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# Measurements of Two-phase Flows in Pipelines Using Radioisotopes and Statistical Signal Processing*

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***Abstract*— This paper presents an application of radiotracers and gamma absorption method in two-phase flow measurements in pipelines. Two different methods were implemented to analysis of acquired signals. Investigated methods are based on the cross-correlation function and the phase of the cross-spectral density distribution. The examples presented in the article illustrate the application of the radioisotopes to evaluation of liquid-gas flow in a horizontal pipe and liquid-solid particles flow in a vertical pipe.**

## I. Introduction

In the natural environment and in industrial applications, two-phase transport often occurs, whether hydraulic (liquid-gas, liquid-solid particles) or pneumatic (gas-solids). To provide a description of such flows, the knowledge of the velocity or flow rate of individual components and their distribution and mixing between the transported phases is necessary [1,2]. Direct measurement of these values is very difficult. However, for several dozen years radioactive isotopes in the form of tracers and sealed sources have been used for this purpose [3-9]. The advantages of nuclear methods include a simple measurement principle and relatively high accuracy. For example, measurement based on the absorption of ionising radiation is non-invasive and allows to determine the flow velocity and concentration of the dispersed phase simultaneously using a couple of sources and detectors. The disadvantages of these methods include the relatively high cost of isotopes and the potential radiological hazard, which requires the application of stringent Atomic Law.

## II. Radioisotope Measurement Methods

### *A. Tracer method*

Radiotracer tests are most often used to measure the flow velocity of any substances in pipelines or channels. The principle of radiotracer measurement is presented in Fig. 1. In this example, the radioactive isotope was dissolved in a liquid and then introduced to the flow in pulse release, where it is mixed in the whole cross-section of the stream and moves at the same velocity $\upsilon_W$ as the rest of the liquid.

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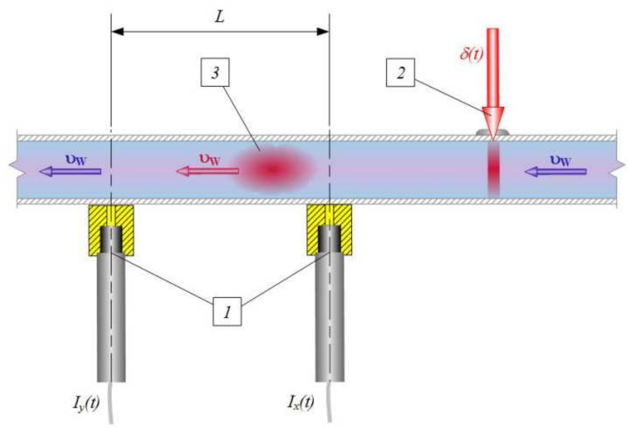


Figure 1. Radiotracer measurement principle: 1 – scintillation detector with collimator, 2 - radioactive tracer injection, 3 – flowing tracer.

The tracer moves successively over the detectors located at the distance $L$ from each other. At the outlet of the probes, one obtains the counts $I_x(t)$ and $I_y(t)$, which after due processing produce signals proportional to the gamma radiation emitted by the tracer. Statistical analysis of registered signals allows to determine the average transport delay $\tau_{0W}$ at the measuring stretch $L$ and the average velocity of the flow of liquid:

$$\upsilon_W = L / \tau_{0W} \qquad (1)$$

### *B. Absorption method*

This method utilises sealed sources of ionising radiation and usually relies on two detectors. The principle of measurement for the example of the water-air flow is shown in Fig. 2. The used radiation sources, with an activity level of 3.7 GBq (100 mCi), emit nearly $4 \cdot 10^9$ photons per second at the full solid angle. After passing through the examined stream, part of the radiation which has not been absorbed or scattered ends up in the scintillation probe situated on the opposite side of the pipeline. A similar set of source and detector is placed at a determined distance $L$ from the first set. At the outlet of the probes impulse waveforms $I_x(t)$ and $I_y(t)$ are recorded. Counting the impulses at a given time allows obtain stochastic signals describing the temporary state of the stream in the cross-section. The analysis of signals using statistical methods allows determine the most probable transport delay $\tau_0$ and the average velocity of the dispersed phase $\upsilon_P$ moving between the probes.

$$\upsilon_P = L / \tau_0 \tag{2}$$

In the example shown in Figure 2, velocity $\upsilon_P$ represents the average velocities of air bubbles. If necessary, the velocity of the second phase (e.g. water $\upsilon_W$) can be determined e.g. using the tracer method discussed earlier.

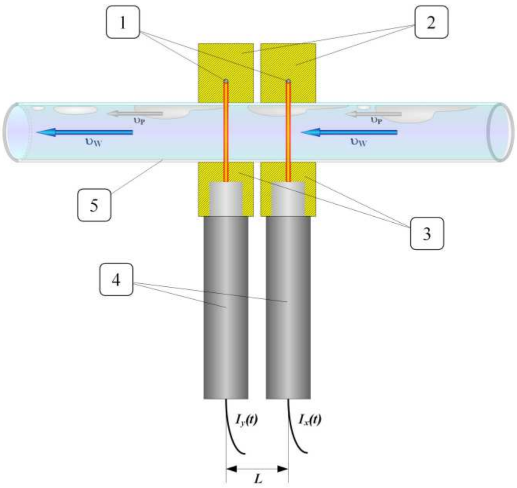


Figure 2. Gamma absorption flow velocity measurement principle: 1 – radioactive source, 2 – collimator of source, 3 - collimator of detector, 4 - scintillation detector, 5 - pipe.

## III. Statistical Methods of Signal Analysis

The signals recorded in the radioisotope measurements contain not only the statistical information on the analysed flow but also interference caused by background radiation, noise floor and fluctuations of nuclear decay. An appropriate selection of measurement conditions (activity of sources, radiation energy, correct formation of radiation beams and selection of probe types) and the use of appropriate processing methods (filtration, averaging) allow to obtain ergodic components. Analysis of such stochastic signals allows to designate the distribution of the minority phase delays at the measurement section $L$ employing statistical methods which use, among others, the standard cross-correlation and cross-spectrum analysis [10-16]. The following examples illustrate the use of the functionality of cross correlation and the phase of the cross-spectral density for this purpose.

### *A. Cross-correlation method*

Impulse waveforms $I_x(t)$ and $I_y(t)$ obtained at the outputs of the scintillation probes counted within the specified time sampling $\Delta t$, after statistical processing form discrete measurement signals $x(n)$ and $y(n)$. Accordingly long parts of the signals with the number of samples $N$ can be used to designate the estimator $\hat{R}_{xy}(l)$ of the cross-correlation function (CCF) from the equation:

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

where: $\tau$ - time delay, $n = t/\Delta t$.

Analysis of the shape of the CCF distribution allows to determine the transportation time delay $\hat{\tau}_0$ [10, 12, 13]:

$$\hat{\tau}_0 = \arg\{\max \hat{R}_{xy}(\tau)\} = \arg\{\hat{R}_{xy}(\tau_0)\} \tag{4}$$

In order to designate CCF, the Fast Fourier Transform is usually applied.

### *B. Cross-spectral density phase method*

Cross-spectral density function (CSDF) $G_{xy}(f)$ and the CCF are connected by the Fourier transform. The CSDF phase $\Phi_{xy}(f)$ is a linear function of frequency $f$ and may be used to determine the transportation time delay from the equation:

$$\tau_0 = \Phi_{xy}(f) / 2\pi f \tag{5}$$

To calculate the spectral density one can use DFT/FFT algorithms and Welch's method [11]. Transportation time delay is then determined from the smoothed estimator $\tilde{\Phi}_{xy}(f)$ after the application of the phase wrapping procedure.

Seeing as the function $\tilde{\Phi}_{xy}(f)$ is nominally linear and passes through the coordinate origin, the $\hat{\tau}_0$ time delay estimator can be calculated based on the slope $a$ of the regression line fitted to the CSDF phase [17,18]:

$$\hat{\tau}_0 = \frac{1}{2\pi}\hat{a} = \frac{1}{2\pi}\left[\sum_{k=1}^{m} f_k \tilde{\Phi}_{xy}(f_k) \Big/ \sum_{k=1}^{m} f_k^2\right] \tag{6}$$

where $m$ represents the number of pairs of phase and frequency values used to determine the regression line, and $k$ is the number of the harmonics.

## IV. Examples of the Use of Radioisotope Methods in Analysing Two-phase Flows

Combined with the statistical analysis of signals, the presented radioisotope methods are applied in studying many types of two-phase flows. In the following sections, selected research installations were described and examples of measurement results were provided.

### *A. The flow of liquid-gas mixture in a horizontal pipeline*

Figures 3 and 4 present a general view and diagram of the experimental hydraulic installation built in the AGH University of Science and Technology in Kraków (Poland). The installation is part of the laboratory stand designed for conduct research on liquid-gas flows, typical for petrochemistry and observed e.g. during transporting the mixture of petroleum and natural gas. The main part of the installation consist of a 4.5 m long horizontal transparent pipe, to which water is fed from the pump and air from compressor through air nozzle. The water-air mixture flows through the horizontal measurement section of the pipe and enters air-removing container. The work stand is equipped with a data acquisition set and a computer with software allowing carry out statistical analysis of recorded signals. In the described experiments, the following equipment was used: gamma radiation sources Am-241 (X103 AEA Technology QSA), emitting photons with the energy 59.5 keV, and type SKG-1 NaI(Tl) probes with scintillating crystals. Velocity control range for the flow mixture went from 0.5 to 2.5 m/s. The stand also includes a Uniflow 990 ultrasonic flow meter to record the flow velocity of the liquid phase. Regardless of that, the velocity of that phase was periodically controlled using radioactive tracers.

Figure 3. A general view of the measurement section of the installation.

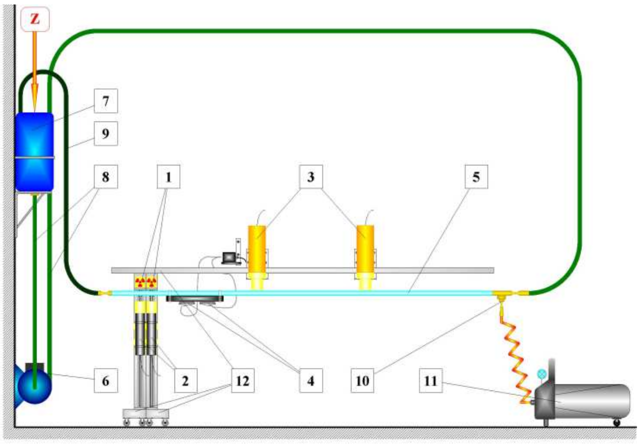


Figure 4. Diagram of the experimental hydraulic installation: 1 – gamma-ray sealed source, 2 – scintillation probe, 3 – scintillation probe for tracer measurements, 4 – ultrasonic flow meter, 5 – horizontal pipe, 6 – pump, 7 – air-removing container, 8, 9 – feeding pipe, 10 – air nozzle, 11 – compressor, 12 - shifting system of gamma absorption set, Z - tracer injection site.

Applying the statistical methods of signal analysis discussed earlier helps to reduce the uncertainty of flow velocity measurements and makes results comparisons possible. These comparisons indicate that in some cases the phase method can be just as accurate as the correlation method. For example, in experiment BUB0006 the same average velocity of the airflow was obtained for CCF and for the CSDF phase: (0.710 ± 0.003) m/s.

### *B. The flow of liquid-solid particles mixture in a vertical pipeline*

In the Water Laboratory at the Wrocław University of Environmental and Life Sciences (Poland), an experimental installation was built in order to study the flow of liquid-solid particles mixture in a vertical pipeline [4,19]. The cited measurements were carried out in the framework of a project aimed at developing a mining technology of polymetallic nodules from the bottom of the Pacific Ocean [20].

A schematic diagram and photographs of selected elements of the installation for studying the hydro-transport of concretions as well as for measurements of velocity and flow rate of the solid and liquid phase are shown in Fig. 5 and 6. Modelling the transport of concretions required adjusting the flow velocity of the mixture from the critical value to 4 m/s and changing of the concentration of the solid phase from individual grains to 0.25. This effect was obtained by constructing two loops feeding the measuring section: in the first loop, solid-phase was fed at a regulated flow rate while in the other one, liquid was fed under pressure which forced the desired flow of the mixture. Both loops were merged (1.5 m before the measuring section), a vertical pipe with an internal diameter of 150 mm. Two absorption sets were built on the 6.55 m long measuring section in order to track changes in the concentration of the solid phase and its velocity at different heights. In addition to that, single probes were used in the tests of flow velocity of the main fractions of the solid phase and water, using radiotracers. After passing through the measuring section, the mixture was separated in the separator. An additional electromagnetic flow meter was placed in the water loop of the installation. The particular pairs of probes were connected to a mobile data acquisition stand with a PC computer. As a result of the conducted experiments, a concept for a measuring device was developed which can be applied to the target mining installation. The device uses the phenomenon of radiation absorption to determine the flow rate of the solid phase $\upsilon_S$, the volumetric concentration $C_{VP}$ and volumetric flow rate $Q_{SV}$.

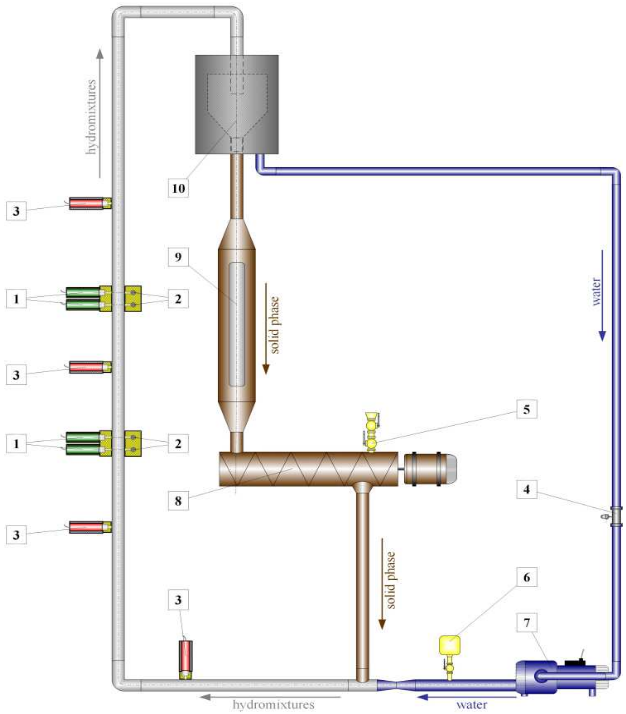


Figure 5. Diagram of the installation in the Water Lab at the Wrocław University of Environmental and Life Sciences: 1 – absorption probes, 2 – sealed sources, 3 – tracers probes, 4 – electromagnetic flow meter, 5 – feeder of marked stones, 6 - feeder of marked water, 7 – pump, 8 – conveyer, 9 – container for solids, 10 – separating container.

Figure 6. Section of the vertical pipe with the transported mixture.

Test flow measurements confirmed the assumptions made and the calculations which used the correlation method. For example, in experiment WRQ0028 the following values were obtained: $\upsilon_S = (2.04 \pm 0.02)$ m/s, $C_{VP} = 0.23 \pm 0.02$ and finally $Q_{SV}$ = $(8.4 \pm 1.0)\cdot 10^{-3}$ $m^3$/s. The additional use of a tracer Tc-99m allowed to determine the flow velocity of water, which was 2.24 m/s for the quoted measurement.

## V. Summary and Conclusion

The article presents basic information about radioisotope methods used in studying two-phase flows: radiotracers and gamma absorption. Radioactive isotopes are most frequently used in these cases due to the easy measurement and the good detectability of tracers, even when significantly diluted. Their disadvantages, however, include: the high costs and the necessity to meet the stringent legal provisions resulting from the radiological risk.

Due to the use of sealed sources of radiation, the absorption method presents a lower risk than radiotracers, and allows carry out contactless measurements of the basic parameters of two-phase flow.

In order to analyze signals obtained from scintillation detectors, using statistical methods is reasonable. Among them, the most known are correlation and phase methods. An important part of the article presents the applications of radioisotope measurements in studying two-phase flows in pipelines. A description was provided of the experimental installations built for the above-mentioned purpose, involving measurements of the flow parameters of the minority phase of liquid-gas and liquid-solid particles mixtures using the absorption method. Examples of the results were quoted for the measurements of flow velocity, volumetric concentration and flow rate of the minority components.

Each studied flow had its own individual character, and carrying out the proper measurements required a careful selection of the radiometric set, in particular, the type and activity of radiation sources, with adequate energy and geometry.

Another major issue is also the calibration of absorption set for a particular medium type, necessary for determining the volumetric concentration and the flow rate, as well as the right selection of analysis methods for signals received by the detectors.

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