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Developing new mechanistic models for predicting pressure gradient in coal bed methane wells

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ABSTRACT

A range of mathematical models and correlations is used to estimate the pressure drop of coal bed methane (CBM) or coal seam gas (CSG) wells. These correlations were originally developed for co-current two-phase flows in conventional wells in the oil and gas industry. However, the upward flow of gas and downward flow of water in the annulus between casing and tubing of a CSG well results in counter-current two-phase flows. The flow regimes developed in counter-current two-phase flows in annuli are noticeably different to co-current two-phase flow regimes in pipes, and thus the existing models used to predict pressure profiles in co-current wells do not adequately describe two phase flows in a CSG well.

In this study, we develop new mechanistic models for predicting holdups and pressure gradients of counter-current bubble and slug flows in vertical annuli following the existing models of co-current and counter-current flows in annuli and pipes. A model based on the work of Taitel and Barnea (Taitel and Barnea, 1983) was also developed to predict the transition from slug to annular flow regime in counter-current flows in annuli. Our comparison of the pressure gradients of co-current and counter-current flows in annuli shows that the pressure gradients of counter-current flows are appreciably different to those in co-current flows under the same conditions at high liquid flow rates. This indicates that the models currently employed in typical commercial well flow simulators may considerably overestimate the pressure gradient across a CSG well.

1. Introduction

Depending on the fluid properties, flow rates, flow direction and geometry of the system, distinct flow patterns can be developed in wells. A range of correlations and mathematical models has been developed in the conventional oil and gas industry to describe these flow regimes and calculate pressure losses along the wellbore. Existing correlations implemented in commercial well flow software packages typically consider both water and gas phases flowing in the same direction (except perhaps under low velocity conditions such as during a shut-in). However, these correlations and models may not be appropriate or accurate for predicting flow characteristics in (pumped) coal seam gas (CSG) wells because such wells operate under a counter-current two phase flow within the annulus between the casing and tubing: upward flow of gas and downward flow of water. Therefore, this may result in significant uncertainties in the calculation of flowing bottom hole pressure and hence in the optimal management of gas inflow performance.

Although co-current gas-liquid flow has been extensively studied with a range of mathematical models available (Duns and Ros, 1963; Hagedorn and Brown, 1965; Orkiszewski, 1967; Beggs and Brill, 1973; Taitel et al., 1980; Barnea et al., 1985; Barnea and Brauner, 1985; Vo and Shoham, 1989; Taitel and Barnea, 1990; Ansari et al., 1990; Caetano et al., 1992a, 1992b; Hasan and Kabir, 1992; Zhang et al., 2003) the hydrodynamic behavior of counter-current flows in vertical annuli has not been adequately investigated to allow reasonable predictions of pressure gradients in pumped CSG wells. Moreover, most of the studies on counter-current two-phase flows are associated with flooding or counter-current flow limitation (Ragland et al., 1989a, 1989b; Jeong, 2008), to name just a few. This paper aims to develop mechanistic models to predict the pressure gradient of counter-current two-phase flows in an annulus which represents a CSG well. Furthermore, we aim to investigate if the predicted pressure

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gradient of counter-current two-phase flows in an annulus is significantly different from the results of models used in industry simulators which are developed for predicting the pressure gradient/profile of co-current two-phase flows in pipes.

The flow map of counter-current gas-liquid flows in vertical pipes was first developed experimentally by Yamaguchi and Yamazaki (1982) for air-water systems. Later, Taitel and Barnea (1983) proposed a flow map for counter-current gas-liquid flows in vertical pipes following a modelling approach for the flow transition and pressure drop. Taitel and Barnea (1983) mathematically predicted that the flow regime maps for co-current and counter-current flows will be very different, and that counter-current flow may not even exist for certain gas and liquid flow rates as a result of the continuous increase in the flow rate of either phase. This phenomenon is referred to as flooding, in which the passage of the other phase becomes blocked and co-current flows are established. Flow patterns of counter-current air-water flows in pipes were also investigated by Ghiaasiaan et al. (1997), Ghosh et al. (2013) and Kim et al. (2001) using different experimental methods. Three flow patterns including bubble, slug/churn/semi-annular and annular flows were identified for counter-current gas-liquid flows in pipes. Noticeably different flow patterns in counter-current flows compared to co-current flows can result in significant changes in pressure profiles along a CSG well. This paper aims to develop mechanistic models to describe the hydrodynamic behavior of counter-current gas-liquid bubble and slug flows in vertical annuli, and in doing so predict the total pressure gradient for a pumped CSG well. The total pressure gradient $(dp/dz)_T$ for a steady-state flow is a summation of hydrostatic pressure, friction loss and convective acceleration as described in Eq. (1).

$$\left(\frac{dp}{dz}\right)_T = \left(\frac{dp}{dz}\right)_G + \left(\frac{dp}{dz}\right)_F + \left(\frac{dp}{dz}\right)_A \tag{1}$$

The model we propose here for counter-current flows in vertical annuli is developed from available mechanistic models for co-current flows in annuli and counter-current flows in pipes. Previous studies have assumed the contribution of the acceleration term $(dp/dz)_A$ to the pressure gradient in counter-current slug flow is negligible (Duns and Ros, 1963; Orkiszewski, 1967; Ansari et al., 1990; Kaya et al., 1999). However, in this study we re-examine the validity of this assumption for slug flow in vertical annuli.

2. Description of the counter-current bubble flow model

The system in our study is defined as a concentric annulus between a casing of diameter D_C and tubing D_T in a vertical annulus operating in a fully-developed slug flow pattern. This study is restricted to concentric annuli and vertical wellbores; however, we acknowledge that in a real CSG well the eccentricity of the annuli and any l wellbore deviations may need to be considered. The effect of annular eccentricity was investigated by Caetano et al. (1992a). They showed that for the fully eccentric annulus, the transition from bubble to slug flow regimes exhibited a slightly earlier onset whilst the churn to annular regime transition displayed no significant differences. The effect of annular eccentricity was also examined by Kelessidis and Dukler (1989), who compared air-water flows between concentric annuli and annuli with 50% eccentricity. It was found that the eccentricity had minimal effect on the global flow regimes.

In a bubble flow regime the gas phase is distributed in the continuous liquid phase in the form of discrete bubbles in which the rising velocity of a gas bubble in a swarm of bubbles relative to the average liquid velocity is given as

$$u_G + u_L = u_\infty (1-\alpha)^{1/2} \tag{2}$$

where α is the gas holdup (void fraction), $(1-\alpha)^{1/2}$ is a correction factor taking into account the effect of bubble swarm and u_∞ is the rise velocity of a single bubble defined as (Harmathy, 1960).

$$u_\infty = 1.53\left[\frac{\left(\rho_L-\rho_g\right)g\sigma}{\rho_L^2}\right]^{1/4} \tag{3}$$

Replacing the gas and liquid velocities with the superficial velocities in Eq. (2) and rearranging the equation gives

$$(u_{SG}-u_{SL})\alpha - u_{SG} + u_\infty \alpha(1-\alpha)(1-\alpha)^{1/2} = 0 \tag{4}$$

Solving Eq. (4) results in values for gas holdup and therefore liquid holdup (H_L). The pressure gradient due to gravity (hydrostatic pressure gradient) is calculated as

$$\left(\frac{dp}{dz}\right)_G = [\rho_L H_L + \rho_G(1-H_L)]g \tag{5}$$

The pressure gradient due to friction is evaluated by

$$\left(\frac{dp}{dz}\right)_F = [\rho_L H_L + \rho_G(1-H_L)]\frac{2f}{D_C-D_T}u_m^2 \tag{6}$$

where f, the Fanning friction factor, is calculated by the correlations proposed by Caetano et al. (1992a) for a concentric annulus. For laminar flow (Re < 1000) the friction factor is a function of the annulus geometry, which can be characterized by $K = D_T/D_C$ the ratio of the tubing and casing diameters, and evaluated by

$$f = \frac{F_{CA}}{\mathrm{Re}}; \quad \text{where } F_{CA} = \frac{16(1-K)^2}{\frac{(1-K^4)}{(1-K^2)} - \frac{(1-K^2)}{\log(1/K)}}. \tag{7}$$

For turbulent flow (Re > 1000) in smooth annuli the friction factor is evaluated using the correlation proposed by Caetano et al. (1992a) following the Gunn and Darling approach (Gunn and Darling, 1963).

$$\frac{1}{\sqrt{f\times\left(\frac{16}{F_{CA}}\right)^{0.45\exp(10^6\times(3000-\mathrm{Re}))}}} = 4\log\left(\mathrm{Re}\sqrt{f\times\left(\frac{16}{F_{CA}}\right)^{0.45\exp(10^6\times(3000-\mathrm{Re}))}}\right) - 0.4 \tag{8}$$

The acceleration pressure drop is negligible in bubble flow regime.