Velocity measurement of two-phase liquid-gas flow in a horizontal pipeline using gamma densitometry

R Hanus[1,4], M Zych[2] and L Petryka[3]

[1]Faculty of Electrical and Computer Engineering, Rzeszow University of Technology, Powstancow Warszawy 12, 35-959, Rzeszow, Poland
[2]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059, Krakow, Poland
[3]Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059, Krakow, Poland

E-mail: rohan@prz.edu.pl

Abstract. This paper presents application of gamma-ray absorption method to liquid-gas flow investigation in a pipeline. In the described measurement two sealed ^{241}Am radioactive sources and probes with NaI(Tl) scintillation crystals have been used. For the analysis of digital signals provided by detectors, a traditional cross-correlation function (CCF), and modified correlation methods based on the quotient of CCF and average magnitude difference function (AMDF), as well as the quotient of CCF, and average square difference function (ASDF) have been proposed. Exemplary results of the mean velocity determination of the gaseous phase transported by a liquid in the water-air mixture flow were demonstrated and the evaluation of its uncertainty have been presented.

1. Introduction

Two-phase flows occur frequently in nature and industry, e.g., in the transportation of such mixtures as a liquid-gas, or liquid-solid particles transported by a gas or liquid. Measuring the velocity or the flow rate of these components is difficult and frequently requires the use of non-invasive methods. The analysis of flow parameters and its control encourages the use of advanced measuring techniques, employing among others electrical tomography, ultrasonic or Coriolis flow meters and radioactive isotopes. The last technique uses tracers injected under certain conditions into the flow, or one based on the sealed radioactive sources emitting gamma ray and application of its absorption [1] - [6]. In the both cases as detectors of radiation, a scintillation probes may be mounted outside of the analyzed stream.

The typical equipment for a gamma-absorption measurement consists of a sealed radioactive source, and a scintillation probe which is used to record density or selected phase concentration in the stream. By employing of two such sets it is possible to measure additionally the velocity of a minority phase of the flow. The sources used in such equipment are placed at the *L* distance one from another at one side of the pipe, as shown in figure 1. Due to two parallel photon beams shaped by collimators, continues analysis of the mixture is possible. At the opposite side of the pipe the probes are installed,

---

and the output of count rates $I_x(t)$ and $I_y(t)$ are recorded. These signals depend on the condition of the mixture in the pipe's cross sections and describes the instantaneous state of the flow [5].
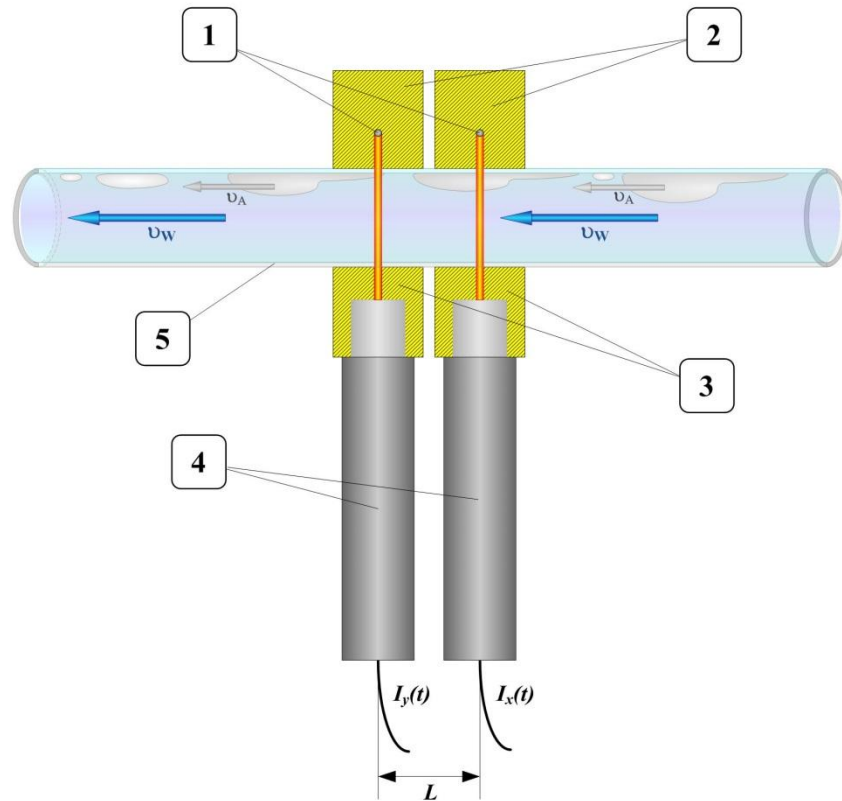
Figure 1. The principle of the gamma-absorption measurement in a horizontal pipeline: 1 – sealed radioactive source; 2 – collimator of the source; 3 - collimator of the detector; 4 - probe; 5 – pipeline.

The statistical comparison of two such signals allows determination of the time delay τ_0 necessary for transportation of the minority phase of the flow, and then its mean velocity v_A from the following formula:

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

2. Laboratory stand
Figure 2 illustrates the piping constructed in the Industrial Radiometry Laboratory of the AGH University of Science and Technology in Krakow, Poland. The installation is part of stand constructed for investigation of the liquid-gas mixture flows, simulating the typical processes which occur e.g. during transportation of the crude oil and natural gas mixture. For investigation purposes a measuring section of 4.5 m pipe from metaplex with 30 mm internal diameter was used, where the linear velocity of the liquid was adjusted in the range from 0.5 to 2.5 m/s.

The station is equipped with a data acquisition system, a computer with appropriate software which permits statistical analysis of signals obtained from the detectors and ultrasonic flow meter. In the presented investigation two [241]Am isotopes emitting photons of 59.5 keV energy were used, as well as the detectors with NaI(Tl) scintillation crystals. Two probes are placed with the distance of $L = 97$ mm between them.
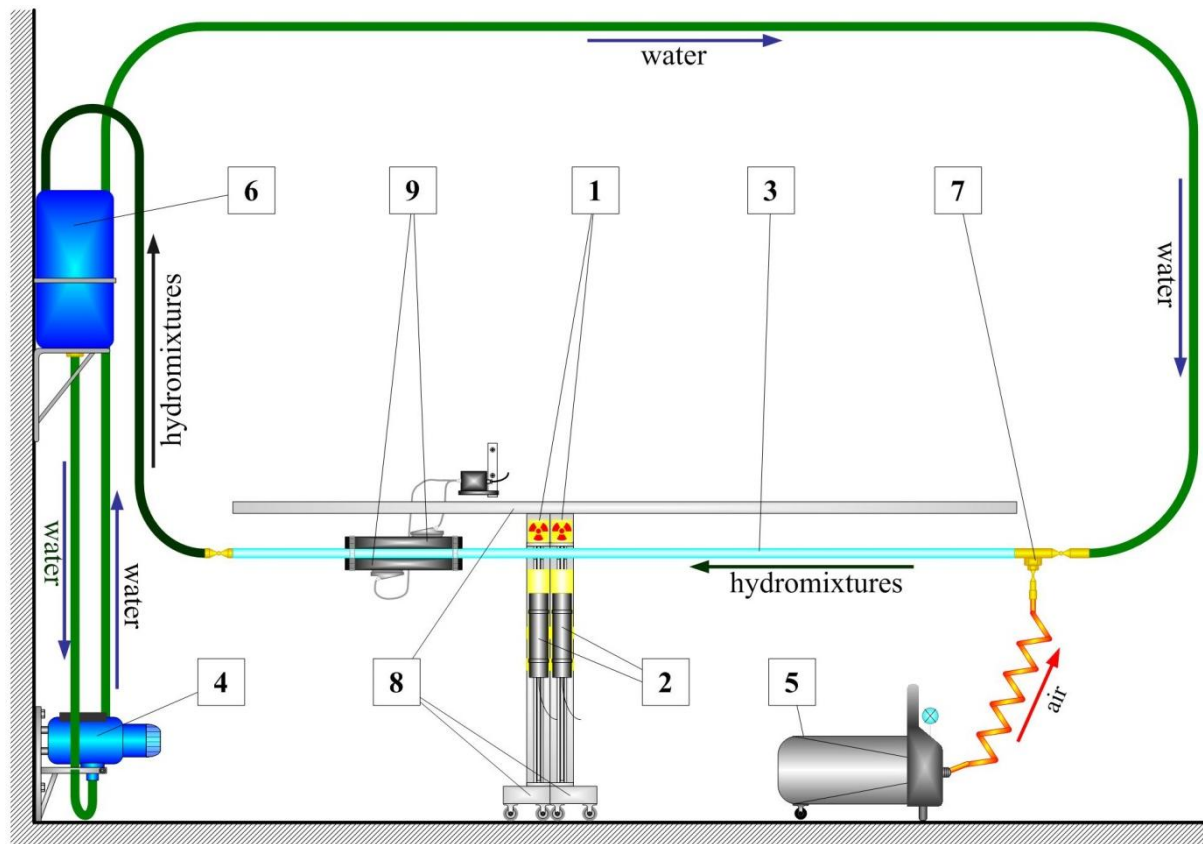
Figure 2. A graphical presentation of the piping for the liquid-gas mixture flow's investigation: 1 – sealed radioactive source; 2 – probe; 3 – pipe; 4 – pump; 5 – compressor; 6 – air-removing container; 7 – air nozzle; 8 – shifting system of probes; 9 – ultrasonic flow meter.

The piping allows additionally application of radiotracers to determine the selected mixture's component transportation. A more detailed description of the station is given in [7].

3. Methods of signals analysis

The voltage pulses $I_x(t)$ and $I_y(t)$ provided by the scintillation probes in accordance with figure 1 were counted within a selected sampling interval Δt, and create discrete time signals $x(n)$ and $y(n)$. These signals as one recorded in radioisotope measurements deliver not only the statistical property of the analyzed flow, but also significant influence of the radiation background, electronic noises, and fluctuations of the nuclear decay. Appropriately long fragments of these signals, after preprocessing (centering, and filtration) are of the ergodic type, and can be fruitfully analyzed by statistical methods in time and frequency domains described in detail in [8] - [16]. The well-known cross-correlation function (CCF), as well as an average magnitude difference function (AMDF), and average square difference function (ASDF), are the methods used chiefly for the estimation of transportation time across the selected distance [4], [9], [14] - [16]. The estimator of mean transportation time delay $\hat{\tau}_0$ can be obtained as the position of the extremum of the discussed functions. The discrete estimators of CCF, AMDF, and ASDF can be presented in the following equations:

$$R_{CCF}(\tau) = \frac{1}{N}\sum_{n=0}^{N-1} x(n)\,y(n+\tau),$$ (2)

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

$$R_{ASDF}(\tau) = \frac{1}{N} \sum_{n=0}^{N-1} [x(n) - y(n+\tau)]^2, \tag{4}$$

where: N – number of samples, τ – time delay.

For the paper we evaluated the above methods and propose to use the combined CCF/AMDF, and CCF/ASDF calculations for analysis of signals obtained in gamma-absorption measurements of the liquid-gas mixture transportation. These calculations were as follows:

$$R_{CCF/AMDF}(\tau) = \frac{R_{CCF}(\tau)}{R_{AMDF}(\tau)}, \tag{5}$$

$$R_{CCF/ASDF}(\tau) = \frac{R_{CCF}(\tau)}{R_{ASDF}(\tau)}. \tag{6}$$

The combination of correlation and AMDF formulas was recently proposed to analyze of acoustic signals [17]. In result of theoretical considerations of the denominators of equations (5) and (6) we proposed to add a small positive number to avoid division by zero. However, for the analysis of real signals, particularly for signals obtained from the scintillation probes it is not necessary.

4. Exemplary results of experiment

Figure 3 presents plots of the normalized CCF, CCF/AMDF, and CCF/ASDF characteristics obtained for the signals recorded in the BUB006 experiment. Normalization was done by dividing values of each function by its maximum value. In the BUB006 experiment, the laminar flow was analyzed and the bandwidth of signals was about 20 Hz. The data acquisition parameters in this experiment were as follows: $N = 180000$, $\Delta t = 1$ ms.

In calculations the selected range of data around the maximum of the CCF, CCF/AMDF, and CCF/ASDF have been approximated with the probability density function $p(\tau)$ of the normal distribution:
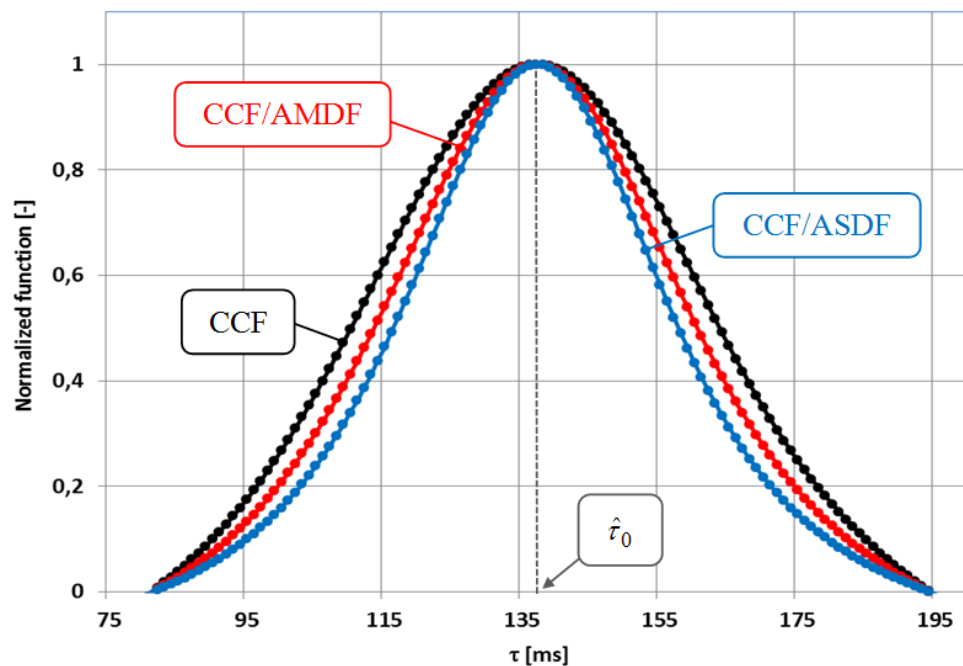
$$p(\tau) = p_0 + \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\tau - \hat{\tau}_0)^2}{2\sigma^2}\right). \tag{7}$$

where: p_0 – normalization level of the Gauss function, σ – standard deviation of the fitted distribution. In these cases the $\hat{\tau}_0$ estimators are determined as the first moment of the fitted distribution [6], [12] and the standard uncertainty of the mean transportation time $u(\hat{\tau}_0)$ is given by:

$$u(\hat{\tau}_0) = \frac{\sigma}{\sqrt{m}}, \tag{8}$$

where m – number of points selected around the maximum.

Figure 3. Plots of normalized CCF, CCF/AMDF, and CCF/ASDF calculated in the BUB006 experiment with $m = 100$.

The combined standard uncertainty $u_c(v_A)$ of the measured phase velocity, with negligible small uncertainties of the acquisition set, depends on an inaccuracy of uncorrelated L and $\hat{\tau}_0$ values determination:

$$u_c(v_A) = \left[\left(\frac{\partial v_A}{\partial L} \right)^2 u^2(L) + \left(\frac{\partial v_A}{\partial \hat{\tau}_0} \right)^2 u^2(\hat{\tau}_0) \right]^{1/2}, \qquad (9)$$

where: $u(L)$ - the standard uncertainty of the distance between the detectors in figure 1.
Results of the mean velocity v_A and its combined uncertainty $u_c(v_A)$ [18] obtained in the BUB006 experiment are presented in the table 1.

Table 1. Results of measurements in BUB006 experiment

Method	Mean velocity v_A (m/s)	Combined uncertainty $u_c(v_A)$ (m/s)
CCF	0.708	0.012
CCF/AMDF	0.708	0.011
CCF/ASDF	0.708	0.009

5. Conclusions

Comparison of the results presented in the paper shows the following order of increasing uncertainty of the gas phase mean velocity: the CCF/ASDF, CCF/AMDF, and CCF. The uncertainties of air

bubbles mean velocity in the described experiment did not exceed two percent, which is a satisfactory for many industrial measurements. According to the authors, the proposed modified cross-correlation method is worthwile for concideration in a similar two-phase flow measurements.

6. References

[1]　Lowenthal GC and Airey PL 2001 *Practical applications of radioactivity and nuclear radiations* (Cambridge: University Press)

[2]　Johansen GA and Jackson P 2004 *Radioisotope gauges for industrial process measurements* (New York: Wiley)

[3]　Kumara WAS, Halvorsen BM and Melaaen MC Single-beam gamma densitometry measurements of oil–water flow in horizontal and slightly inclined pipes 2010 *International Journal of Multiphase Flow* **36** 467–480

[4]　Jung SH, Kim JS, Kim JB and Kwon TY Flow-rate measurements of a dual-phase pipe flow by cross-correlation technique of transmitted radiation signals 2009 *Applied Radiation and Isotopes* **67** 1254-1258

[5]　Petryka L, Hanus R, and Zych M Application of gamma absorption method to two phase flow measurement in pipelines 2012 *Przeglad Elektrotechniczny* **88** 185-188 (in Polish)

[6]　Zych M, Petryka L, Kepiński J, Hanus R, Bujak T and Puskarczyk E Radioisotope investigations of compound two-phase flows in an open channel 2014 *Flow Measurement and Instrumentation* **35** 11–15

[7]　Hanus R, Szlachta A, Kowalczyk A, Petryka L, and Zych M Radioisotope measurement of two-phase flow in pipeline using conditional averaging of signal 2012 *Proc. IEEE Mediterranean Electrotechnical Conference MELECON 2012 (Yasmine-Hammamet Tunisia March 25-28)* (IEEE Press) 144-147

[8]　Bendat JS and Piersol AG 2010 *Random data - analysis and measurement procedures* (New York: Wiley)

[9]　Beck MS and Plaskowski A 1987 *Cross correlation flowmeters - their design and application* (Bristol: Adam Hilger)

[10]　Hanus R Investigation of the correlation method of time delay estimation with Hilbert Transform of measuring signal 2012 *Przeglad Elektrotechniczny* **88** 39-41 (in Polish)

[11]　Mosorov V A method of transit time measurement using twin plane electrical tomography 2006 *Measurement Science and Technology* **17** 753-760

[12]　Petryka L, Zych M and Murzyn R The non-stationary two-phase flow evaluation by radioisotopes 2005 *Nukleonika* **50** 43-46

[13]　Kowalczyk A, Hanus R and Szlachta A Investigation of the statistical method of time delay estimation based on conditional averaging of delayed signal 2011 *Metrology and Measurement Systems* **17** 335-342

[14]　Fernandes CW, Bellar MD, and Werneck MM Cross-correlation-based optical flowmeter 2010 *IEEE Trans. Instrum. Meas.* **59** 840-846

[15]　Hanus R Satistical error comparison of time delay estimation using cross-correlation function and phase of cross-spectral density function 2008 *Przeglad Elektrotechniczny* **84** 301-303 (in Polish)

[16]　Jacovitti G and Scarano G Discrete time technique for time delay estimation 1993 *IEEE Trans. Sign. Proc.* **41** 525-533

[17]　Chen J, Benesty J and Huang Y Performance of GCC- and AMDF-based time-delay estimation in practical reverberant environments 2005 *EURASIP Journal on Applied Signal Processing* **1** 25–36

[18]　*Guide to the expression of uncertainly in measurement* 1995 (International Organisation for Standardisation)