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# Performance of horizontal wells with fracture networks in shale gas formation

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ABSTRACT

With micro fractures (MF) in shale gas (SG) reservoirs, complex fracture networks can easily develop along horizontal wells after stimulated reservoir volume (SRV) treatments. Due to the intricate flow characteristics, performance investigations for horizontal wells with fracture networks (HWFN) are extreme challenges. Hence, lots of work needs to be done to overcome this difficulty.

In this paper, we proposed a semi-analytical method to predict the performance of HWFN in SG formation. First, based on symmetry, the fracture networks were approximated as a mixture of multiple hydraulic fractures (HF) and MF. Then, a new semi-analytical model was proposed by discretizing all these fractures into small segments with consideration of fracture interferences, SG diffusion, SG adsorption, and effect of stress-sensitivity of permeability. By solving this model, the transient pressure performance of HWFN was obtained. To verify the semi-analytical method, both analytical and numerical validations were conducted. After validation, the effects on performance of HWFN were studied including fracture number, fracture length, fracture conductivity, SG diffusion coefficient, SG adsorption index, and stress-sensitivity coefficient. Finally, type-curve matching and parameter estimations for a field case were conducted.

Results show the type curves of HWFN have two unique features: (1) a "dip" which occurs by the end of bilinear flow period and (2) a disappearance of early radial flow. The possible flow regimes for HWFN in a finite SG formation are: (a) bilinear flow, (b) "MF-HF support", (c) first linear flow, (d) bi-radial flow, (e) SG diffusion flow, and (f) boundary-dominated flow. In addition, results of sensitivity analysis indicate that the "MF-HF support" is stronger with the increase of MF number, MF length, and MF conductivity; it is weaker with the increase of HF number, HF length and HF conductivity.



## 1. Introduction

With the development of exploration and production technologies, SG has made great change in the world energy structure, becoming a global hot spot. Due to the features of ultra-low permeability and nanoscale pores, horizontal wells with SRV treatments have been verified as the most effective tools to enhance SG productivity (Javadpour et al., 2007; Soliman and Kabir, 2012; Tian et al., 2014). Undoubtedly, performance predicts of these wells are urgent tasks for reservoir engineers.

The model of multiple fractured horizontal well (MFHW) is firstly put forward to tackle this issue. This model denotes a horizontal well with multiple HF, as shown in Fig. 1. Huge amount of work has been done on performance investigation of this model. The methodologies can be approximately classified into three types: (1) analytical method (Brown and Ozkan, 2011; El-Banbi, 1998; Ezulike and Dehghanpour, 2013; Ozkan et al., 2011; Soliman et al., 1990; Stalgorova and Mattar, 2012a; Stalgorova and Mattar, 2012b; Xu et al., 2013). The analytical method is the most rapid and convenient one, but it is inaccurate due to the ignorance of fracture interferences; (2) semi-analytical method (Chen and Raghavan, 1997; Guo and Evans, 1993; Horne and Temeng, 1995; Larsen and Hegre, 1991; Raghavan et al., 1997). Fracture interferences can be easily considered by using the semi-analytical method, and the semi-analytical solution is always obtained by using Stehfest numerical inversion (Stehfest, 1970); (3) numerical method (Al-Kobaisi and Ozkan, 2004; Freeman, 2010; Karcher et al., 1986; Olorode et al., 2012; Valko and Amini, 2007; Yu et al., 2014). Dynamic SG properties can be considered when applying this method. However, the modeled fractures are always not in line with practices because of the limitation of grid numbers (Chen et al., 2014).

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**Nomenclature**

| | |
|---|---|
| $C_m$ | shale matrix compressibility, atm$^{-1}$ |
| $C_g$ | SG compressibility, atm$^{-1}$ |
| $C_{MF}$ | MF conductivity, D.cm |
| $C_{HF}$ | HF conductivity, D.cm |
| $D$ | diffusion coefficient, cm$^2$s$^{-1}$ |
| $h$ | formation thickness, cm |
| $i$, $k$ | fracture wing number, integer |
| $j$, $l$ | fracture wing segment number, integer |
| $x$, $y$, $z$ | coordinates, cm |
| $a$ | adsorption index, dimensionless |
| $K$ | permeability, D |
| $L$ | length, cm |
| $M_g$ | molecular weight of shale gas, g/mol |
| $M$ | the number of segments for each fracture wing, integer |
| $m$ | pseudo-pressure, atm$^2$/cp |
| $n_{MF}$ | total number of MF number, integer |
| $n_{HF}$ | total number of HF number, integer |
| $p$ | real pressure, atm |
| $q$ | flow rate, cm$^3$/s |
| $q_{fw}$ | flow rate of fracture wing in the wellbore, cm$^3$/s |
| $q_f$ | flow rate of per unit fracture length, cm$^2$/s |
| $r$ | radial distance, cm |
| $R$ | gas constant, Jmol$^{-1}$K$^{-1}$ |
| $s$ | Laplace transformation variable, dimensionless |
| $t$ | time, s |
| $T$ | temperature, K |
| $v$ | SG flow velocity, cm/s |
| $V$ | SG concentration, cm$^3$/cm$^3$ |
| $W$ | fracture width, cm |
| $Z$ | SG Z-factor, fraction |

*Greek*

| | |
|---|---|
| $\mu$ | viscosity, mPa.s |
| $\alpha$ | permeability modulus, atm$^{-1}$ |
| $\alpha'$ | modified permeability modulus, atm$^{-1}$s |
| $\alpha_D$ | stress-sensitivity coefficient, dimensionless |
| $\omega$ | storage ratio, fraction |
| $\rho$ | density, g/cm$^3$ |
| $\phi$ | porosity, fraction |

*Subscript*

| | |
|---|---|
| $g$ | gas |
| $he$ | fracture heel |
| $r$ | reference |
| $i$ | initial |
| $L$ | Langmuir |
| $m$ | matrix |
| $sc$ | standard condition |
| $w$ | wellbore |
| $MF$ | micro fracture |
| $HF$ | hydraulic fracture |
| $D$ | dimensionless |
| $E$ | external |
| $e$ | boundary |
| $f$ | fracture |

*Superscript*

| | |
|---|---|
| – | Laplace transform |

Although a lot have been achieved in the performance predicts of MFHW, the issue is far from settled. Much fracturing imaging strongly shows that with the MF in SG formation, complex fracture networks can easily develop along horizontally fractured well, as shown in Fig. 2 (Cipolla et al., 2011; Cipolla et al., 2009; Cipolla et al., 2010; Weng et al., 2011; Weng, 2014). Unluckily, MFHW which simulates a horizontal well with HF cannot deal with the cases with complex fracture networks. Thus, further researches are needed to be done.

To begin with, numerical methods were used to deal with this challenge. In-home or commercial simulators are applied to investigate the performance of HWFN (Cipolla et al., 2011; Cipolla et al., 2009; Cipolla et al., 2010; Mirzael and Cipolla, 2012; Weng et al., 2011; Xu et al., 2010; Zhou et al., 2012). For example, Cipolla et al. (2009, 2010) and Xu et al. (2010) used conventional reservoir simulators to discuss the effect of fracture complexity on performance of HWFN. In their studies, the fractures were treated as refined high-permeability grid cells in the structured/unstructured grid systems. However, this equivalent conductivity method (Chen et al., 2014) can certainly cause errors. Further, approaches of gridding and simulating are severely difficult as well as time-consuming. What's more, special knowledge is required when using this method. All these weaknesses make the numerical method less attractive.

To overcome these shortages, Lin and Zhu (2012) and Hwang et al. (2013) applied semi-analytical methods to estimate the performance of HWFN. In these studies, each HF was connected to the wellbore, and MF was connected to HF. There are two main weaknesses in these literatures. The first one is that fluid moving in the HF is considered as radial flow. However, it should be more aligned with linear flow due to the fracture shape (Stalgorova and Mattar, 2013). Another weakness is that the MF is assumed to be infinite-conductivity. But, compared with HF, the MF conductivity is lower, which virtually requires much more consideration.

In addition, based on a dual-porosity model (Ozkan et al., 2011), Dehghanpour and Shirdel (2011) introduced a triple-porosity model (TPM) to forecast the performance of HWFN. In this work, the horizontally fractured well was connected to macro fracture networks, and the matrix blocks were considered as dual-porosity medium. Ezulike and Dehghanpour (2014a; 2014b) also proposed a quadrilinear flow model (QFM) to describe the performance of a horizontal well with HF and MF. In this model, there were three medium: matrix, MF, and HF. MF were perpendicularly connected to HF. The matrix was divided into two sub-domains to feed HF and MF respectively. Type curves and flow regimes were also obtained in this work. These novel models provided significant references for performance predicts of HWFN. Regretfully, their objectives are the area around a HF, and fracture interferences were not considered. Thus, a more comprehensive research needs to be conducted.

In this paper, based on the TPM and QFM, some improvements are made to completely study the performance of HWFN: (1) SG reservoir between the fracture networks is still treated as a dual-porosity media which is comprised by matrix and natural fracture subsystem, (2) the objective is an area including the whole fracture networks, and (3) all fracture interferences are considered. This study provides key references for reservoir engineers to analyze transient data of horizontal wells with fracture networks