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Multiple fracturing parameters optimization for horizontal gas well using a novel hybrid method

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Hydraulic fracturing technique has been widely used to develop tight and low-permeability reservoirs, while it has been a great challenge to optimize the fracture parameters for horizontal wells, especially for the horizontal gas wells associated with strong heterogeneity. The traditional mathematical models only can perform well in homogeneous reservoirs. Although the reservoir numerical simulation techniques can take heterogeneity into consideration, the fitting process of parameters is time-consuming, and the simulation results may not be accurate enough due to the limitations of local grid refinement. In this study, a novel hybrid methodology combining the Dual-Porosity Volumetric Source (DPVS) model in gas reservoirs, reservoir numerical simulation technique, and Reservoir Classification (RC) method based on well-logging analysis has been proposed to optimize fracture parameters in horizontal heterogeneous gas wells. First, the RC method is used to subdivide the horizontal wellbore into several blocks which can be treated as homogeneous and heterogeneous blocks, respectively, according to their absolute permeability distribution. Then, DPVS model is applied to optimize the fracture parameters including fracture number, fracture length, and fracture conductivity for the homogeneous blocks and fracture conductivity for the heterogeneous blocks. The reservoir simulation technique is applied to optimize the fracture number and fracture length for the heterogeneous blocks. Besides, the reservoir simulation technique is used to investigate the influence of reservoir heterogeneity including permeability distribution pattern and proportion of permeability value on the fracture optimization results. It has been found that the permeability distribution pattern along the wellbore has a minor influence on the fracture parameter optimization results, but the proportion of permeability value plays a significant role in the fracture parameter optimization. This novel technique has a higher accuracy and is particularly suitable for fracture parameter optimization of multistage fracturing technique in heterogeneous tight gas reservoirs.

1. Introduction

The multistage fracturing technique has been introduced into the oil industry for enhancing hydrocarbon production since the late 1980s (Soliman and Boonen, 1996). Recently, the multistage fracturing technology has been widely used in the horizontal wells to develop tight/low permeability formations efficiently (Soliman and Boonen, 1996; Hashemi and Gringarten, 2005; Lee et al., 2009; Cheng et al., 2015; Yuan et al., 2015a; Yuan and Wood, 2015). The performance of the fractures is affected by various factors mainly including geological properties and fracturing parameters (Root, 1978; Osorio and Lopez, 2009). In general, the geological properties, such as lithology, porosity, permeability and rock strength, are uncontrollable, but the fracture parameters, such as fracture number, fracture length, and fracture conductivity, can be optimized and designed to improve the performance of the multistage fracturing technique. Therefore, it is of fundamental and practical importance to optimize the fracture parameters before implementing the multistage fracturing technique in the tight/low permeability formations.

Many techniques have been proposed to optimize and design the fracture parameters (Yuan et al., 2015b, 2016), while point

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source functions (Green's function) and reservoir numerical simulation technique are the most commonly used methods (Gilbert and Barree, 2009; Lin and Zhu, 2010; Belyadi et al., 2010; Panfili et al., 2015). Point source functions can solve the problems of transient flow successfully (Gringarten and Ramey, 1973; Ozkan and Raghavan, 1991a,b, 1994), which make the prediction of productivity for multi-fractured horizontal wells possible (Zerzar and Bettam, 2003; Lin and Zhu, 2010). Although point source functions have high estimation accuracy, their calculation efficiency is very low due to the summation of infinite series and the calculation of abnormal integral. In addition, Ogunsanya et al. (2005, 2006) found that the point source functions without consideration of volume can not perform well in thin formations. Accordingly, the volumetric source parameter was taken into account into the point source functions, while a new "solid bar source" model was developed. Furthermore, Magalhaes et al. (2007) developed a Distributed Volumetric Source (DVS) model to optimize fracture parameters for homogeneous reservoirs, while the performance of the DVS model has been validated by applying it to a multi-fractured horizontal well. It has been found that the DVS model not only can avoid the singular value problem during the solving process but also can reduce the influence of the volume sources on the pressure solutions of the model. Therefore, compared with the point source functions, the DVS model has better applicability. However, up to the present, the aforementioned methods (i.e. point source functions and DVS model) have not been applied to optimize fracture parameters in heterogeneous formations due to their complex mathematical models (Zerzar and Bettam, 2003; Valkó and Amini, 2007; Lin and Zhu, 2010).

Recently, the reservoir numerical simulation technique has been applied to optimize fracture parameters in heterogeneous reservoirs, where the fractures are represented by refining the local grids. Gilbert and Barree (2009) employed the reservoir simulation technique to evaluate the performance of the multistage fractured horizontal wells, while they found that both the formation permeability and the interference between fractures play a significant role in optimizing fracture parameters including fracture number and fracture length. Gilbert and Barree (2009) also concluded that, compared with the other fracture parameters, the fracture number is the most influential parameter determining the productivity of the multistage fractured horizontal well, while their conclusion was consistent with that of Belyadi et al. (2010). As for the studies above, although the reservoir numerical simulation technique has been applied to optimize the fracture number and length successfully, the fracture conductivity which has been considered as one of the most influential parameters affecting the performance of the multistage fractured horizontal wells has been ignored (Wang et al., 2015). That is because the reservoir numerical simulation has to face higher computational expense due to the finer Local Grid Refinement (LGR) and the parameter fitting process will be more time-consuming by taking the fracture conductivity into account (Taylor et al., 2010; Panfili et al., 2015). Therefore, it has been recommended that the reservoir numerical simulation technique should be combined with other methods to improve the accuracy and efficiency of fracture parameters optimization for the multistage fractured horizontal wells (Taylor et al., 2010).

In this study, a hybrid methodology has been proposed to optimize fracture parameters including the fracture number, fracture length, and fracture conductivity for multistage fractured horizontal gas wells associated with strong heterogeneity. First, the gas reservoir is recognized by analyzing the logging profiles. Then, along the horizontal gas well, the gas reservoir is divided into several blocks which can be classified as homogeneous blocks and heterogeneous blocks, respectively, based on their absolute permeability distribution. A new Dual-Porosity Volumetric Source (DPVS) model which is derived on the basis of DVS model is applied to optimize all the fracture parameters (i.e., fracture number, fracture length, and fracture conductivity) for the homogeneous blocks and the conductivity of fractures for the heterogeneous blocks. The reservoir numerical simulation technique is used to optimize the other two fracture parameters (i.e., fracture number and fracture length) for the heterogeneous blocks. Finally, the optimization results have been presented, analyzed and discussed.

2. Methodology

2.1. Reservoir classification method

As for the lithological-control gas reservoirs, especially the channel-sand-body-development gas reservoirs, there exists great interstratification between the low permeability sand layers and mud layers resulting in strong heterogeneity. In this kind of gas reservoirs, the performance of the hydraulic fracturing can hardly achieve design expectation if the multistage fracturing technique was designed and implemented based on the assumption of the homogeneous reservoir. Therefore, it is practically necessary to evaluate the homogeneity/heterogeneity of the formation along the to-be-fractured horizontal well to choose the proper optimization method.

Although pressure interference between the fractures may occur after the fractured wells are put into production, it needs a long time, sometimes more than one year, to happen when the permeability between the fractures is lower than 0.001mD (Gilbert and Barree, 2009). Therefore, the lower permeability interstratification whose permeability is lower than 0.001mD can be treated as "non-effective formation". In this study, the "non-effective formation" is first recognized to divide the whole formation along the to-be-fractured horizontal well into several sections which can be treated as homogeneous sections and heterogeneous sections, respectively, based on their permeability distributions. Then, the theoretical model method, i.e., DPVS model proposed in this study, is applied to optimize the fracture parameters for the homogeneous sections, while the reservoir simulation technique is applied to optimize the fracture parameters for the heterogamous sections which is the core idea of the newly proposed hybrid methodology in this study. In this paper, the CX-1H horizontal well drilled in a gas reservoir located in Sichuan Province, China, is taken as a case study, while the permeability distribution curve of the gas reservoir along the horizontal wellbore is shown in Fig 1 (a). As can be seen, there exists high heterogeneity in the gas reservoir along the well horizontal direction, while, on the well perpendicular direction, the permeability of the region around the wellbore is assumed to be the same as the permeability of the area far from the wellbore. As shown in Fig. 1 (b), the gas reservoir can be separated into three sections, i.e., Section A, B, and C, by recognizing two "non-effective formation" whose permeability is lower than 0.001mD and thickness is larger than 1 m, along the well horizontal direction.

In each section, the following equation is applied to evaluate its homogeneity/heterogeneity:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \eta)^2}, \quad \eta = \frac{1}{L_N}\sum_{i=1}^{N} x_i l_i \tag{1}$$

where σ is the standard deviation of permeability distribution, N is the number of subsections divided in each section, x_i is the permeability of the ith subsection, l_i is the thickness of the ith subsection, L_N is the width of each section, and η is the weighted average of permeability in each section. In this study, to satisfy the engineering design requirement, it is suggested that, when σ is less