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Application of nuclear techniques in two-phase liquid-solid particles hydrotransport investigations

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Abstract. The paper presents gamma radiation application to two-phase flow investigation in a vertical pipeline, where the flow of solid particles transported by water was examined by use of both: radiotracers and gamma-absorption method. The simultaneous use of two methods allows analyzing of important parameters of solid particles hydrotransport. In the described experiments as solid phase the ceramic models representing natural polymetallic ocean nodules were used. Radiotracers allow to track the movements of selected models, representing specified grain size and the designation of its velocity. However gamma-absorption method enables measurement of average solid-phase velocity. For analysis of electrical signals obtained from scintillation detectors the cross-correlation method has been applied.

1 Introduction

Two-phase liquid-solid particles flow occurs often in the mining industry. An example would be vertical pipeline hydrotransport of minerals, e.g. polymetallic nodules. Nodules are porous organic and mineral compositions which contain a various metals (mostly Mn, Si, Fe, Al, Na, Mg, Ni, K, Cu) [1-4]. They occur on the bottom of seas and oceans, but the richest deposits can be found at the Pacific Ocean bed in depth about 5000 m in the so called Clarion-Clipperton zone. The ocean nodules usually have the form of irregular grains with the diameter of several mm up to 0.5 m and density of about 2 g / cm^3 in wet state. The mining of nodules using the hydraulic method requires nodules vertical transport by water to sea level in extremely hard and varying environment. Determination of the velocity of nodules of various sizes in the vibrating pipeline at a significant depth is a very difficult task and requires the use non-invasive measurement techniques [5, 6].

One of these techniques, which are employed for many years in measurements of two-phase flows in pipelines and open channels, is a method using radioactive isotopes. In nuclear techniques radiotracer is injected under certain conditions into the flow and/or sealed radioactive sources are used [7-19]. In both cases as detectors of radiation the scintillation probes are mounted outside of the analyzed stream.

Typically in such measurements the mutually delayed stochastic signals are provided by detectors located on the outer walls of the pipeline. Measured time delay of signals is applied to determine the velocity of the marked phase (radiotracers method) or averaged velocity of the solid phase (absorption method). In the carried out experiments solid phase has been modeled using ceramic particles representing three grain sizes of natural polymetallic ocean nodules.

The processing of stochastic signals from scintillation probes requires the use of statistical methods in the time and frequency domain [20-26]. The cross-correlation function (*CCF*) is the most known methods of time delay estimation applied for stationary random signals.

2 Application of radioisotopes to investigations of nodules hydro-transport in a vertical pipeline

The basic principle of gamma-ray absorption measurement is based on fact that the intensity of a collimated gamma beam decreases as it passes through matter [5-7, 10-17].

Radiotracer idea is based on marked particle tracking using a scintillation probes placed along the pipeline [7, 8, 18].

The principle of both methods and typical gamma-radiation measuring equipment for liquid–solid particles flow evaluation in a vertical pipeline is presented in figure 1.

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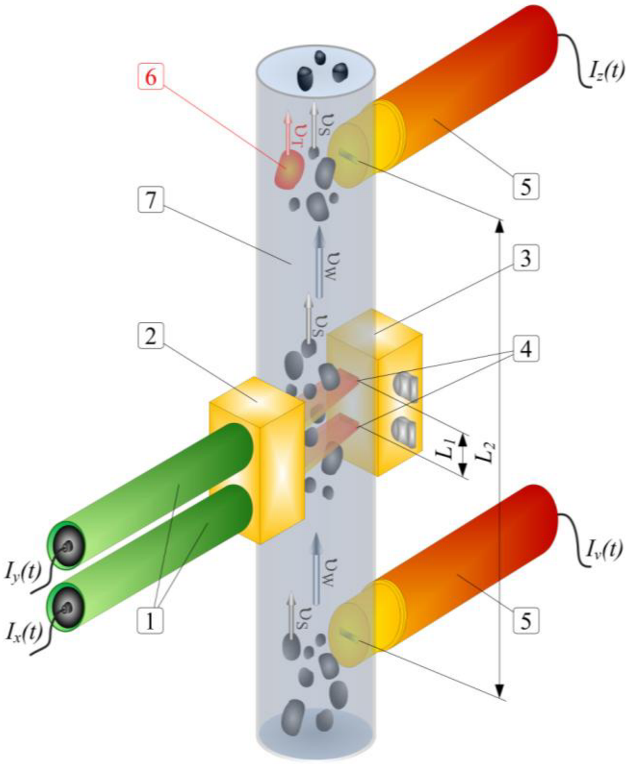


Figure 1. The gamma radiation measuring equipment: 1 – scintillation probes of gamma-absorption, 2 – detector's collimator, 3 – two gamma-radiation sources with collimator, 4 – gamma-rays, 5 – scintillation probe for radiotracer measurements, 6 – marked particle, 7 – pipeline with two-phase flow, υ_S, υ_W – velocities of solid particles and water respectively, υ_T – velocity of marked particles.

Two sealed radioactive sources in collimator (3) emit gamma radiation beams shaped by the collimator. Photons pass through the pipeline (7) with the multiphase mixture. The changes in the intensity of radiation are recorded by the scintillation probes of the absorption set (1) with collimators (2) and next converted into output electrical impulses [7]. Count rates I_x and I_y at the outputs of probes depend on the flowing medium content in the test cross section. In the present investigations a linear ^{241}Am γ-ray sources with an activity of 100 mCi and probes with 2" NaI(Tl) scintillation crystal were used. Two such sets were mounted on the pipe with the distance of L_1 = 90 mm between them. Based on the time delay of signals I_x and I_y and the distance L_1 one can calculate the average velocity of the solid phase.

Probes for radiotracer measurements (5) are based on the longer distance of L_2 = 1882 mm. These probes record the radiation intensity I_v and I_z from the marked particle (6). Velocity of the marked particle can be determined as before by determining time delay between signals.

The current study has been performed for a mixture of water and artificial nodules at volumetric concentration 0.05. The density of the particles representing the nodules was 2000 kg / m^3.

Table 1 presents the characteristics of solid particles and figure 2 shows image of particles before experiments.

Table 1. Characteristics of the artificial nodules.

Particle size grade	Dimensions (mm)	Weight, (g)
I - small	29.5x26.9x20.5	18.5
II - medium	31.2x47.7x27.0	47.9
III - big	59.6x43.7x54.1	128.3

Figure 2. The image of the particles (right-hand side: the particle with a bore for the isotope Tc-99m).

3 Experimental set-up

The measuring system presented in figure 1 has been installed in the experimental set-up located in the Water Laboratory of the Wroclaw University of Environmental and Life Sciences, Poland. The entire experimental installation presented in figure 3 has been used for investigation of the polymetallic nodules hydrotransport.

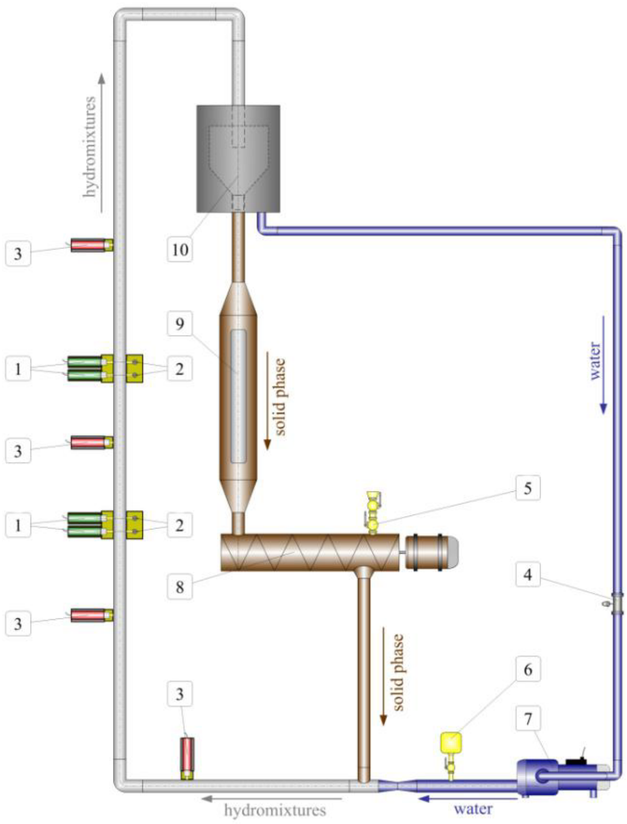


Figure 3. Diagram of experimental set-up: 1 – absorption probes, 2 – sealed sources, 3 – probes recording radiotracers, 4 – electromagnetic flow meter, 5 – marked particles feeder, 6 – feeder of marked water, 7 – pump, 8 – conveyer, 9 – container for solid particles, 10 – separating container.

The key part of the installation is a vertical pipeline of length 7.75 m and with an internal diameter of 150 mm made of acrylic glass. The laboratory set-up has been described in details in papers [5, 13, 16]. The view of some parts of the experimental installation together with measuring section and gamma-absorption set as well as probe for radiotracer experiments is shown in figure 4.

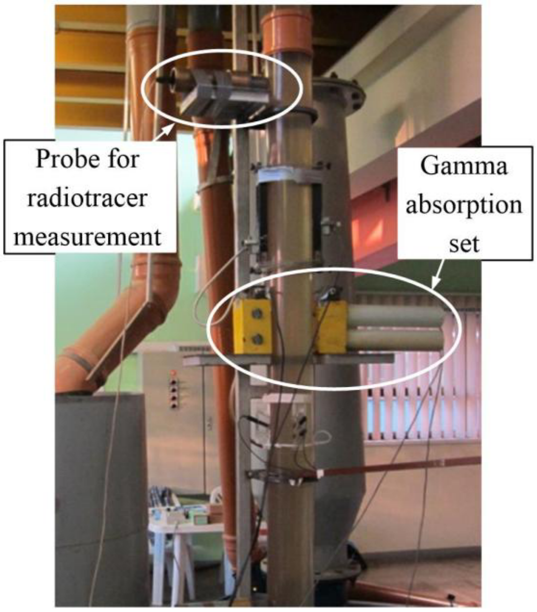


Figure 4. Test section view of the experimental set-up.

The data acquisition equipment was comprised of the dedicated 8-channel EC Electronics counter of HSC 8000 connected to PC using a USB port.

4 The analysis of signals

Signal pulses I_x, I_y, I_v and I_z from the four probes are counted within the selected sampling time $\Delta t = 1$ ms and create mutually delayed discrete stochastic signals $x(t)$, $y(t)$, $v(t)$ and $z(t)$.

An examples of the time records $v(t)$ and $z(t)$ obtained in the WRS0057 experiment (particle size grade I) are presented in figure 5, where s1, s2, s3, s4 denote consecutive marked particle passes through a measuring section of the pipe.

For comparison, the signals $x(t)$ and $y(t)$ from the probes of absorption set recorded at the same experiment is shown in figure 6.

The signals recorded at two spatially separated location within the distance L_1 allow determination of the τ_{0S} time delay (transit time) necessary for transportation of the solid particles through the measuring section of the pipe. The particles average velocity υ_S can be calculated from the following formula:

$$\upsilon_S = L_1 / \tau_{0S} \qquad (1)$$

The velocity of the marked particles υ_T is calculated as follows:

$$\upsilon_T = L_2 / \tau_{0T} \qquad (2)$$

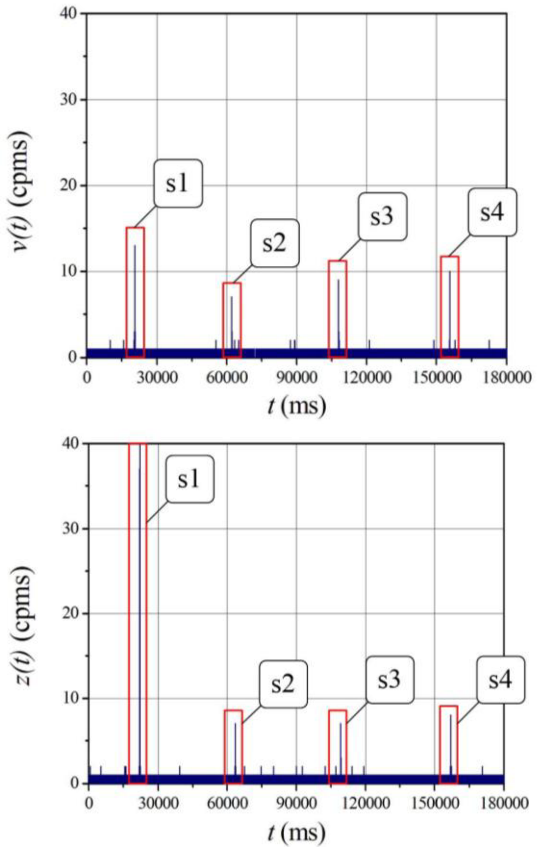


Figure 5. Time records of signal $v(t)$ and $z(t)$ obtained in the WRS0057 experiment.

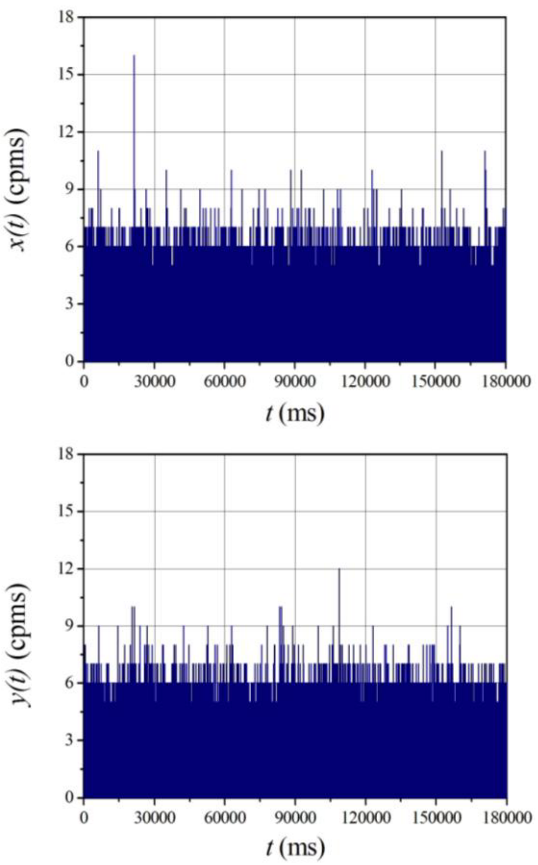


Figure 6. Time records of signal $x(t)$ and $y(t)$ in obtained from absorption set in the WRS0057 experiment

The frequently used method of time delay estimation of the ergodic random signals $x(t)$ and $y(t)$ is based on the cross-correlation function (CCF) $R_{xy}(\tau)$, defined by equation [20-24]:

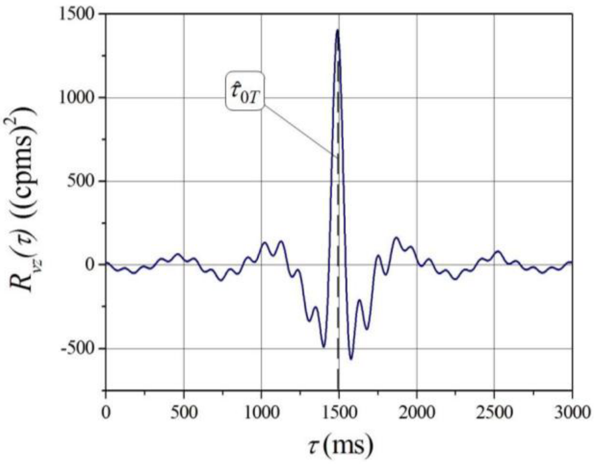
$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)\cdot y(t+\tau)dt \qquad (3)$$

where T is the averaging time, τ – time delay.
The transportation time delay τ_0 is determined base on position of the CCF global maximum.

5 Results

The graphs of the cross-correlation functions obtained in the WRS0057 experiment are shown in figure 7. Figure 7a presents CCF for $v(t)$ and $z(t)$ signals obtained for marked particle and figure 7b presents CCF for signals from absorption set.

a)



b)

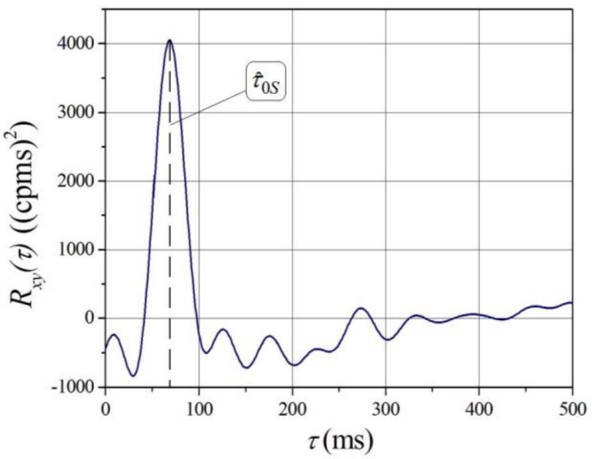


Figure 7. *CCF* calculated in the WRS0057 experiment; (a) for signals from radiotracers (b) for signals from absorption set.

For correct interpretation of absorption and radiotracers experiments simultaneously conducted for different distances L_1 and L_2, the $CCFs$ were converted to the function of inverse velocity. The converted $CCFs$, which include amplitude adjustment, are shown in figure 8.

The combined standard uncertainty $u_c(\upsilon)$ of the solids velocity, with negligible small uncertainties of the acquisition set, depends on an inaccuracy of uncorrelated L and τ_0 determination [27]:

$$u_c(\upsilon) = \left[\left(\frac{\partial\upsilon}{\partial L}\right)^2 \cdot u^2(L) + \left(\frac{\partial\upsilon}{\partial\tau_0}\right)^2 \cdot u^2(\tau_0)\right]^{1/2} \qquad (4)$$

where $u(L)$ is the standard uncertainty of the distance between detectors.

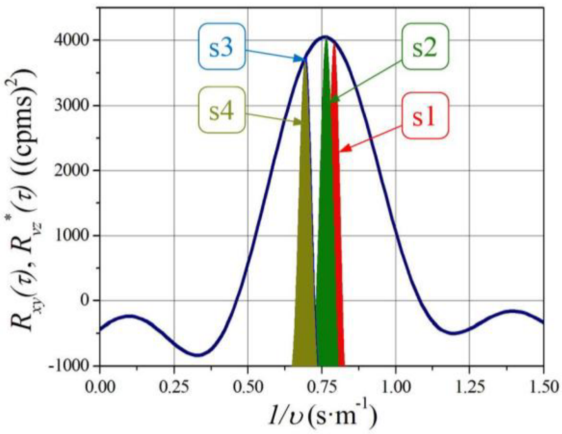


Figure 8. *CCF* for signals obtained for marked particles (colored areas) and for signals from absorption set (solid line) in the WRS0057 experiments.

Table 2 shows the results of the marked solid particle velocity υ_T obtained from radiotracer measurements and its uncertainty. The average particle velocity υ_S calculated using absorption method is $\upsilon_S = 1.323$ m / s with uncertainty $u_c(\upsilon_S) = 0.031$ m / s.

Table 2. Results of the marked solid particle velocity measurement in the WRS0057 experiment.

Type of experiment	υ_T (m/s)	$u_c(\upsilon_T)$ (m/s)
tracer, s1	1.2632	0.0023
tracer, s2	1.3078	0.0026
tracer, s3	1.4373	0.0030
tracer, s4	1.4435	0.0013
average	1.3630	0.0048

From the analysis of figure 8 and Table 2 it can be seen that velocity of the marked particles are in the range of greater υ_S values of the CCF distribution determined for absorption measurement. Velocities for s1, s2, s3, s4 are arranged within $\pm 1\sigma$ (where σ is standard deviation) aforementioned CCF.

The tracer experiment gives the ability to track individual selected grains whose velocity depends on the position in the flow. In the case of large number of radiotracer experiments when the number of passes indicated in the installation of stones is over 50, the calculated velocity values should be close to the CCF distribution obtained from absorption measurements.

6 Conclusions

Radiotracer experiments allow tracking the behavior of the selected grain size classes of the solid phase in the liquid-solids particle flow in vertical pipeline. This is important for the development of technology of hydrotransport of polymetallic nodules from the seabed.

The absorption measurements give an average velocity of the entire population of solid particles. The resulting distribution of the *CCF* can be considered as distribution of all possible time delays (velocities) of the moving grain population.

Comparison of the results of both methods indicates that the velocities of marked particles obtained for s1, s2, s3, s4 are arranged within $\pm 1\sigma$ aforementioned *CCF*.

Measurements of radiotracers, due to the use of open radioisotopes must be performed under conditions of radiological protection. However, in many cases of flow measurements there is no alternative method that gives similar opportunities.

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