Radiation Measurements 82 (2015) 154–162

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Dual-modality and dual-energy gamma ray densitometry of petroleum products using an artificial neural network

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HIGHLIGHTS

- Several experiments in annular regime were performed.
- The simulated dual modality densitometry was validated.
- Volume fractions were measured independent of the liquid phase density changes.
- ANN eliminated necessity of recalibration in changeable density of 3 phase flows.
- The trained network is able to predict the volume fractions with a MRE of 0.7%.

ARTICLE INFO

Article history:
Received 8 February 2015
Received in revised form
4 July 2015
Accepted 7 July 2015
Available online 10 July 2015

Keywords:
Gamma-ray
Independent of density changes
MCNP
Multiphase flow meter
Three-phase flows

ABSTRACT

The prediction of volume fractions in order to measure the multiphase flow rate is a very important issue and is the key parameter of multi-phase flow meters (MPFMs). Currently, the gamma ray attenuation technique is known as one of the most precise methods for obtaining volume fractions. The gamma ray attenuation technique is based on the mass attenuation coefficient, which is sensitive to density changes; density is sensitive in turn to temperature and pressure fluctuations. Therefore, MPFM efficiency depends strongly on environmental conditions. The conventional solution to this problem is the periodical recalibration of MPFMs, which is a demanding task. In this study, a method based on dual-modality densitometry and artificial intelligence (AI) is presented, which offers the advantage of the measurement of the oil–gas–water volume fractions independent of density changes. For this purpose, several experiments were carried out and used to validate simulated dual modality densitometry results. The reference density point was established at a temperature of 20 °C and pressure of 1 bar. To cover the full range of likely density fluctuations, four additional density sets were defined (at changes of ±4% and ±8% from the reference point). An annular regime with different percentages of oil, gas and water at different densities was simulated. Four features were extracted from the transmission and scattered detectors and were applied to the artificial neural network (ANN) as inputs. The input parameters included the ^{241}Am full energy peak, ^{137}Cs Compton edge, ^{137}Cs full energy peak and total scattered count, and the outputs were the oil and air percentages. A multi-layer perceptron (MLP) neural network was used to predict the volume fraction independent of the oil and water density changes. The obtained results show that the proposed ANN model achieved good agreement with the real data, with an estimated root mean square error (RMSE) of less than 3.

1. Introduction

Accurate measurement of the flow rate of oil–gas–water mixtures in pipelines remains one of the key challenges in the petroleum industry (Thorn et al., 2013). Volume fraction measurements, which are needed to measure the multiphase flow rate, are known as the key parameter of multi-phase flow meters (MPFMs). Currently, obtaining volume fractions using nuclear techniques (especially gamma-ray attenuation techniques) is known as one of the most precise methods. In 1980, for the first time, Abouelwafa and co-worker presented a method to measure

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http://dx.doi.org/10.1016/j.radmeas.2015.07.006
1350-4487/

the component ratios in multiphase systems using gamma-ray attenuation (Abouelwafa and Kendall, 1980). In 1993, a neural network was combined with dual-energy gamma densitometry in order to analyze multiphase flows (Bishop and James, 1993). It was shown that neural network techniques combined with dual-energy gamma densitometry, provide a powerful and accurate approach for the non-invasive analysis of multiphase flows. In 1999, the performance of single-beam and multi-beam gamma-ray densitometry was examined (Abro and Johansen, 1999), elucidating the relationship among the sensitivity of single-beam densitometers, the flow regime and the beam. According to the multi-beam low-energy gamma-ray measurement principle, the dependence on flow regime is negligible when several detector responses are combined. Later, Abro and co-workers determined the void fraction and flow regime using a neural network trained on simulated data (Abro et al., 1999). This method allowed the determination of the void fraction with an error of 3% for all flow regimes, and the three types of flow regime were always correctly distinguished. Fluid properties such as density and salinity strongly affect the performance of MPFMs based on gamma-ray attenuation (Corneliussen et al., 2005). In response to this problem, Johansen and Jackson proposed a new approach to measure the gas volume fraction in oil–gas–water pipe flows independent of water salinity (Johansen and Jackson, 2000). Dual-mode densitometry was presented as a novel method of measuring the void fraction in multiphase flows independent of the salinity of the water component, using the different changes in photoelectric attenuation and Compton scattering in response to changes in salinity. In 2010, Saetre and co-workers presented a multiphase flow measurement method independent of salinity and flow regime (Sætre et al., 2010). They found that a measurement setup combining multiple gamma beam and dual modality densitometry measurements could determine the gas volume fraction independently of the flow pattern, as well as monitor changes in water salinity. In the same year, Salgado et al. identified flow regimes and predicted volume fractions in multiphase flows by means of gamma-ray attenuation and ANNs (Salgado et al., 2010). Their system comprised four ANNs. The first ANN identified the flow regime, and the other three ANNs were specialized for volume fraction predictions for each specific regime. Rabiei and co-workers presented a structure with four detectors to determine precise void fractions and flow regimes by means of MCNP code (Rabiei et al., 2012). By using simulation data as input to the neural networks, the void fraction was determined with an error less than 3% regardless of the flow regime. In 2014, Salgado et al. investigated the response of attenuation gamma rays in a volume fraction prediction system for water–gas–oil multiphase flows considering variations in water salinity. The approach is based on the recognition of pulse height distribution patterns by ANNs (Salgado et al., 2014). In 2014, based on nuclear technique in an annular multiphase regime using only one detector and a dual energy gamma-ray source, a proposed ANN architecture was used by Roshani and co-workers to predict oil, water and air percentages precisely (Roshani et al., 2014). In their work, the number of detectors and ANN input features were reduced to one and two, respectively. The ANN input parameters were the first and second full energy peaks of the detector output signal, and the outputs were the oil and water percentages. In the same year, Nazemi and co-workers introduced a novel idea to predict the void fraction in two-phase flows independent of liquid phase density changes (Nazemi et al., 2014). Because of changes in fluid properties such as density, MPFM recalibration is vital. They proposed a new method to eliminate any dependency of MPFMs on the fluid properties in two-phase flows. Roshani et al. proposed a precise system that identifies the flow regime and then uses the regime to predict the volume fraction using dual modality densitometry and MLP in two-phase flows (Roshani et al., 2015). The availability of flowmeters that can monitor flowrates in the reservoir itself is becoming an important requirement for improved production management, but there are some problems with this approach. These problems include the need to design a flowmeter capable of reliably working at different pressures, temperatures and salinity percentages. The need for recalibration is therefore a serious limiting factor (Thorn et al., 2013). To the best knowledge of the authors, in all previous studies of three-phase flows, the phase densities were considered constant for flow regime identification and volume fraction measurements. Fluctuations in the density of the phases due to temperature and pressure fluctuations can cause major errors in determination of the volume fractions. Gamma ray attenuation techniques are performed based on the mass attenuation coefficient, which is highly sensitive to density changes. Density is dependent on temperature and pressure, and therefore MPFM efficiency depends strongly on environmental conditions. In this study, an approach is proposed based on dual modality and dual energy densitometry using MLP to measure the volume fractions of three-phase flows in situations where the density of the liquid phase is changing.

2. Methodology

First, several experiments were performed using an annular regime, and the results were recorded. The experimental setup was simulated using MCNPX code due to the large number of data points required to train the neural network. The simulation was validated by comparing the results with experimental data. A large amount of data for different fractions and different densities of oil and water was generated using the simulation. These data were applied to the MLP network to predict the volume fraction of each phase independent of density changes.

2.1. Experimental setup

To validate the simulation data, several experiments were carried out using an annular regime. The experimental setup has been described precisely in a previous publication (Nazemi et al., 2014). A plexiglass pipe with an inner diameter of 9.5 cm was used as the main pipe, and several separator pipes with various diameters were used to construct annular regime systems with different phase distributions. In separator pipes, the wall thickness should be as thin as possible because the walls can affect detector counts. Deformation of the cylindrical shape of the separator pipes due to liquid pressure limits the selection of suitable thicknesses. PVC (polyvinyl chloride) films with thicknesses of 0.15, 0.25, and 0.40 mm were tested. Only the 0.40-mm PVC pipes were not deformed, and these were selected as the separator pipes. The source was collimated in order to produce a narrow beam (cubic collimator with 0.6 cm width, 2 cm height and 10 cm length). One 1-inch NaI detector (transmission detector) was located 50 cm from the source, and another one (scattered detector) was placed 20 cm from the pipe at an angle of 45° to the source-transmission detector axis (Jing et al., 2006). The distance between source and pipe was 30 cm. The transmission detector and source were placed at these distances from the pipe in order to reduce the buildup factor effect. The experimental setup is shown in Fig. 1(a) (Nazemi et al., 2014). The transmission detector was connected to a Multi-Channel Analyzer (MCA), and the scattering detector was connected to a Single-Channel Analyzer (SCA). The reproducibility of the experimental setup was validated with three independent measurements for each case.