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Comparison of noise reduction methods in radiometric correlation measurements of two-phase liquid-gas flows

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ABSTRACT

Two-phase liquid-gas flows occur frequently in the mining, energy, chemical, and petrochemical industries. One of non-contact methods used to analyse these flows is the gamma ray absorption method. However, the signals received from radiation detectors contain a significant stochastic noise, which makes them difficult to analyse. The article describes four methods of noise reduction in cross-correlation measurements of water-air mixture flows in a horizontal pipeline. In addition to the classical method of digital filtering of signals, the methods consisting in signal spectrum filtering, discrete wavelet transformation, and Nadaraya-Watson kernel estimator are described. Sample results of the measurements carried out in the horizontal pipe having the inner diameter of 30 mm for the air bubbles velocity ranging from 0.7 to 1.4 m/s are presented. In the research, the absorption set composed of two linear Am-241 gamma-ray sources and two scintillation NaI(Tl) probes was used. It was found that the lowest measurement uncertainty of the dispersed phase flow velocity is obtained when the cross-correlation distributions of the recorded signals are smoothed using the Discrete Wavelet Transform or the Nadaraya-Watson kernel estimator.

1. Introduction

Two-phase liquid-gas flows can be observed in mining, chemical, petrochemical, food, and energy industries. Measuring parameters of such flows, for example the velocities of individual phases and their involvement in the mixture, etc., is not simple and requires sophisticated and often non-invasive measurement techniques. In recent years, methods using capacitive, resistive, optical, or X-ray tomography have been developed [1–5]. Other techniques are: particle image velocimetry (PIV), speed camera, and ultrasonic or Coriolis flowmeters [6–11]. For many years, two-phase flows have also been studied by radioisotopes [12–15].

For the liquid-gas flow, the mean velocity of the dispersed phase can be calculated on the basis of its transportation time delay recognized between two signals obtained from the scintillation probes. After specific pre-processing, these signals become ergodic, so due to the stochastic nature of radiation, they can be analysed in time and frequency domains. The methods to be applied in this case may include such functions as: differential or combined cross-correlation (*CCF*), *CCF* with Hilbert transform, conditional averaging, deconvolution, and the phase method [16–23]. However, the signals received directly from the probes are often inconvenient for analysing due to the presence of significant noise (background radiation, nuclear decay fluctuations, noise generated by the electronics, etc.) [23,24]. Often, the level of disturbances is so high that the most commonly used cross-correlation method does not always give accurate results. Therefore, the noise level in the recorded signals is to be reduced before calculating the CCF. Alternatively, smoothing of the CCF can be applied. The use of advanced noise reduction methods can give a more accurate determination of the dispersed phase transportation time delay and then its velocity, as well as other parameters of the flow. The considered procedure is also of high importance in other fields of science and technology, e.g. in geophysics, or medicine [25–30].

The article describes the application of selected noise reduction methods in cross-correlation measurements, with the liquid-gas mixture flow in a horizontal pipeline as an example. In addition to classical digital filtering of recorded signals, three other methods: the method based on "spectrum filtering", the discrete wavelet transform, and the Nadaraya-Watson kernel estimator, are applied [31–39]. Section 2 gives the description of the experimental setup used for conducting the

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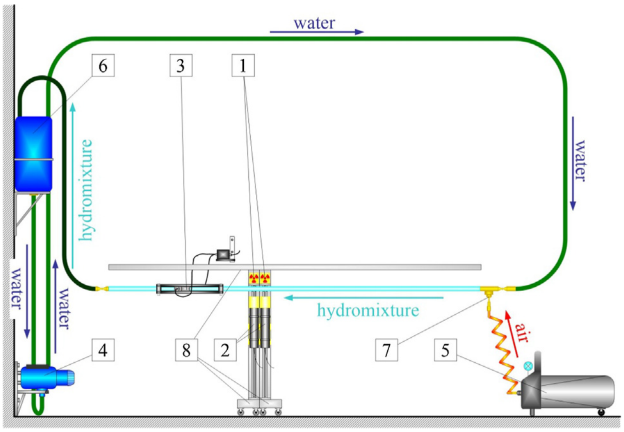

Fig. 1. Diagram of installation used for liquid-gas mixture flow tests: 1 - lead collimators of gamma radioactive sources, 2 - scintillation probes, 3 - ultrasonic flowmeter, 4 – rotary pump, 5 - air compressor, 6 - expansion tank, 7 - air nozzle, 8 - shifter kit of the absorption set [16].

study. Section 3 presents the idea of the radioisotope method and the absorption set used for the measurement. In Section 4, the basic information about the time delay estimation using cross-correlation techniques is overviewed, while Section 5 describes the noise reduction methods used in the article. Section 6 summarizes the obtained results, and the final section presents conclusions drawn from the research.

2. Experimental setup

The analysis presented in the article makes use of the results of experiments performed on an experimental setup built at the AGH University of Science and Technology in Krakow, Poland, the Faculty of Physics and Applied Computer Science [16,20,23]. The main part of the setup is a hydraulic installation the diagram of which is shown in Fig. 1. The installation consists of a horizontal pipeline made of Plexiglas with length of 4.5 m and inner diameter of 30 mm. It is connected via a hose to a rotary pump (4), which forces the water circulation. The expansion tank (6) acts also as a venting system. To produce the mixture, the required air volume is forced into the pipeline from the compressor (5) via the nozzle (7). The absorption measuring set consists of the radioactive sources in collimators (1) and two scintillation probes (2). The set is mounted in a sliding arrangement (8) to allow the equipment to move along the pipe. The geometry of the deployed absorption set is described in detail in Section 3. A complementary element to the radiometric system is the ultrasonic meter Uniflow 990 (3) which measures the water flow rate.

Adjusting the pump speed within the range between 1000 and 2800 rpm allows to generate various flow patterns in the measuring section of the pipeline. Three characteristic flow structures selected for analysing in the paper are shown in Fig. 2.

3. Measuring technique of gamma-ray absorption

In the hydraulic installation, an absorption set composed of two gamma-ray sources and two probes spaced by the distance $L = 97$ mm was applied. The principle of the gamma absorption measurement and the geometry of the absorption set are shown in Fig. 3.

The gamma radiation beam (5) emitted by the source shaped in the lead collimators (1) passes through the pipe with the flowing liquid-gas mixture (4). As a result of the impact of gamma rays on atoms of the flowing mixture, a weakened beam reaches the scintillation probes (2) mounted in collimators (3) which protect the detectors against scattered and dispersed radiation (7). The measurement geometry allows for registering radiation force changes in a given pipe cross section. The slots in source collimators are 3 mm wide and 20 mm long, while those in detector collimators have dimensions of 4 mm and 40 mm, respectively. Based on earlier gained experience and performed calculations, the geometry of the measurement system was established in such a way as to ensure the most optimal measurement environment (precise X-ray of the given section with the gamma radiation beam).

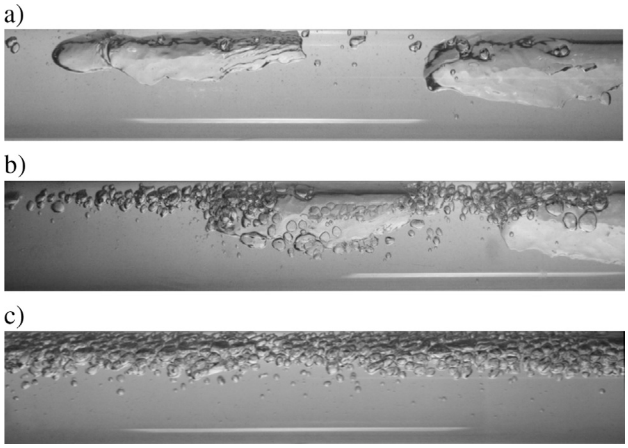

Fig. 2. Flow patterns selected for analysing: a) plug flow, b) transitional plug – bubble flow, c) bubble flow.

For the measurements, the linear radioactive sources Am-241 X.103 AEA Technology QSA, emitting the energy of 59.5 keV and 100 mCi activity, and the probes with scintillation crystals NaI(Tl) type SKG-1, TESLA Company were used.

The gamma radiation intensity changes caused by the water-air mixture flowing through the measuring pipe section give the signals $I_x(t)$ and $I_y(t)$ at outputs of the scintillation probes (Fig. 4a, b).

In each experiment, the signals were sampled uniformly after time $\Delta t = 1$ ms and recorded within the time interval of 300 s. This resulted in their digital representation having the form of functions $x(n)$ and $y(n)$, where $n = t/\Delta t$.

4. Time delay estimation by cross-correlation

The signals from scintillation probes can be used to determine the transportation time delay τ_0. The best-known classical method of time delay estimation of an ergodic random signal is based on the cross-correlation function defined as follow [17,18]:

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)y(t+\tau)dt \tag{1}$$

where T is the averaging time and τ is the time delay.

The transportation time delay τ_0 is determined based on the *CCF* maximum position:

$$\hat{\tau}_0 = \arg\{\max R_{xy}(\tau)\} = \arg\{R_{xy}(\tau_0)\} \tag{2}$$

The discrete estimator for the cross-correlation function can be expressed by the following formula:

$$R_{xy}(\tau) = \frac{1}{N} \sum_{n-0}^{N-1} x(n)y(n+\tau) \tag{3}$$

where N is the number of values of discrete signals $x(n)$ and $y(n)$.

For large data sets, the *CCF* is calculated using the *DFT/FFT*.

Once the estimation of the transportation time delay and the distance L between the probes are known, the average gas phase velocity υ can be calculated from the formula:

$$\upsilon = L/\hat{\tau}_0 \tag{4}$$

The experimental setup described in Section 2 was used for a number of experiments with various parameters of the water-air flow.