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The performance evaluation and design optimisation of multiple fractured horizontal wells in tight reservoirs

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ABSTRACT

Multiple fractured horizontal wells (MFHWs) are recognised as the most efficient stimulation technique to improve recovery from unconventional gas assets. Although multistage fracture treatment has been very successful in stimulating these reservoirs, very little work has been done on multi-stage design optimisation.

In most of the published works, the improved MFHWs design is recommended to be determined by sensitivity analysis of one variable while keeping all the other variables fixed. Several researches suggested that this optimisation should be typically performed based on economic objectives such as Net Present Value (NPV).

This paper initially describes the results of an exercise that uses statistical algorithms coupled with numerical reservoir simulations to evaluate the simultaneous impacts of important pertinent parameters on the performances of different MFHW designs at various production periods. It is shown that the impact of the individual parameter, quantified by Spearman's rank correlation coefficients technique, on different objective functions e.g. total gas production during the production period, varies depending on the governing flow regimes. For example, it is demonstrated that the impact of fracture length on the performance of MFHWs decreases over the production time while the number of fractures exhibits almost a fixed effect. It was also shown that the general trend of the importance of parameters on productivity index (PI) is similar to those observed for some of other objective functions including total gas production and NPV.

In addition, these results confirm the applicability of available well productivity models developed for the early, middle and boundary dominated flow conditions to optimise the design of MFHWs in tight reservoirs. The result of the study confirms provided maximising a desired objective in the long term (longer than the time to reaching the compound linear flow) is targeted; the pseudo-steady state productivity indices models are appropriate to be used for the design optimisation of MFHWs. Otherwise, if a shorter-term objective is targeted, this optimisation could be performed based on appropriate productivity index models available for the early or middle production periods. These results are also confirmed by performing reservoir simulation-based optimisation of the MFHWs design using the genetic algorithm approach for various cases.

This work provides a general, fit for purpose set of guidelines, suitable for an improved well design of MFHWs in tight reservoirs. In addition, a new and easily to use workflow based on the productivity index equations is developed to optimise MFHWs design in tight gas reservoirs for a chosen targeted time while considering the practical limits and economics.

1. Introduction

Conventionally the formations with permeability varying between 1μD and 0.1 mD are classified as tight reservoirs. In these reservoirs, enlarged drainage area by the horizontal well with multiple transverse fractures increases the well productivity significantly. Therefore, multiple fractured horizontal wells (MFHWs) have been considered as the most efficient stimulation technique to improve recovery from such low permeability reservoirs. Fig. 1 shows that the folds of PI increase due to enlarged drainage area by MFHWs with respect to conventional horizontal wells could be as large as about 12 in tight reservoirs ($K_m < 0.1$ mD) provided that each fracture is properly cleaned up and has infinite conductivity (Jamiolahmady et al., 2014a, 2014b).

Several parameters such as formation permeability, well completion and fracture properties could affect the benefits obtained from installing MFHWs. The optimisation of the parameters such as fracture spacing, number, half-length and conductivity is necessary to ensure determining the optimum MFHWs design that delivers the maximum

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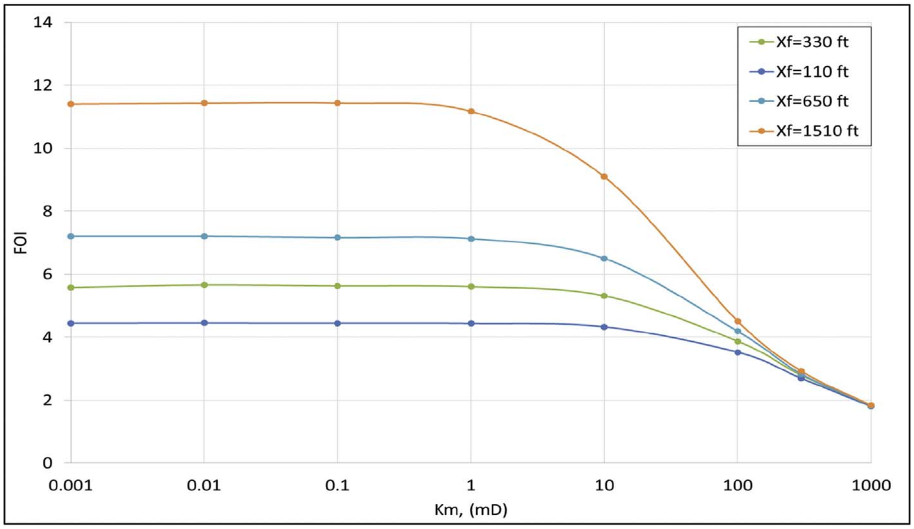

Fig. 1. Folds of PI increase (FOI) versus matrix permeability for various Open-hole MFHWs completion with infinite conductivity and $N_f = 5$ in an anisotropic formation ($K_v/K_h = 0.1$).

added-value possible. Therefore, the development of a workflow to optimise production in an efficient and practical manner is clearly desirable.

Many researchers used dimensionless fracture conductivity measure (Cinco-Ley and Samaniego-V, 1981; Prats, 1961; Jamiolahmady et al., 2014c) to design hydraulically fractured vertical wells usually installed in conventional reservoirs.

In the case of unconventional reservoirs, despite the success of MFHW stimulation techniques in increasing productivity of the reservoirs and efforts directed toward their modelling and performance prediction, there is no general agreement on how their designs should be optimised particularly in tight formations. The reasons are that any decisions regarding optimum designs of MFHWs in such low permeability formations should include; 1) the impacts of mutual parameters such as fracture number, length, spacing etc., 2) the impact of existence of a relatively long transient flow, 3) the important economic considerations for potentially such as the low total production capability of the reservoirs.

In most of the published works, the MFHW's optimum design is determined by performing sensitivity analysis on one variable while keeping all other variables fixed (Britt and Smith, 2009; Marongiu-Porcu et al., 2009; Zhang et al., 2009; Bhattacharya and Nikolaou, 2011; Schweitzer and Bilgesu, 2009). Several researches suggested that this optimisation should be performed based on common economic objectives such as Net Present Value (NPV) (Schweitzer and Bilgesu, 2009; Soliman et al., 1990; ElRafie and Wattenbarger, 1997; Lolon et al., 2007; Meyer et al., 2010; Sepehrnoori and Yu, 2013; Gorucu and Ertekin, 2011; Barree et al., 2015). This includes production forecasting by either numerical reservoir simulations, or analytical/semi-analytical models or proxy models and fracturing cost estimation.

Numerical simulation of all plausible scenarios is time-consuming, especially noting that each case requires employing a massive local grid refinement for explicit modelling of the fractures.

The problem with analytical forecasting models of MFHWs in tight reservoirs is that they do not capture all of the flow regimes (as will be discussed in Section ý2) and/or requires information about the expected flow regimes during production time (Marongiu-Porcu et al., 2009; Meyer et al., 2010; Gao et al., 2013; Barree et al., 2015; MoradiDowlatabad and Jamiolahmady, 2017). For instance, the methodology proposed by Meyer et al. (2010) neither included any equations for capturing the compound linear flow regime around MFHWs nor considered the impacts of interference between fractures (i.e. considering complex flow regimes around MFHWs). Several of these equations have been developed based on various assumptions mainly valid in either conventional or ultra-tight formation, which are not applicable for tight reservoirs. For instance, MoradiDowlatabad and Jamiolahmady (2017), Dowlatabad (2015) addressed the deficiencies of the widely-used models and developed a new flow equation to model the compound linear flow regime, the most important flow regime for characterising the fractured well and formation. In addition, it should be noted that many of the equations used are borrowed from well testing (i.e. rate constant solution) which may not necessarily be accurate for the constant pressure production strategy, which is commonly employed by the industry in these reservoirs.

Proxy models have recently been used to correlate the objective functions such as NPV to pertinent parameters for estimating their values in unconventional reservoirs (Sepehrnoori and Yu, 2013; Gorucu and Ertekin, 2011; Kalantari-Dahaghi et al., 2015). Apart from the issues related to the accuracy of these models in predicting the performance of such complex well geometries, these approaches still require a certain number of reservoir simulations or information about the already drilled wells in the field to create the proxy models.

The more adopted trend in the industry for optimising MFHWs design is towards installing the longest possible fractures with more stages/clusters and tighter spacing in unconventional reservoirs or applying learnings from the previous successful operations in the field. This approach commonly results in higher initial production rates and a much higher decline rate later, which is easy to justify if only the short-term production objectives were considered (Britt and Smith, 2009; Bagherian et al., 2010). Closely spaced fractures also have some other practical disadvantages (Bunger et al., 2012; El Rabaa, 1989) such as the fractures do not remain planar and influence propagation of each other (Crosby et al., 2001). These cause the final fracture configuration to be suboptimal.

Traditionally, for conventional reservoirs, the optimum design of a fractured vertical well is chosen based on the PI index at pseudo-steady (steady) state (PSS) flow conditions because of the very short transient flow regime. In the case of unconventional reservoirs, some researchers also proposed that an optimum design at PSS condition is the optimum design for the transient flow period too. Nevertheless, there is no proof to confirm whether this approach can be applicable in tight reservoirs with MFHWs, where transient flow period lasts much longer (months or years).

Here, a new approach, shown in Fig. 2, is followed by applying statistical algorithms to evaluate various MFHWs design strategies while considering various objective functions at different times during a production period. Based on the results of the cases investigated, it is shown that, for example, the PSS based PI model could be used to optimise the overall performance of MFHWs provided long-term objectives are considered. In other words, the design that optimised the well