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Identification of liquid-gas flow regime in a pipeline using gamma-ray absorption technique and computational intelligence methods

Robert Hanus[a,*], Marcin Zych[b], Maciej Kusy[a], Marek Jaszczur[c], Leszek Petryka[d]

[a] Rzeszów University of Technology, Faculty of Electrical and Computer Engineering, Powstańców Warszawy 12, 35-959 Rzeszów, Poland
[b] AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Al. Mickiewicza 30, 30-059 Kraków, Poland
[c] AGH University of Science and Technology, Faculty of Energy and Fuels, Al. Mickiewicza 30, 30-059 Kraków, Poland
[d] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Al. Mickiewicza 30, 30-059 Kraków, Poland

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ABSTRACT

Liquid-gas flows in pipelines occur frequently in the mining, nuclear, and oil industry. One of the non-contact techniques useful for studying such flows is the gamma ray absorption method. An analysis of the signals from scintillation detectors allows us to determine the number of flow parameters and to identify the flow structure.

In this work, four types of liquid-gas flow regimes as a slug, plug, bubble, and transitional plug – bubble were evaluated using computational intelligence methods. The experiments were carried out for water-air flow through a horizontal pipeline. A sealed Am-241 gamma ray source and a NaI(Tl) scintillation detector were used in the research. Based on the measuring signal analysis in the time domain, nine features were extracted which were used at the input of the classifier. Six computational intelligence methods (K-means clustering algorithm, single decision tree, probabilistic neural network, multilayer perceptron, radial basic function neural network and support vector machine) were used for a two-phase flow structure identification. It was found that all the methods give good recognition results for the types of flow examined. These results confirm the usefulness of gamma ray absorption in combination with artificial intelligence methods for liquid-gas flow regime classification.

1. Introduction

It is well known that two-phase liquid-gas flows frequently occur in nature and industry, especially in mining, nuclear, pharmaceutical, petrochemical, energy and environmental engineering. They are of particular importance in describing heat transfer, momentum and mass processes in a number of devices such as heat exchangers, reactors and bioreactors, distillation columns, absorption and rectification columns, and in pneumo- and hydrotransport processes. Two-phase flows are difficult in mathematical description. Therefore, experimental research and the development of methods of measuring such flows are of major importance [1].

Two-phase flow may be investigated using several methods, such as computer tomography (resistive, capacitive, optical and X-rays), particle image velocimetry (PIV, and its modifications DPIV, HPIV), laser Doppler anemometry (LDA), magnetic resonance imaging (MRI), Coriolis flowmeters, speed camera and nuclear techniques [2–8]. Radiation methods, particularly methods based on gamma ray absorption are reliable and non intrusive, therefore they are used in research and industry [9–12]. These methods are very accurate, but due to ionizing radiation require compliance with strict safety standards.

In the liquid-gas flow through a horizontal pipeline the same volume of gas may be transported by liquid in different ways, evolving from bubble up to annular flow. It depends on many parameters, such as the liquid phase velocity, viscosity and existence of turbulence. Knowledge of a two-phase flow structure is of great importance to properly conduct a number of industrial processes. Therefore, flow regime identification inspires many studies which often make use of machine learning methods for example artificial neural networks (ANN).

The flow structures identification using machine learning methods is comprised of three steps: data acquisition and pre-processing, signal features extraction, and flow structures classification. Generally, computational intelligence methods exploit different features of signals from the detectors of various types in the time, frequency and state-space domain [13–18]. Below are presented examples of the application of gamma radiation and scintillation detectors for this purpose. Bishop and James [19] applied gamma-ray densitometry and ANN to the

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[*] Corresponding author.
E-mail addresses: rohan@prz.edu.pl (R. Hanus), zych@geol.agh.edu.pl (M. Zych), mkusy@prz.edu.pl (M. Kusy), jaszczur@agh.edu.pl (M. Jaszczur), ltpetryka@gmail.com (L. Petryka).

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determination of oil, water and gas fractions in multiphase flow in pipelines. They stated that the analysis of data from the dual-energy gamma densitometers using the multilayer perceptron (MLP) allows for both phase fractions and phase configuration to be determined with high accuracy. Abro et al. [20] used broad beam gamma densitometer and ANN to identify the flow regime and to measure void fraction oil/gas pipes. Their system comprised of a Am-241 source (59 keV energy), and three NaI(Tl) detectors were simulated by using the Monte Carlo EGS4 software package. The simulations were done with annular, homogeneous and stratified flow regimes and all three regimes were recognized correctly. In the work [21], gamma-ray scattering energy spectrum detected by one scattering detector was used as the input of the radial basis function neural network (RBFN) to identify the gas-liquid flow regime in a vertical pipe. The RBFN was trained on the simulated gamma-ray data and then used to identify the flow regime. The results of the simulations show that annular and homogenous regimes can be completely recognized and most of the slug flows are distinguished by the neural network. Salgado et al. [22] utilized a system composed of one dual gamma-ray source (Am-241 and Cs-137) and two NaI(Tl) detectors for flow regimes identification and volume fraction predictions in water-oil-gas multiphase systems. One detector was aligned to the source (180°) and the other was located at 45° with respect to the source. Their approach was based on gamma-ray pulse height distribution (PHDs) pattern recognition by means of the ANNs. The system was comprised of four MLPs. The MCNP-X code was utilized to provide training, test and validation data for the ANNs for annular, stratified and homogeneous flow regimes. The applied ANNs could correctly recognize all the three flow regimes with satisfactory precision. Roshani et al. [23] proposed the Cs-137 gamma radiation source (662 keV energy) and two NaI(Tl) detectors (transmission and scattering) to liquid-gas two-phase flow investigations in the vertical pipeline. They used MLP to first recognize the flow regime and then predict the void fraction. By applying this method, they correctly distinguished three flow regimes as stratified, homogenous and annular and estimated the void fraction of each phase in the range of 5–95% with an error of less than 1.1%. The results were consistent with earlier performed simulations in the MCNP-X code. Next year Roshani et al. presented a detection system comprised of one Co-60 source and one NaI detector in order to identify the flow regime and determine void fractions in liquid-gas flows [24]. Three MLPs were used for this purpose. The selected types of two-phase flow regimes as homogenous, stratified and annular were simulated by the MCNP-X code. At the first step, 3 features (a count under the full energy peaks of 1.173 and 1.333 MeV, and a count under the Compton continuum) were extracted from the registered gamma spectrum and used as inputs of the MPLs. A primary network was trained for recognizing the flow regimes. After testing many different structures, it was found that just two regimes, the stratified and annular, could be correctly identified. Next, two specific MLPs were also implemented for predicting the void fraction. Void fraction percentages were predicted with a mean relative error smaller than 0.42%. In the article [25] a system consisting of two transmission NaI(Tl) detectors, one Cs-137 source and four RBFNs were introduced to identify the flow regime and to determine void fraction in gas–liquid flows in vertical pipes. The experimental results were utilized in a static flow configuration for annular, stratified and bubbly flow. One RBFN was used to classify the data into three classes (regimes) and three other RBFNs were trained to predict the void fraction according to the distinguished regime. All of the regimes in both the training and testing data sets were classified correctly. A similar configuration which uses artificial neutral network is described in publication [26,27].

It is worth to notice that the works discussed above contain analysis for static conditions only, and utilize mainly two types of neural networks: MLP and RBFN.

This paper shows how features of the signals from the gamma absorption set, obtained in dynamic experiments, can be used to identify the structure of liquid-gas flow in a horizontal pipeline. Six computational intelligence methods are tested for this purpose. Section 2 presents the idea of the gamma-absorption method and the laboratory stand in which the experiments were conducted. The third section describes the processing of signals obtained from the scintillation detector and features extraction method. In this section basic information about computational intelligence methods used in the article are also given. Section 4 presents the obtained results. The last section contains the conclusions drawn from the research.

2. Principle of gamma-ray absorption technique and the laboratory set-up

The gamma absorption method is based on Beer-Lambert's law:

$$\mathrm{I} = \mathrm{I}_0 \exp(-\eta \cdot \mu \cdot d) \tag{1}$$

where I_0 is the inlet to absorbent radiation intensity, I is the outlet intensity detected after the beam has traveled a distance d through the absorbing materials, η and μ represent the density and mass absorption coefficient of these materials respectively [11].

If the basic Eq. (1) is applied to an air-water mixture then the corresponding expression is:

$$\mathrm{I} = \mathrm{I}_0 \exp[-(\eta_G \cdot \mu_G \cdot d_G + \eta_L \cdot \mu_L \cdot d_L)] \tag{2}$$

where indices G and L for η, μ and d denote the gas and the liquid, respectively.

The basic design of a gamma ray absorption measuring set is shown in Fig. 1. This set contains a sealed radioactive source (1) in a collimator (2) and a scintillation detector (5) with the collimator of detector (4). The beam of the gamma ray (3) emitted by the source and formed by the collimator is partially absorbed by the flowing medium. The changes of the intensity of radiation are recorded by the scintillation detector and converted into electrical impulses $I_x(t)$.

The article uses the results of experiments performed on a laboratory station built at the Faculty of Physics and Applied Computer Science at AGH University of Science and Technology in Kraków, Poland. The set-up is designed to investigate the use of single-phase and two-phase flow in horizontal pipelines [10,12]. The main part of the station is a hydraulic installation, whose diagram is shown in Fig. 2. The installation includes a horizontal transparent pipe (3) with a length of 4.5 m and an inner diameter of 30 mm. The absorption measuring set consists of two radioactive sources in the collimators (1) and two scintillation probes (2). This type of configuration is usually applied for measuring the velocity of the dispersed phase based on time delay estimation of two signals from probes. For the simultaneous identification of the flow structure only one signal is used. The gamma-absorption set

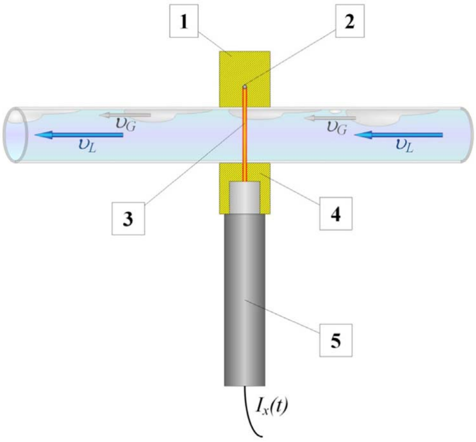

Fig. 1. Principle of gamma-absorption method: 1 – collimator, 2 – gamma radioactive source, 3 – gamma ray, 4 – collimator of the detector, 5 – scintillation detector, υ_G – velocity of gas, υ_L – velocity of liquid.

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