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An improved version of drift-flux model for predicting pressure-gradient and void-fraction in vertical and near vertical slug flow

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ABSTRACT

Slug flow research has received continuous and strong attention by many investigators for many years and various predictive models have been developed for calculating slug hydrodynamics. Some researchers relied on experimental data correlation while some modelled the slug flow to simulate the behaviour sufficiently accurately to estimate pressure drops. Because slug flow is the most common flow in producing wells, this leads to the pressure drop being underestimated/overestimated significantly. The intent of this study is to present an alternative approach to modelling slug flow. The proposed model considered wall shear stress in the liquid slug zone and the wall shear stress in the film zone in estimating the pressure drop in slug flow which have been neglected in most literatures. The proposed models are compared with published data from diverse sources and agree well with the experimental data.

1. Introduction

In general multiphase fluids refer to a mixture of solids, liquid and gas. The solid phase is in the form of drilled cuttings, sands; proppant etc. The liquid phase is usually comprised of water and oil. The gas phase is most often nitrogen, air, or natural gas. Multiphase flow effects in wellbores and pipes can have a strong impact on the performance of reservoirs and surface facilities (Shi et al., 2003). Due to the complex nature of gas–liquid two-phase flow in pipes, many prediction models have been developed for gas–liquid two-phase flow with both empirical and mechanistic approaches (Dukler et al., 1969; Beggs and Brill, 1973; Mukherjee and Brill, 1985; Brill and Beggs, 1988). This approach has dominated practical design procedures. The importance of accurate calculations of pressure losses in pipes takes root due to the fact that practically all oil well production design involves multiphase flow. Studies on multiphase flow in vertical pipe have sought to develop a technique with which the pressure drop can be calculated. Pressure losses in flow of gas and liquid phase (two-phase) are quite different from those encountered in dry gas phase (single-phase) alone (Adekomaya et al., 2011). Since the late 1980s, the trend has shifted towards a more fundamental modelling approach, also referred to as the mechanistic approach (Barnea and Taitel, 1993; Ouyang and Aziz, 2000; Sun et al., 2002; Khasanov et al., 2009). A reliable and accurate way of predicting pressure drop in vertical multiphase flow is essential for the proper design of well completions and artificial-lift systems and for optimisation and accurate forecast of production performance. Because of the complexity of multiphase flow, mostly empirical or semi-empirical correlations have been developed for prediction of pressure drop. Numerous correlations have been developed since the early 1940s. Most of these correlations were developed under laboratory conditions and are consequently inaccurate when scaled-up to oil field conditions (Osman and Ayoub, 2003). To date, available models cover only a limited range of the operating conditions in terms of inclination angle, pipe diameter, fluid properties, pressure and so on. Further improvements in this area have been identified in previous studies (Ansari et al., 1990; Xiao et al., 1990; Taitel, 1994; Aggour et al., 1996). Taitel and Barnea (1990) reviewed the mechanistic modelling of slug flow and various options of modelling the hydrodynamic parameters and pressure drop by using a unified approach applicable for the vertical, horizontal, as well as the inclined pipes. In order to improve the method of predicting multiphase, literatures were reviewed according to modelling methodology. The key objective of well production monitoring is to control productivity index and well potential for every well during the life cycle. This requires the well bottom hole pressure (BHP) to be determined. In some cases direct measurement of the bottom hole is either difficult or economically insufficient, that is why BHP calculation is still a relevant problem (Osman and Ayoub, 2003; Khasanov et al., 2009).

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Nomenclature

g	acceleration due to gravity
R_e	Reynolds number
L	length
S	superficial
V	velocity
Q	volumetric flow rate
P	pressure
f	Moody friction factor
e	absolute roughness
d	diameter of the pipe
C_o	distribution parameter
A_L	cross sectional area of pipe
ΔV	change in velocity
ΔQ	change in volumetric flow rate
ΔP_T	total pressure drop
ΔP_{su}	pressure drop across the slug unit
ΔP_f	pressure drop in film region
f_g	void fraction
τ_{WL}	wall shear stress
τ_{WG}	interfacial shear stress
τ_s	liquid shear stress
S_L	length of pipe wall in contact with liquid

Greek symbols

Δ	difference
ρ	density
μ	viscosity
τ	shear stress

Subscript

g	gas
l	liquid
ms	slug mixture
f	film
s	slug

When an oil company operates thousands of wells, it is important for them to use their regular analysis to choose those wells the optimisation of which would be most beneficial (Khasanov et al., 2007). For such cases, the use of mechanistic models can be rather cumbersome because of lengthy computational times for iterative procedures. The purpose of this work is to improve on drift-flux model developed in the literatures by (i) considering the contributions of wall shear stress in the liquid slug zone and the wall shear stress in the film zone in vertical and near vertical pipe at various angle which were neglected in most published models, (ii) developing a simple unified form of void-fraction expression for slug flow pattern, and (iii) developing a simple mechanistic model for pressure-gradient prediction that is applicable for vertical and near vertical pipes.

2. Model development

The model proposed is based on a flow-pattern approach that has been very successful in predicting vertical multiphase flow data. The flow patterns observed in pipes that are slightly deviated from vertical are generally those that are also observed in vertical flow. Thus, the major flow patterns are bubbly (and dispersed bubbly), slug, chum, and annular flow. The churn and slug flows are often lumped together and are called intermittent flow because they are difficult to distinguish and they behave similarly. For systems that are highly deviated (close to being horizontal), the bubbly-flow pattern is sometimes absent. The difficulties associated with a two-phase-fluid model can be reduced significantly by formulating two-phase flow in terms of drift-flux modeling (Khasanov et al., 2007). The energy balance equation is given (Van Hout et al., 2001) as

$$\Delta p_{total} = \Delta p_{frictional} + \Delta p_{gravitational} + \Delta p_{accelerational} \tag{1}$$

where each of the terms in the right hand side of Eq. (1) represents contribution due to friction, gravity and acceleration respectively. The most important term in Eq. (1) is the static-head loss term, which may contribute more than 90% of the total pressure loss for slightly deviated wells when flow is dominated by any combination of single-phase and slug flow.

2.1. Frictional pressure drop ($\Delta P_{frictional}$)

The frictional pressure drop for slug flow is given as

$$\Delta P = \frac{f_{TB} v^2{}_{MS} \rho_{MS}}{2 g_c d} \tag{2}$$

where f_{TB} is the Taylor bubble friction factor that depends on the slug flow pattern, gas and liquid flow rates and physical properties as well as pipe diameter, roughness and inclination.

The slug mixture velocity (V_{ms}) is expressed as

$$V_{MS} = V_{sl} + V_{sg} = \frac{Q_l + Q_g}{A} \tag{3}$$

where V_{sg} and V_{sl} are respectively the superficial gas and liquid velocities.

The drift-flux approach is based on the consideration of two fluids as a mixture in which properties are represented as an average of the properties of the two fluids (Khasanov et al., 2009). In Eq. (2) the slug mixture density is defined as

$$\rho_{MS} = \rho_l (1 - f_g) + \rho_g f_g \tag{4}$$

From Eq. (4), one can realise an accurate estimation of gas void fraction, f_g, in both vertical and deviated well which depends on the in-situ velocity of the gas phase, V_g is relative to the mixture velocity, V_m. The difference between V_g and V_m is caused due to the terminal rise velocity of the gas bubbles stemming from the density difference and the tendency of the gas phase to flow through the central portion of the channel, where the in-situ mixture velocity is higher than the cross-sectional average value.

2.2. Slug flow improvement

It is known from experiment that slug flow has an intermittent structure: Taylor bubbles are followed by liquid slugs which contain gas in the form of small rising bubbles. Through the literatures reviewed, it was found that most researchers used drift velocity, V_d for gas void fraction estimation without accounting for major important factors. Runge and Wallis (1965) and Zukoski (1966) show that the terminal rise velocity of a Taylor bubble in slug flow is significantly influenced by the pipe inclination. These data generally indicate that the terminal rise velocity gradually decreases with increasing deviations and finally becomes zero for