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A new analytical multi-linear solution for gas flow toward fractured horizontal wells with different fracture intensity

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ABSTRACT

This paper presents a new analytical solution to study the interplay between flowing pressure and production rate for horizontal wells completed within stimulated reservoir volumes (SRV) in tight gas reservoirs. Field practice has shown that all fracturing stages are not effective in production; this has been explained through varying fracture intensity inside and outside of SRVs along the well (fully fractured zone, partially activated zone and non-activated zone). Despite the existing solutions, the novelty of this model is in integrated approach to consider fracturing stages with different fracture intensity, consistent with observations in the field. In addition, the presented model considers wellbore storage effects, stress-dependent and non-Darcy flows considering threshold pressure gradient.

Implementing the Laplace transform technique, our multi-linear analytical solution is obtained from the diffusivity equation. We validate the analytic solution with field data; our results are consistent with the field observation. A sensitivity analysis is conducted to study impacts of fracture intensity, threshold pressure gradient, compaction, and size of the stimulated reservoir volume (SRV) on appearance of different flow patterns and ultimate well productivity. Our results suggest a relation between SRV aspect ratio and occurrence of various flow patterns when fracture intensity is changing along the well.

In practice, this septa-linear flow model is simple, practical and time-efficient for the transient pressure analysis and production prediction. Furthermore, this work is one step forward to make the analytic solutions more realistic by incorporating different fracture intensity of each fracturing stage.

1. Introduction

In tight gas reservoirs, there are significant incidences of natural complex mineralized or plugged fractures. Fracturing of horizontal wells with hybrid fluid or slick water (SWF) (Grieser et al., 2003; Fisher et al., 2004; Britt and Smith, 2009) not only increase fracture-formation contact areas by creating SRVs, but also reactivate natural fractures to some extent, which is vital to tight gas production (Cipolla, 2009; King, 2010; Ozkan et al., 2009; Stalgorova and Mattar, 2012; Clarkson, 2013).

It is still an extreme challenge to predict fractured horizontal well performance with complex SRVs. But it is still possible to develop some analytical, semi-analytical and numerical models to present pressure transient and production behaviors in tight gas.

Semi-analytical models were introduced by Crosby et al. (2002) and Wan and Aziz (2002) to study the pressure responses to the horizontal well with fractures rotated at any angle. Al-Kobaisi et al. (2006) presented a hybrid numerical-analytical transient pressure model of horizontal wells with vertical fractures. Zhu et al. (2007) and Lin and Zhu (2010) developed volumetric source methods to model fractured horizontal wells in box-shaped reservoirs and describe pressure behaviors. Rbeawi and Tiab (2013) introduced analytical models to study pressure behaviors and flow regimes of horizontal well with multiple longitudinal or transverse, vertical or incline, symmetrical or asymmetrical fractures.

However, these methods just focused on fluid flow in primary fractures but ignoring fluid flow inside secondary fractures and matrix. It is essential for simulations to model complex fracture networks similar to the real field geological situations. But now it is

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still impossible to establish flow model of complex fracture networks without any simplifications.

Assuming the uniform distribution of identical hydraulic fractures along horizontal well, tri-linear model was presented by Ozkan et al. (2009), Meyer et al. (2010), Brown et al. (2011) which can handle key characteristics of complex flow of multiple transverse fractures with finite conductivity of horizontal wells. Stalgorova and Mattar (2012) then developed the tri-linear flow model to a five-region flow model, which took into account the partially stimulated reservoir volume and fluid supplement from matrix. Apaydin et al. (2012) developed the analytical tri-linear flow model with composite blocks to describe the effect of micro-fractures on matrix permeability. Zhao et al. (2014) also extended the conventional multiple hydraulically fractured horizontal (MFH) well into a composite model to describe the stimulated reservoir volume (SRV). Despite obvious advantages of "tri-linear" and "five-region" models, there are still some drawbacks of them. However, in fact, it is not possible for uniform density of micro-fractures distributed in the formation, due to fracturing effects, the properties quality of micro-fractures (aperture, density and conductivity) near horizontal wells would be better than those fractures remote to the wells.

In this paper, we present one new analytical multi-linear flow model considering the variant fracture densities versus the distance with wellbores (primary hydraulic fractures, secondary fractures and then the partially open but not fully connected natural fractures), wellbore storage, non-Darcy fluid flow and reservoir stress-sensitive effects using Equivalent Continuous Medium Model (Liu et al., 2000; Cai and Yu, 2011). This model can simply but effectively describe the effects of different properties of fractured areas on transient pressure behavior of fractured horizontal wells with SRVs. We assume threshold pressure gradient to describe the non-Darcy effects on gas flow (Prada and Civan, 1999; He et al., 2002) in tight reservoirs. We validated our model by matching the results with field examples.

2. Physical model and parameters definition

2.1. Physical model and assumptions

In tight gas reservoirs, large-scale hydraulic fracturing could not only create secondary fractures along primary fracture, but also reactivate non-constitute natural micro-fractures in the vicinity of horizontal wells. These primary hydraulic fractures combined with partially activated natural fractures and secondary fractures form highly conductive SRVs which are the key sources of gas production.

Assuming that gas flow is along linear direction perpendicular to the surface of primary fractures or SRVs, this multi-linear flow model involved with interferences between SRVs is presented for single-phase gas with constant compressibility in box-shaped tight gas reservoirs with no-flow boundary. The fluid could only flow towards wellbore through primary fractures. The pressure loss along horizontal wellbore is neglected.

In Fig. 1, the flow model of fractured horizontal well with N SRVs in gas reservoir could be presented by considering single SRV produced at a rate equal to q_f (inner fractures) or q_{fe} (outer fractures) from a rectangular gas reservoir, where flow rate of outer fracture and that of inner fracture are not identical due to their locations. The no-flow boundary between fractures are at the middle-distance between two fractures, $y_e = L_h/2N$. The lateral boundary perpendicular to fracture surface are at $x_e = W_r/2$ from the center of fractures. The fracture elements have a half-length x_f, width of w_f and penetrates the whole vertical formation, h.

The multi-linear flow model involves linear flow in seven-contiguous-flow regions as described in Fig. 2. Fluid flow in every region is different.

Region I ($0 \le x \le x_f$): The insides of primary hydraulic fractures with symmetrical wings along the horizontal well and completely penetrated reservoir vertically are assumed finite-conductivity. We also assumes one-dimensional fluid linear flow along fracture orientation, and wellbore-storage effect is incorporated.
Region II ($0 \le x \le x_f, 0 \le y \le f$): We use Tensor Theory and Law of equivalent flow resistance to simulate continuous stimulated secondary fracture networks, and assume the fluid flow as linear flow perpendicular to the primary fracture plane. We take into account the stress-sensitivity index and threshold pressure gradient to describe particular features of gas flow in tight gas reservoirs.
Region III ($0 \le x \le x_f, f \le y \le l$): In this region, the natural micro-fractures could be reactivated partially by fracturing disturbances. The quality of fractures are worse than those in Region II. We assumed the linear flow in the direction y as Fig. 2, and consider reservoir stress-sensitivity and non-Darcy flow effects.
Region IV ($0 \le x \le x_f, l \le y \le y_e$), region V ($x_f \le x \le x_e, 0 \le y \le f$), region VI ($x_f \le x \le x_e, f \le y \le l$) and region VII ($x_f \le x \le x_e, l \le y \le y_e$): Those regions are matrices zones without any induced fractures, but have different flow direction due to the relationships with the proximity of fractures. Additionally, gas flow in those regions consider reservoir stress-sensitivity and threshold pressure gradient in matrixes. The variant flow directions could be seen in Fig. 2.

2.2. Definitions of variables

For tight gas reservoirs, we usually define pseudo-pressure to describe gas flow accurately

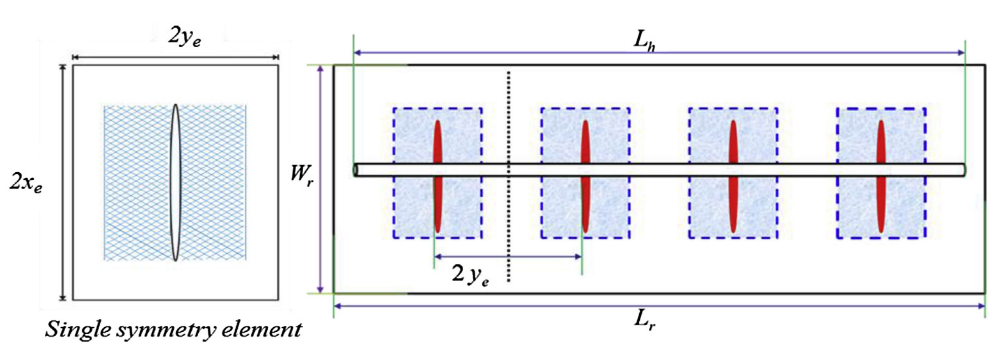

Fig. 1. Arrangement of SRVs and single symmetry SRV element for fractured horizontal well.