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Short Communication

Velocity measurement of the liquid–solid flow in a vertical pipeline using gamma-ray absorption and weighted cross-correlation

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ABSTRACT

Developing technology for the deep-sea mining of polymetallic nodules requires, theoretical analyses, simulation and numerous experimental studies. In this paper authors focused on nuclear methods adoption to velocity of solid phase measurement in an extremely hard and varying environment. Selected results of the experimental studies of two-phase liquid–solid particles flow in a vertical pipeline obtained by probing with photon beams are presented. With the use of the sealed ^{241}Am isotopes emitting gamma radiation of 59.5 keV, and the scintillation probes with NaI(Tl) detectors, the average transport velocity for ceramic models representing natural polymetallic nodules were determined. In the paper for analysis of the signals coming from the probes, the cross correlation function (CCF) and its modifications consisting in the combination of the CCF with such procedures as the average square difference function (ASDF) and the average magnitude difference function (AMDF) were used. An example of measurement is presented and its resulting uncertainties determined. In described experiment the relative values of the combined uncertainty of solid particles average velocity estimation are equal to: 3.2% for the CCF, 3.0% for the CCF/AMDF and 2.8% for the CCF/ASDF.

1. Introduction

The measurements of parameters of such two-phase flows as liquid–solid particles, require the use of advanced and non-invasive measurement techniques [1–7]. In investigations of this type the methods using radioactive isotopes have been applied for more than 50 years [8–13]. Those measurements can be divided in two types: tracer one where isotopes introduced into the flow in specific conditions are applied, and the absorption method based on the analysis of the mixture flowing through a beam of photons emitted by a closed gamma-ray source. The latter method is non-invasive and relatively simple in application. The factor constraining the use of isotopes is the need to meet restrictive safety requirements for personnel and the environment so that both are protected from the effects of ionizing radiation and radioactive pollution.

In this study the application of the absorption method for measurement of an average velocity of solid particles transported by a liquid in a vertical pipeline is presented. The measurement results obtained on the research stand built within the project for the development of polymetallic nodules hydrotransport from the sea bottom were used [14]. Nodules are a porous organic and mineral composition occurring on the bottom of seas and oceans which contain various metals (mostly Mn, Si, Al, Na, Mg, Ni, K, Cu) [15,16]. The richest nodule deposits can be found at the Pacific Ocean bottom at the depth of 4.000–6.000 m in the so called Clarion-Clipperton zone [ibid]. Investigations into the development of mining these materials are being carried out in several countries, including Poland. It is anticipated that industrial scale use of these technologies will occur in the near future. The ocean nodules usually occur in the form of grains with the diameter between 1 cm and 15 cm and have the density of about 2 g/cm^3 in wet state [ibid]. The mining of nodules using the hydraulic method requires grain vertical transport by water to sea level, but this velocity should be limited with energy losses for pumping. To meet these conditions the liquid flow velocity has to be adapted to the current amount of nodules in the lower part of the pipeline and an appropriate system to control the operation of the pumps is necessary. Measurement of water velocity can be performed by the use of ultrasonic or electromagnetic flow meters. However, the measurement of the velocity of the solid phase with particles of various sizes in the vibrating pipeline at a significant depth is a difficult task. The authors believe that in that case the gamma-ray absorption method can be successfully used [11–14].

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Nomenclature

DFT	Discrete Fourier Transform
$I_x(t)$, $I_y(t)$	count rates in counts per millisecond [cpms]
L	measuring distance [mm]
M	number of samples in CCF, AMDF and ASDF calculations (delay range)
N	number of recorded samples
p	number of samples for interpolation
R_{AMDF}, AMDF	average magnitude difference function
R_{ASDF}, ASDF	average square difference function
R_{CCF}, CCF	cross-correlation function
t	time [ms]
u_A, u_B	standard uncertainties
u_c	combined standard uncertainty
$x(n)$, $y(n)$	discrete series
Δt	sampling interval [ms]
σ	standard deviation [ms]
τ	time delay [ms]
τ_0	transportation time delay (flow transit time) [ms]
γ	gamma-ray
υ_S	average velocity of solid phase [m/s]

In the velocity measurements of two-phase flows the cross-correlation method is often applied for the analysis of such signals as provided by scintillation probes [11,17–21]. This method can also be used in investigation of the hydrotransport of ocean nodules [14,17]. In this paper certain modifications of this method are proposed which consist of the combination of classic correlation with such advanced signal processing as: average square difference function (ASDF) and average magnitude difference function (AMDF) which makes it possible to increase the accuracy of results.

2. The gamma-ray absorption method in two-phase flow investigation

The idea of the application of gamma-ray absorption method to liquid–solid particles mixture flow analysis in a vertical pipeline is presented in Fig. 1. The typical measurement equipment for this method consists of a sealed radioactive source (1), and a scintillation probe (4). With that equipment the density or the selected phase concentration in the stream is recorded. By using two such sets it is possible to measure the grain's velocity as a minority phase of the compound. The radiation sources used in this measurement are placed at a distance L from one another on one side of pipe (5). Due to this the transmission of the two parallel photon beams shaped by the lead collimators (2), (3) can be used for analysis of the flow. On the other side of the pipe two probes with scintillation detectors are installed, and on the output of them the count rates I_x and I_y are recorded. In consequence recorded signals depend on the condition of the mixture within appropriate cross sections of the pipe. Fig. 2 presents count rates $I_x(t)$ and $I_y(t)$ provided by probes during the WRS012 experiment lasting 300 s.

The flow of the mixture through the observed section L provides a stochastic signal which describes the instantaneous state of the flow. The analysis of signals recorded at edges of L by cross-correlation methods allows the determination of the transit time τ_0 necessary for transportation of the solid phase through the measuring section of the pipe. In consequence, the average velocity of solid particles flow υ_S is calculated from the formula:

$$\upsilon_S = L/\tau_0 \tag{1}$$

3. Experimental installation

The experimental rig built in the Water Laboratory of the Wroclaw University of Environmental and Life Sciences (Poland) for investigation of the hydrotransport of polymetallic nodules is shown in Fig. 3a. In the investigations carried out the solid phase had specially prepared ceramic models resembling the shape and density of wet natural nodules but possessed higher mechanical strength. In Fig. 3b a part of the measuring section pipeline and a mixture being transported is shown.

In Fig. 4 the diagram of the installation is presented. The basic part of the installation is a vertical pipeline with a pipe internal diameter of 150 mm made of acrylic glass (PMMA Plexiglas). This allows a continuous observation of the flow and concurrent photo documentation. On the measurement section of the length of 7.55 m two absorption sets were fastened to control the transportation of grains in consecutive parts of the pipeline. Each set consisted of a linear gamma-ray source (2) of ^{241}Am X.103 (QSA Global) type of the activity 3.7 GBq and a probe (1) with the NaI(Tl) crystal of SKG-1, Tesla. The gap between the probes in each

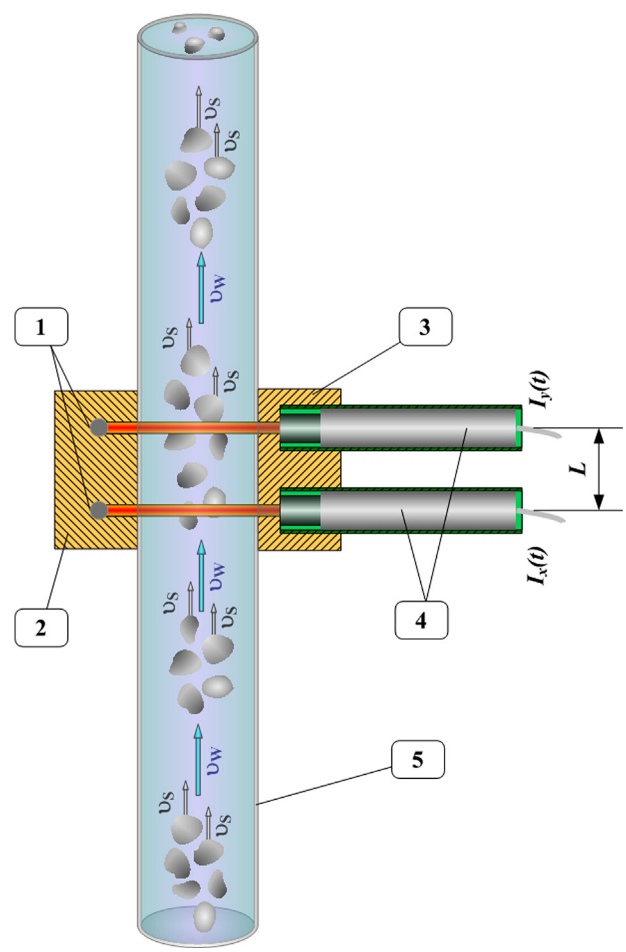

Fig. 1. The idea of gamma-ray absorption measurement of two phase flow in a vertical pipeline: 1 – radioactive source, 2 – collimator of the source, 3 – collimator of the detector, 4 – scintillation probe, and 5 – pipe.