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Pressure drop estimation in horizontal annuli for liquid–gas 2 phase flow: Comparison of mechanistic models and computational intelligence techniques

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ABSTRACT

Frictional pressure loss calculations and estimating the performance of cuttings transport during underbalanced drilling operations are more difficult due to the characteristics of multi-phase fluid flow inside the wellbore. In directional or horizontal wellbores, such calculations are becoming more complicated due to the inclined wellbore sections, since gravitational force components are required to be considered properly. Even though there are numerous studies performed on pressure drop estimation for multiphase flow in inclined pipes, not as many studies have been conducted for multiphase flow in annular geometries with eccentricity. In this study, the frictional pressure losses are examined thoroughly for liquid–gas multiphase flow in horizontal eccentric annulus.

Pressure drop measurements for different liquid and gas flow rates are recorded. Using the experimental data, a mechanistic model based on the modification of Lockhart and Martinelli [18] is developed. Additionally, 4 different computational intelligence techniques (nearest neighbor, regression trees, multilayer perceptron and Support Vector Machines – SVM) are modeled and developed for pressure drop estimation.

The results indicate that both mechanistic model and computational intelligence techniques estimated the frictional pressure losses successfully for the given flow conditions, when compared with the experimental results. It is also noted that the computational intelligence techniques performed slightly better than the mechanistic model.

1. Introduction

Two-phase flows in different geometries are of importance in boilers, nuclear reactors, oil production, drilling operation, electronic cooling, and various types of chemical reactors. Because of its extensive application in different fields, several studies were performed for flow patterns identification, void fraction prediction and pressure drop estimation in annular geometries using different data prediction models, such as linear and nonlinear regression and Artificial Neural Networks [22], as well as mechanistic models [38].

In drilling industry, frictional pressure prediction in wellbore is one of the most critical factors, at which drillstring configuration should be taken into account [10,11] especially in any underbalance operation and detection of kick by intelligent drillpipe [15,16], because it is used as input for determining numerous other key hydraulics parameters, including the equivalent circulated density (ECD). The aerated fluids have a potential to increase rate of penetration, minimize formation damage, minimize lost circulation, reduce drill pipe sticking and therefore, assist in improving the productivity. Recently, the technology of drilling using aerated fluids has reached even in the area of offshore drilling. The use of compressible drilling fluids in offshore technology has found applications in old depleted reservoirs and in the new fields with special drilling problems. Both hydraulic behavior and mechanism of cutting transport of the drilling fluids formed by gas–liquid mixture are not fully understood yet, especially there is a large uncertainty in prediction of frictional pressure losses. So, the study of annular two phase flow is still continuing because of the need for increasing the accuracy of predicted models for new application areas.

Two-phase flow in horizontal pipes has been on the focus for a lot of theoretical and experimental studies for some time, as a

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Nomenclature

ρ_G	density of gas at flow conditions, lb/ft^3
ρ_L	density of liquid at flow conditions, lb/ft^3
D	diameter, ft
g	gravitational constant, 32.2 ft/s^2
μ_G	viscosity of gas, cp
μ_L	viscosity of liquid, cp
v_{SL}	superficial liquid velocity, ft/s
v_{SG}	superficial gas velocity, ft/s
$(\frac{\Delta P}{\Delta L})_{SG}$	gas surface pressure gradient, psi/ft
$(\frac{\Delta P}{\Delta L})_{SL}$	liquid surface pressure gradient, psi/ft
ANN	Artificial Neural Networks
SVM	Support Vector Machines
SVR	Support Vector Regression
RMSE	Root Mean Square Error
R	correlation coefficient
AAPE	Average Absolute Percent Error
APE	Average Percent Error

SI metric conversion factors
ft × 0.3048 E+00 = m
inch × 25.4 E−03 = m
cp × 0.001 E+00 = pascal second
gal/min (gpm) × 6.309 E−05 = m^3/s
Psi × 6.8948 E−03 = MPa
lb/ft^3 × 1.001 E+02 = kg/m^3

result several different models are developed. These models are generally categorized into two main groups, empirical models and mechanistic models. Initially, the empirical models treated the two-phase flow as one-phase using simplified versions of the actual flow configuration, furthermore, the flow pattern types are not considered in these models. The most notable studies of this type are Wallis [37], Lockhart and Martinelli [18], Duns and Ros [9]. After these initial models, flow pattern identification became the area of concentration; different empirical and mechanistic models were developed during that time. The studies of Dukler et al. [8] and Beggs and Brill [3] used equations based on experimental data for identifying flow patterns. Mechanistic models used corresponding equations constructed for each different flow pattern, once the flow pattern was identified. Taitel and Dukler [31], Barnea [2], Xiao et al. [38], Petalas and Aziz [25] were among the developed important mechanistic models. Transition boundaries between the flow patterns were investigated based on conservation equations by Taitel and Dukler [31]. In this study, equilibrium condition for stratified flow was assumed. After that, the Lockhart and Martinelli parameter was used in order to determine equilibrium liquid holdup. The Kelvin–Helmholtz inviscid theory was modified in order to predict the initiation of slugs. The transition of intermittent to annular flow is assumed to be dependent only on liquid level. Jeffrey's theory for wave initiation is used to determine the transition of stratified smooth to stratified wavy flow pattern. They investigated turbulent and buoyant forces acting on a gas pocket for the boundary between dispersed bubble flow and intermittent flow. Dimensionless parameters were also developed to express the transition conditions. Barnea [2] studied the transition mechanisms for each individual boundary and proposed a unified model. The developed mechanisms were applicable for the whole range of pipe inclinations. The dimensionless maps were developed to incorporate the effects of flow rates, fluid properties, and pipe size and inclination angle. This model was verified with the conducted experiments. Xiao et al. [38] developed a comprehensive mechanistic model for two-phase flow in horizontal and near horizontal pipes. Taitel and Dueler's [31], and Barnea [2] dimensionless groups were used to predict flow pattern transitions.

Although there are a lot of studies regarding with two-phase flow in circular pipes, limited investigation have been conducted for two-phase flow through annulus. Some examples are; Sadatomi et al. [27], Caetano et al. [6], Hasan and Kabir [13]. Sadatomi et al. [27] were most probably the first one to develop the flow pattern maps for the flow through annuli. Hasan and Kabir [13] recognized four major flow regimes-bubbly, slug, churn and annular from the estimated void fraction for air–water systems. In case of bubbly flow, they found out that the terminal rise velocity was not affected significantly by either the variation in the inner tube diameter or the channel deviation from the vertical. Similarly, in this regime they concluded that the void fraction was not affected by inclination angle. Caetano et al. [6] carried out experimental and theoretical study of upward gas–liquid flow through vertical concentric and eccentric annuli with air–water and air–kerosene mixtures. They identified flow patterns and developed flow pattern maps based on visual observations in conducted experiments. Moreover, they developed mechanistic models for prediction of average liquid holdup and pressure drop for each flow pattern in concentric and eccentric annular geometries. Sunthankar [30] modified Taitel and Dukler [31] transition equations for determining the flow patterns for annular geometries by using the definition of hydraulic diameter. He also compared the estimated results by experimental results. Lage et al. [17] experimentally and theoretically studied two-phase fluid flow in horizontal and inclined annulus. Equations from Taitel and Dukler [31] were used to determine flow patterns. Ozbayoglu and Omurlu [24] formed a mechanistic model to determine the flow patterns and to calculate the frictional pressure losses of gas–liquid mixture fluid in horizontally located annular. Based on experimental observations, Osgouei et al. [21], Osgouei et al. [12] developed a mechanistic model for determining the total pressure losses and volumetric distribution of two phase fluids flow within the inclined wellbore for a particular drilling condition. Their proposed model is reasonably accurate for estimating the frictional pressure losses when compared with the measured values.

Since mechanistic models were mostly concerned about identifying the correct flow patterns, other techniques such as Artificial Neural Networks (ANN) were approached for estimating the flow rates. However, the amount of studies and models developed for two-phase flow in horizontal annulus has been limited, some notable ones include Ternyik et al. [32] and [22]. These studies used experimental data sets provided by other researchers. Ozbayoglu and Ozbayoglu [23] provided several different neural network models for flow pattern prediction and pressure drop estimation using flow rates and fluid parameters and the implemented models provided promising results. Alizadehdaknel et al. [1] compared the performance of CFD models with ANN in pressure drop estimation in multiphase flow and observed that CFD results were more accurate than ANN [1].

There are also other computational intelligence models developed in similar problems. Timung [34] used a probabilistic neural network for identifying flow patterns through different circular micro-channel settings (Timung [34]), using water–gas flow. Zhao developed an SVM model in predicting pressure drop for cyclone separators [39].