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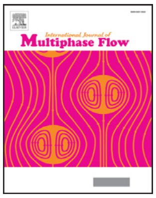

Prediction of water holdup in vertical and inclined oil–water two-phase flow using artificial neural network

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ABSTRACT

This paper presents the application of artificial neural network (ANN) in prediction of water holdup of oil–water two-phase flow in a vertical and an inclined pipe (90°, 75°, 60°, and 45° from horizontal) without knowing the type of flow pattern. For this purpose, superficial velocity of water and oil and the inclination angles of the pipe were used as input parameters, while water holdup values of two-phase flow were used as output parameters in training and testing of the multi-layer, feed-forward, back-propagation neural networks. Experimental data (468 data points) were taken from literature and used for developing of the ANN model. The obtained results showed that the network predictions have very good agreement with the experimental water holdup data. The accuracy between the neural network predictions and experimental data was achieved with low average absolute percent error (AAPE) and high coefficient of determination (R^2) for both training data (AAPE = 2.34% and $R^2 = 0.999$) and testing data (AAPE = 2.89% and $R^2 = 0.997$) sets. In addition, a comparison of the prediction results of the proposed ANN model with Mukherjee et al. (1981) correlation (AAPE = 9.83% and $R^2 = 0.961$) revealed that the correlation had more deviations.

Introduction

Oil–water two-phase flow is commonly observed in petroleum and chemical industries, such as well bores, sub-sea pipelines and related equipment in oil field. One of the most important parameters to design and operation of oil–water flow systems is holdup. It is defined as the ratio of the domain occupied by water or oil to the total domain occupied by the two-phase flow mixture. The holdup is a key dimensionless quantity for determining numerous other important parameters. These parameters include density and viscosity of mixture and relative averaged velocity of each phase. Moreover, the holdup is very important for predicting flow pattern transitions, heat transfer, pressure drop and corrosion rates in oil–water flow. In general, in multiphase flows, each phase flows at a different velocity. As a result, the in-situ volume fraction (holdup) of each phase is different from its input fraction (phase cut).

Based on the previous experimental studies, the holdup behaviors are strongly affected by oil–water flow patterns and inclination angle (see for example Mukherjee et al., 1981; Flores et al., 1998; Vedapuri, 1999; Hasan and Kabir, 1999; Oddie et al., 2003; Abdovayt et al., 2006; Vigneaux et al., 1988). Unlike gas–liquid flows where several empirical correlations have been proposed by researchers for prediction of holdup, there are few correlations for liquid–liquid flows.

Although Oddie et al. (2003) studied water–gas, oil–water and oil–water–gas multiphase flows in inclined pipe, the current authors did not find any correlation for prediction of holdup in oil–water flow in their work. Oddie et al. (2003) used three equations to calibrate their nuclear densitometer for determining the holdup and compared the holdup computed from the gamma densitometer and shut-in valve (quick closing valve). The data was approximately within ±20% for 93% of the data points. Also, Oddie et al. (2003) compared observed holdup data with predictions from the Petalas and Aziz (2000) mechanistic model only for oil–water–gas and water–gas because the Petalas and Aziz (2000) mechanistic model was not proposed and applicable for liquid–liquid flow.

The most common models for predicting holdup or pressure drop are two-fluid (separated) model, homogenous (no-slip) model and drift flux model. These different techniques for analyzing two-phase flow parameters are explained in details in Section 6 of the book chapter by Awad (2012) on two-phase flow.

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In addition to the prediction of holdup, two-fluid (separated) model, homogenous (no-slip) model and drift flux model are applied to predict the pressure drop. The present authors mentioned the results of those works, not only for holdup but also for pressure drop due to some investigators used these models for predicting both pressure drop and holdup.

There are several studies of water holdup in vertical and inclined oil–water two-phase flow in literature. For example, Jana et al. (2007) investigated experimentally pressure drop and holdup during simultaneous flow of oil and water through a vertical pipe. The measured holdup and the pressure drop were analyzed with the above mentioned models according to their respective flow patterns. The results revealed that the homogeneous model is suitable for dispersed bubbly flow whereas bubbly and churn-turbulent flow pattern is better predicted by the drift flux model. Hasan and Kabir (1990) proposed a semi-mechanistic method based on the flow pattern map for predicting in-situ oil volume fraction (oil holdup), H_o, and pressure drop when co-current oil–water flow occurs in a vertical wellbore. In another work, Hasan and Kabir (1999) reported the results of an experimental study and a semi-theoretical analysis of two-phase oil–water flow in vertical and deviated systems. Their study focused on water-dominated flow patterns (bubbly flow, pseudo slug flow, and churn flow). They suggested a method, based on the drift flux approach for estimating H_o during oil–water flow in vertical and deviated wells. Flores et al. (1998) carried out experimental and theoretical studies on liquid–liquid flow in a transparent test section (5.08 cm diameter) using mineral oil (viscosity = 20 cP, density = 845 kg/m^3) and water for inclination angles of 90°, 75°, 60°, and 45° from horizontal. They proposed a mechanistic model to predict the holdup in vertical wells. To calculate the holdup, a drift flux approach for the high slippage flow patterns and a homogeneous model for flow patterns showing negligible slippage were found to be adequate.

In the above mentioned models, flow pattern or pressure drop needs to be known to estimate the holdup, while one of the main reason for knowing the holdup is prediction of flow pattern or pressure drop. Also, accurate determination of flow pattern, particularly in liquid–liquid flows, is a difficult task. Mukherjee et al. (1981) investigated the effect of inclination on pressure drop and water holdup for inclinations ranging from ±30° to ±90° from the horizontal in a 3.81 cm diameter pipe and proposed two correlations for water holdup in uphill and downhill flow based on their experimental studies for the range of inclination angles studied independent of flow pattern determination.

It is difficult to perform an accurate prediction of holdup, pressure drop and flow pattern because of the inherent complexity of multiphase flows, particularly for different inclined positions of pipe. Several investigators suggested the artificial neural network (ANN) methods to solve this problem for gas–liquid flows (see for instance Osman and Aggour, 2002; Abro et al. 1999; Malayeri et al., 2003; Zhang et al., 2002; Zhang et al., 2007; Castillo et al.; 2012). ANN techniques have been proposed as a powerful and computational tool to model and solve the complex problems that cannot be described with simple mathematical models (see for example Zhang et al., 2002; Sablani et al., 2003; Goutorbe et al., 2006; Bassam et al., 2009). This technique does not require a detailed knowledge of the physical phenomena describing the system under analysis. Osman (2001) presented an ANN model for prediction of pressure drop in horizontal and near-horizontal gas–liquid flow. Osman and Aggour (2002) developed a three layer back-propagation neural network (BPNN) for predicting liquid holdup in horizontal gas–liquid flow with a correlation coefficient (R) of 0.9896. Shippen and Scott (2002) trained a multilayer perceptron (MLP) neural network with 7 input variables (pipe diameter, superficial velocity of liquid and gas, density, viscosity and surface tension of liquid and no-slip liquid holdup) as a comprehensive model to predict the holdup in horizontal gas–liquid two-phase flows. The holdup values predicted by their neural network had a correlation coefficient (R) of 0.985 for all data sets. Malayeri et al. (2003) trained a radial basis function (RBF) network for predicting cross-sectional and time-averaged void fraction in gas–liquid flow at elevated temperature. Temperature has an effect on the void fraction or holdup in the sense that it affects the physical properties like viscosity, density, etc. Alizadehdakhel et al. (2009) predicted pressure drop of air-water two-phase flow in a 1.93 cm diameter tube by using ANN. They selected the slope of the test section, the dimensionless gas velocity number and liquid velocity number as the input parameters, and the average pressure drop (Pa/m) as output of ANN. The ANN could evaluate pressure drop with root mean square error (RMSE) of 0.6577 and coefficient of determination (R^2) of 0.9931 for the test set. Castillo et al. (2012) developed an ANN model to derive a void fraction correlation for modeling two-phase flow mechanisms inside geothermal wells with coefficient of determination (R^2) of 0.972. Sobhanifar et al. (2015) developed an ANN model for prediction of heat transfer coefficients (HTCs) of air–water two-phase flow in a pipe at horizontal and slightly upward inclined positions (2, 5, and 7 deg.). The superficial Reynolds numbers of liquid and gas as well as the inclination of the pipe were chosen as input variables of network. The used ANN model had a high prediction performance with mean relative error (MRE) of 2.92% and correlation coefficient (R) of 0.997 for all data.

The survey of the past literature showed that most of the investigators have concentrated their attention on gas–liquid flows and few studies have been published on liquid–liquid two-phase flow for prediction of its main parameters using ANN. Shirley et al. (2012) trained and compared four networks, feed-forward back-propagation (FFBP), Radial basis function (RBF), probabilistic neural network (PNN) and learning vector quantization (LVQ) for recognition of oil–water two-phase flow pattern in a horizontal conduit based on the flow pattern map reported by Raj et al. (2005). They found that PNN is the best network for this application. Al-Wahaibi and Mjalli (2014) developed an artificial neural network (ANN) model with five inputs including oil and water superficial velocities, pipe diameter, pipe roughness and oil viscosity to predict pressure gradient of horizontal oil–water flow. The results revealed that the ANN model has an average absolute error of 2.9%.

Artificial Intelligence (AI) has proven to be an alternative solution to several problems where physics and classic statistics fail to provide satisfactory solutions due to limiting assumptions and complicated reality. AI methods proved their applicability in the oil and gas industry by decreasing the error when compared with the other methods (Al-Mudhafer and Alabbas, 2012, Mohaghegh 2001, Mohaghegh et al., 2000, Mohaghegh et al., 1994, Martinez 1994).

Different AI methods include Fuzzy Logic (ANFIS), Neural Networks (ANNs), Support Vector Machine (SVM), and Decision tree (DT). It is well known the flow characteristics of oil–water mixtures are generally different from liquid–gas systems, so the results of liquid–gas flow cannot be applied directly to oil–water flow in most cases (Oddie et al., 2003, Brauner and Moalem Maron, 1992). That is why it is impossible to ensure about the ability of ANN to predict the main parameters of liquid–liquid flow beforehand. To the best of the authors' knowledge, there is no ANN model quite similar to the current proposed ANN model for prediction of holdup in two-phase flow.

It should be noted that nearly all authors who proposed and reported ANN models in literature applied the neural network toolbox of Matlab, for example, Castillo et al., 2012, Shirley et al., 2012, Rosa et al., 2010, and Sun and Zhang, 2008.

Furthermore, using the neural network toolbox of Matlab, the reader is assured that the authors do not make a mistake in programming the neural network. Also, the reader can apply easily the