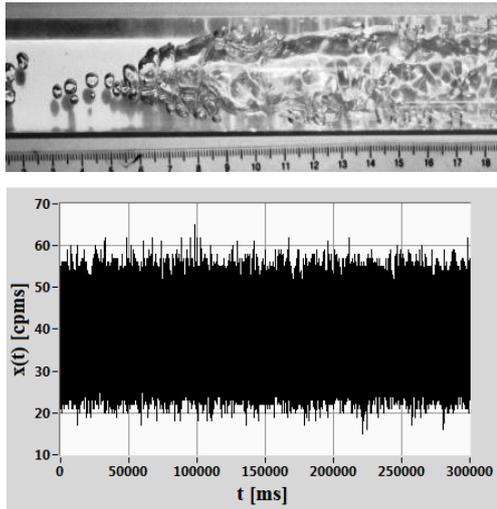$$m_3 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu)^3 \tag{6}$$

- kurtosis:

$$g_2 = \frac{m_4}{m_2^2} - 3 \tag{7}$$

a)

b)
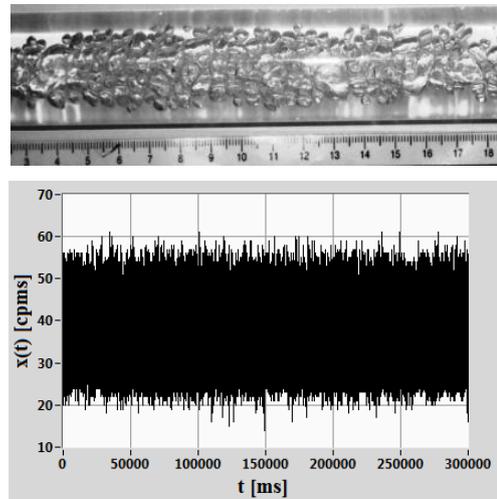

c)

**Figure 4.** Pictures of the flow structures, and time records of signals $x(t)$ obtained in experiments (a) BUB6, (b) BUB 4 and (c) BUB1.

The data presented in figure 5 show values of the statistical parameters as a function of a segment number. In the analyses, the following settings, determined experimentally, were applied: width of moving average window: 20 samples, overlapping: 80% [35].
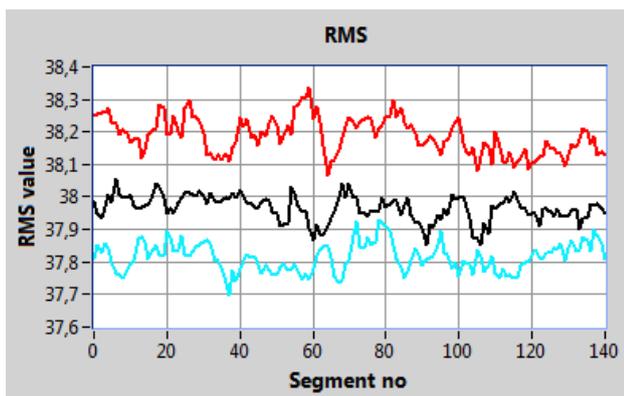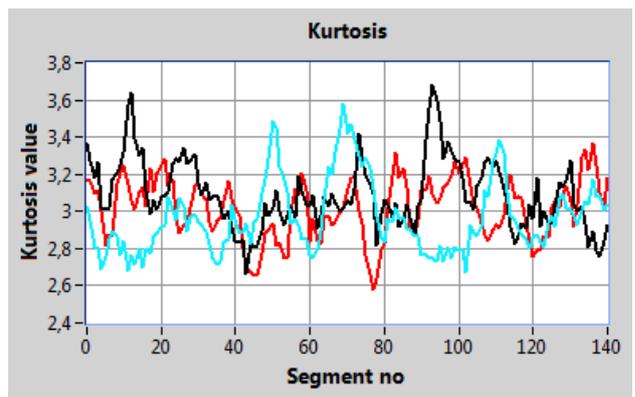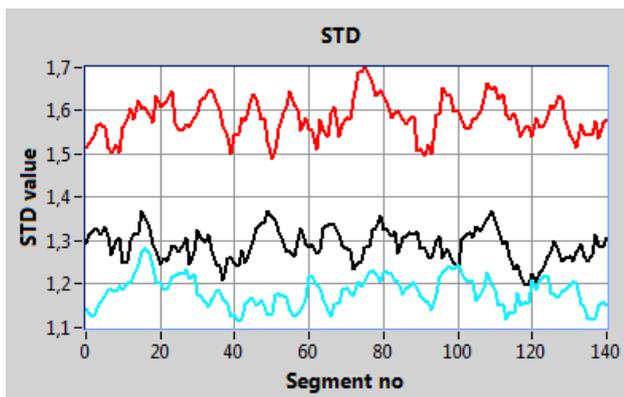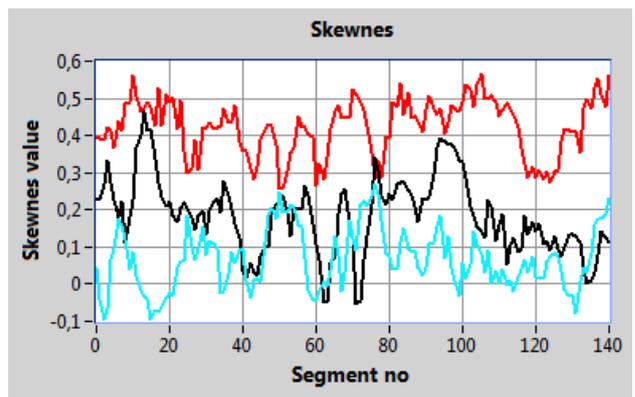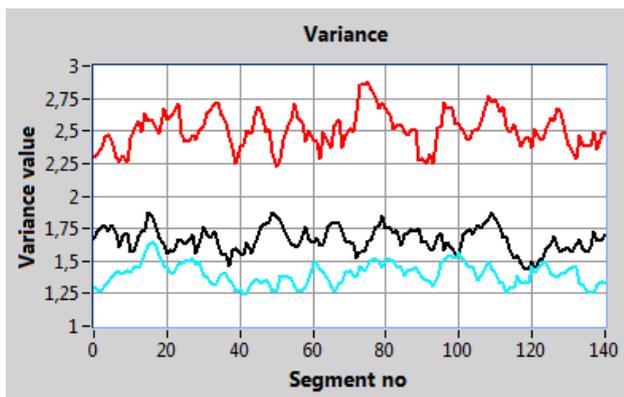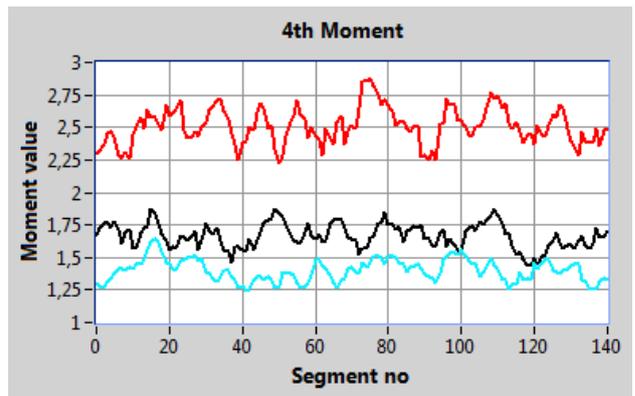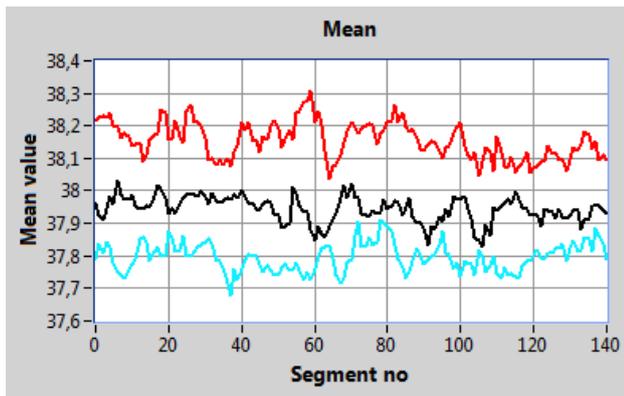
BUB601 - plug flow
BUB401 - transitional plug – bubble flow
BUB101 - bubble flow

Figure 5. Statistical parameters ("features") of BUB601, BUB401, BUB101 data records, obtained for segments length of 10,000 samples.

On the basis of the graphs presented in figure 5, it was found that the best separation for signals BUB601, BUB401 and BUB101 have mean, RMS, STD, variance and 4th order moment. The last three features are the best to separate the class "plug flow" (BUB601). It turned out that skewness and kurtosis do not allow the separation of flow structures.

6 Conclusions

In the paper an application of the gamma-absorption method to recognition of the gas-liquid flow regime in a horizontal pipeline has been presented. In the tests on laboratory installation the gamma-absorption set based on [241]Am radioactive sources and NaI(Tl) scintillation probes has been used.

Three structures ("classes") of air-water as plug, bubble, and transitional plug – bubble one have been considered. For these types of flow the signals from probes were recorded and analyzed. The selected parameters ("features") of signals in time domain were extracted to flow pattern recognition.

The best suitability for the recognition of flow structures are parameters for which the differences between classes are the greatest. On the basis of experiments it was found that the best indicator considered patterns have mean, RMS, standard deviation, variance and 4th order moment.

Further works will involve the application of the most useful features to flow recognition using machine learning methods.

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