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Large-scale study of the effect of wellbore geometry on integrated reservoir-wellbore flow

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ABSTRACT

Extraction of coal seam gas (CSG) prior to mining is crucial for reducing the potential risks of gas outburst and explosions during underground coal mining as well as gas production purposes. Many numerical and experimental studies have been carried out to identify the factors affecting the gas productivity. These factors include coal properties, gas content and wellbore geometries. Two different flow conditions determine the gas production efficiency: The gas flow inside the wellbore injected from wall, and the flow through porous coal medium. The full understanding of simultaneous flow of fluids through reservoir and wellbore is critical for analysing the reservoir behaviour. However, previous studies examined the flow of these fluids separately. In this research, a large scale three-dimensional model for simulation of integrated reservoir-wellbore flow is developed to study the effect of wellbore geometry on flow characteristics and wellbore productivity. Four different wellbore diameters of 0.075, 0.10, 0.125 and 0.15 m as well as three different lengths of 50, 100, and 150 m were chosen to accomplish the parametric study of wellbore geometry. It is assumed that the wellbores were in a steady-state condition for two different single phase scenarios of water and methane gas flow. The simulation results were validated against the pressure drop models for internal single phase gas and water flow reported in the literature. The obtained results revealed that increasing the wellbore diameter led to reduction of fluid pressure in the coal seam. Regarding the effect of wellbore length, it was observed that at a specific distance from wellbore outlet, the pressure distribution is independent of the wellbore length and upstream effects. It is also shown that wellbore production could be enhanced by increasing the diameter and the length of wellbore for both gas and liquid flow. The developed integrated framework can be used further for study of any enhanced gas recovery method by changing the boundary conditions based on the physical model.

1. Introduction

Coal seams naturally contain a large amount of gases such as methane (CH_4) and carbon-dioxide (CO_2). In a general estimation, the gas content for different types of coal varies between 0.1 and 25 m^3 per tonne of coal. Coal seam gas (CSG) is mainly composed of methane (CH_4), which is estimated at 80%–95% of overall gas content. There are still many technical challenges associated with gas production from deep coal seams with high gas content and low permeability. In order to overcome these challenges, wellbores are commonly drilled directionally from vertical to horizontal sections with different diameter and lengths. A reliable prediction of CSG flow depends on the appropriate consideration of coal structure and reservoir properties as well as production wellbore geometry. Previous investigations of CSG production has been focused mainly on either reservoir simulations or wellbore flow characteristics.

Many studies have been carried out to simulate flow of fluids from different types of reservoirs into wellbores (Jenkins and Aronofsky, 1953; Aronofsky and Jenkins, 1954; Al-Hussainy et al., 1966; Yao et al., 2013). Early theoretical models or numerical simulations were developed primarily for oil and gas applications. Jenkins and Aronofsky (1953) presented a numerical method for describing the transient flow of gases in a radial direction through a porous medium for which the initial and terminal pressure and/or flow rates are specified. They developed a simple means for

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Nomenclature

D	wellbore diameter, m
L	wellbore length, m
g	gravitational acceleration, m/s^2
h	reservoir thickness, m
J_D	dimensionless productivity index
k	reservoir permeability, m^2
q	volumetric production rate, m^3/s
P	pressure, *Pa*
S_i	momentum sink term, kg/m^2 s^2
S_m	mass source term, kg/m^3 s
V	velocity, m/s
x,y,z	cartesian coordinates, m
Greek letters	
μ	dynamic viscosity, *Pa s*
ρ	density, kg/m^3
τ	shear stress, *Pa*
Subscript	
0	reference values
g	gas phase
l	liquid phase
w	wellbore

predicting the well pressure at any time in the history of a reservoir. In their next study (Aronofsky and Jenkins, 1954) an effective drainage radius was suggested for which the steady-state gas flow assumption could be used to predict the well pressure in the process of gas reservoir depletion. In a rigorous model, Al-Hussainy et al. (1966) considered the effect of variations of pressure dependent viscosity and gas law deviation factor on the flow of real gases through porous media. They used pseudo-pressure as change of variable to reduce the equations to a form similar to diffusivity equations. Yi et al. (2009) simulated gas flow through a reservoir using a two-dimensional solid-gas coupled software package (RPFA). They studied the effect of permeability, wellbore spacing and diameter and gas content on reservoir pressure and drainage radius. Packham et al. (2011) used SimedWin to simulate CSG flow in an attempt to demonstrate the ability of enhanced gas recovery. Based on their reservoir model calibrated by history matching, they concluded that with regard to increased gas flow rate and decreased drainage time, enhanced gas recovery through injection of nitrogen is achievable. Most of these researches have focused only on reservoir aspects of simulation and their assumptions, such as defined boundary conditions at wellbore and one- or two-dimensional modelling, require further improvements. The errors associated with the simplifying assumptions limit the range of application of these reservoir simulators. Moreover, the wellbore flow is defined as a boundary condition and is not included in the mathematical modelling and governing equations of the reservoir simulators. Therefore, the interaction between the reservoir and wellbore interface is neglected.

On the effect of wellbore wall influx/outflux, a number of studies have been carried out to understand the flow filed behaviour and pressure drop along wellbores (Asheim et al., 1992; Yuan, 1997; Su and Gudmundsson, 1998; Yuan et al., 1999). Siwoń (1987) developed a one-dimensional model for steady state flow of incompressible fluid in a horizontal pipe perforated with circular orifices. Ouyang et al. (1998) continued this study by developing a pressure drop model for pipes with perforated wall that can easily be used in reservoir simulators and analytical models. This model considers different types of pressure drops including frictional, accelerational, gravitational and pressure drop caused by inflow. They concluded that for laminar flow, the wall friction increases due to inflow whereas for turbulent flow, the wall friction decreases as a result of inflow. Based on this approach, more attempts have been made to develop the most accurate pressure drop models for wellbore flow. Yalniz and Ozkan (2001) investigated the effect of inflow from horizontal wall on flow characteristics and pressured drop experimentally and theoretically. They developed a generalized friction factor correlation that was a function of Reynolds number, the ratios of influx to wellbore flow rate and perforations to wellbore diameter. Wang et al. (2011) measured pressure drop due to inflow in a horizontal perforated pipe loop by using water as working fluid. Their experimental results showed that pressure drop grew as a result of increased injection flow rate. They developed a model suggesting total pressure drop consisting of two parts including perforated pipe wall friction loss and an additional pressure drop term. In a recent study, Zhang et al. (2014) presented a comprehensive model for prediction of pressure drop based on previous studies and some new experiments. Their results show that this model presents more accurate results for their experiments when compared with previous models.

In addition to theoretical models, some researchers have simulated wellbore flow using numerical techniques to avoid the simplifying assumptions (Folefac et al., 1991; Seines et al., 1993; Siu et al., 1995; Su and Lee, 1995; Yuan et al., 1998; Ouyang and Huang, 2005). Guo et al. (2006) developed a numerical model to study the deliverability of multilateral wells. Their model was capable of coupling the inflow performance of the individual laterals with hydraulics in curved and vertical well sections. Zeboudj and Bahi (2010) simulated wellbore flow with pipe injection using Computational Fluid Dynamics (CFD) simulation as a replacement for further experiments. They discussed the experimental measurement shortcoming in the assumption of a constant momentum-correction factor, which was not true in the case of wall inflow. CFD simulation, however, allowed the exact calculation of this parameter by considering all variations of velocity in radial direction by eliminating the need for making flawed assumptions. In another study, Ouyang et al. (2009) studied single-point wall entry for oil and gas wellbores. The significant effect of wellbore hydraulics on production predictions, performance evaluations and completion design for horizontal and multilateral wellbores needed to be well understood. In this respect, they used CFD modelling using ANSYS to investigate flow profiles and pressure distribution along the wellbore thoroughly. Their simulation results showed that moving the entry point closer to the outlet section reduced the significant impact of inflow on the total pressure drop along the wellbore.

Depending on wellbore geometry, the flow characteristics through the coal seam and wellbore may vary significantly. Some theoretical models and reservoir simulators have been presented accordingly. However, these models need further improvements with regard to the simplification of boundary condition assumptions on the reservoir-wellbore interface. Efficient production of coal seams gas requires a better understanding of reservoir and wellbore conditions and their interactions. In this study, a large-scale three-dimensional model is developed using CFD simulations to study the integrated reservoir-wellbore flow during CSG production. The specific influence of wellbore diameter and length on the coal seam flow behaviour, pressure drop and production performance is investigated. A schematic of