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Development of new type curves for production analysis in naturally fractured shale gas/tight gas reservoirs

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ABSTRACT

As a result of ultra-low rock permeability and hydraulic fracturing, both shale gas and tight gas production exhibit long-term transient and linear flow behaviour. Previous studies have introduced the type curves for linear flow reservoir and assumed that the production is dominated by the stimulated reservoir volume (SRV). Later the type curves were extended to include the production contribution from un-stimulated region which has been assumed to be a homogeneous system. At present, no type curves have been developed for naturally fractured shale gas/tight gas reservoirs in which the un-stimulated region has double porosity flow behaviour.

In the current study, we have developed new analytical solutions for shale gas/tight gas reservoirs with multi-stage fractured horizontal well in order to account for the un-stimulated region as a dual porosity system. The solutions are more general for type curve analysis and applicable in both homogeneous and naturally fractured reservoirs. Numerical models were used to validate the analytical solutions and obtained an excellent agreement. We have also developed new type curves for shale gas/tight gas evaluation. The flow regimes are identified to show linear flow and transition flow alternately, and are more complicated than the assumption of homogeneous un-stimulated reservoir in late period. We have compared the new type curves with the curves based on SRV and Brohi's solutions. It is concluded that the double porosity behaviour of un-stimulated region has a positive effect on production even if the fracture permeability is in the order of matrix permeability and the matrix bulk shape factor is low.

1. Introduction

Production data analysis (PDA) has been used as an effective method for production forecasting and reserves estimation in shale gas/tight gas reservoirs, including decline curve analysis (DCA) and type curve matching. Since the permeability of tight gas and shale reservoirs is low, the technologies of horizontal well drilling and hydraulic fracturing are commonly used to make the development commercial. The combination of these technologies results in a rectangular reservoir called the stimulated reservoir volume (SRV), which is usually monitored by micro-seismic technique (Bello and Wattenbarger, 2010; Inamdar et al., 2010), and an outer un-stimulated reservoir. Due to the ultra-low matrix permeability and high conductivity fracture, the shale gas/tight gas production shows long-term transient linear flow behaviour and exhibits a minus one-half slope of gas rate versus time on a log–log plot. Therefore, the PDA for shale/tight gas is different from conventional methods based on radial flow and boundary dominated flow, which were developed first by Arps (1945), and modified by other authors such as Fetkovich (1980), Palacio and Blasingame (1993), and Agarwal et al. (1999). Also shale gas reservoirs contain both free gas in macro-pores and adsorbed gas on matrix surface area.

To use production analysis technique for tight gas and shale gas reservoirs, Lee and Gatens (1985) and Hazlett et al. (1986) constructed a set of type curves for the Devonian shales using a solution for constant pressure production in a bounded dual-porosity reservoir based on the Warren–Root model. Lewis and Hughes (2008) proposed production data analysis for shale gas using a modified material balance time to account for desorption. However, these methods were based on radial flow. It was found that a best-fit match with Arps' hyperbolic decline gives constant values (b) greater than 1 (Baihly et al., 2010). This can cause to have physically unreasonable properties (Lee and Sidel, 2010). As a result, Valkó and Lee (2010) developed a stretched exponential production decline model. Duong (2010) also introduced a derived decline model that is based on long-term linear flow in a large

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Nomenclature

A_{cw}	well face cross-sectional area to flow, ft^2
B	formation volume factor, fraction
c_d	desorption compressibility, psi^{-1}
c_f	rock compressibility, psi^{-1}
c_g	gas compressibility, psi^{-1}
c_t	total compressibility, psi^{-1}
k	permeability, md
L	fracture spacing for slab model, ft
$m(p)$	pseudo-pressure (gas), psi^2/cp
p_i	initial reservoir pressure, psi
p_L	Langmuir pressure, psi
$\overline{p}$	average reservoir pressure, psi
q	gas rate, Mscf/day
T	absolute temperature, °R
T_{sc}	absolute temperature at standard conditions, °R
t	time, days
t_a	pseudo-time, days
V_L	Langmuir volume, ft^3/ft^3
x	dimension of Cartesian coordinate parallel to horizontal wellbore, ft
y	dimension of Cartesian coordinate perpendicular to horizontal wellbore, ft
y_f	the distance of stimulated reservoir boundary to wellbore, ft
y_e	the distance of reservoir boundary to wellbore, ft
z	vertical dimension of Cartesian coordinate, ft
Z	compressibility factor, fraction
$\overline{Z}$	compressibility factor at average reservoir pressure, fraction
Z_{sc}	compressibility factor at standard conditions, fraction

Greek symbols

λ	dimensionless interporosity parameter
μ	viscosity, cp
ω	dimensionless storativity ratio
φ	porosity
σ	shape factor, ft^{-2}
ξ	dimensionless fracture permeability ratio
η	dimensionless transmissivity ratio

Subscript

D	dimensionless
i	initial
f	fracture
m	matrix
$f+m$	total system (fracture+matrix)
1	inner reservoir
2	outer reservoir

number of wells in tight and shale gas reservoirs. Wattenbarger et al. (1998) presented a linear flow approach to analyse production of fractured tight gas wells. The model was based on homogeneous and linear reservoirs with infinite conductivity hydraulic fracture. El-Banbi (1998) developed a transient dual porosity model for linear reservoirs. Recently several authors developed and applied type curves developed based on the transient dual porosity model and analysed shale gas production, such as Bello and Wattenbarger (2008, 2009, 2010), Moghadam et al. (2010), Nobakht and Mattar (2010), Al-Ahmadi et al. (2010), and Anderson et al. (2010). However, desorption was ignored in these literatures, and also production was assumed to be from SRV only. Ozkan et al. (2009) and Brohi et al. (2011) presented tri-linear flow solutions for tight gas and shale gas reservoirs, which account for the production contribution of un-stimulated reservoir, and model it as a single porosity system. It was concluded that outer un-stimulated reservoir is subject to supply gas production in later times, which depends on the permeability of the outer region. Up to the present, no type curves are available to consider the un-stimulated reservoir as a double porosity system, which is common in shale gas and tight gas reservoirs.

In the following sections, first, we have reviewed the possibilities of physical model for multi-stage fractured horizontal well. Then we built the mathematical model to describe the flow behaviour and obtained the analytical solutions which were verified subsequently using numerical models. Based on the solutions, the new type curves were developed and parameters sensitivity was also investigated. Furthermore, we have compared the new solutions with the SRV and Brohi's solutions in order to show the feature and importance of dual porosity behaviour in un-stimulated reservoir.

2. Physical description

Hydraulic fracturing probably creates planar, bi-wing fractures. However in naturally fractured reservoirs, the interaction between induced fracture and primary fracture may result in complex fracture network. Therefore, for homogeneous reservoirs, the multi-stage fracturing in horizontal well commonly causes to have multi-transverse fractures distributed along the wellbore, as shown in Fig. 1a. For a dual porosity shale reservoir, the effect of hydraulic fracturing leads to a stimulated reservoir volume (SRV) around the wellbore, as seen in Fig. 1b. The more probable scenario is that the proppant is concentrated in dominated

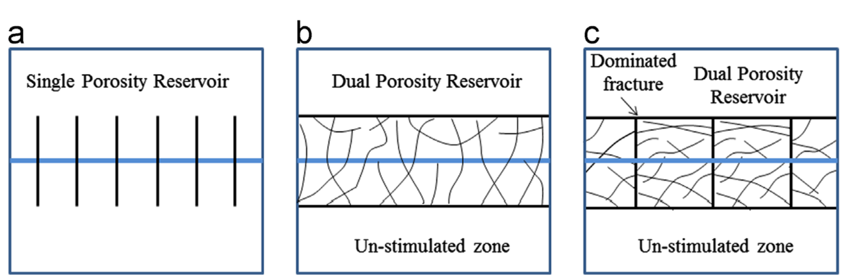

Fig. 1. Hydraulic fracturing in single porosity and dual porosity reservoirs (modified from Clarkson and Pedersen, 2010). (a) Planar fractures, (b) SRV and (c) SRV region with dominated fractures.