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Numerical study of the effect of uneven proppant distribution between multiple fractures on shale gas well performance

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HIGHLIGHTS

- Effect of uneven proppant distribution on well performance is investigated.
- Reservoir model with hydraulic fractures is validated using field production data.
- Sensitivity studies are performed to quantify the key parameters.
- The range for gas production due to proppant distribution is obtained.

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ABSTRACT

Uniform proppant distribution in multiple perforation clusters after hydraulic fracturing plays an important role in the commercial production of shale gas. However, it is very challenging to achieve a uniform proppant distribution during operation. In some cases, proppant distribution is uneven in different clusters within the same hydraulic fracturing stage. The effect of the uneven proppant distribution on well performance is not well understood and has been largely neglected in most reservoir simulations. Hence, it is paramount to develop a reservoir simulation approach to properly examine the relationship between proppant distribution and well performance for shale gas reservoirs. In this paper, we use numerical reservoir simulation to model the proppant distribution. The reservoir model with multiple hydraulic fractures is validated by field production data from Marcellus shale. Effects of gas desorption and stress-dependent fracture conductivity are considered in the simulation model. We perform sensitivity studies to quantify the key parameters affecting the well performance between uniform and non-uniform proppant distribution. The six variables, which are cluster spacing, initial reservoir pressure, fracture conductivity, fracture half-length, fracture height, and matrix permeability, are investigated. The fracture conductivity ratio of 1:1.5:2.5:4 for four clusters in the same fracturing stage is investigated for the uneven proppant distribution scenario. This work provides insights into a better understanding of the effect of proppant distribution on well performance.

1. Introduction

Development of unconventional resources such as shale gas and tight oil has been boosted by the advancements in two key technologies: horizontal drilling and multi-stage hydraulic fracturing. Most horizontal wells are drilled in the direction of minimum horizontal stress with the purpose of creating multiple transverse hydraulic fractures. The plug-and-perf operation is one common completion technique, which is widely used to create multiple fractures through spaced perforation clusters within one isolated fracturing stage. Proppants such as sand and ceramic with small size are injected with the fluid into the fractures, which can hold fractures open to provide a conductive path for fluid flow from reservoir to wellbore. Multiple long hydraulic fractures with uniform proppant distribution and sufficient fracture conductivity play an important role in achieving effective well stimulation and economic production of shale reservoirs [1–7]. Cipolla et al. [8] studied the effect of proppant distribution in the fracture network on well performance and showed that proppant distribution significantly affects the fracture network conductivity and treatment design. Gu et al. [9] presented that proppant transport in natural fractures has an important impact on critical fracture conductivity required for stimulation of shale reservoirs. However, it is very challenging

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Nomenclature

CMG	Computer Modeling Group
CFD	computational fluid dynamics
EUR	estimated ultimate recovery
Fcd	fracture conductivity, md-ft
LGR	local grid refinement
MMSCF	10^6 standard cubic feet, ft^3
SRV	stimulated reservoir volume

SI metric conversion factors

ft × 0.3048 M
ft^3 × 0.02832 m^3
(°F−32)/1.8 °C
cp × 0.001 Pa s
psi × 6.895 kPa
md × 1e−15 m^2

to achieve uniform proppant distribution and maintaining such fracture conductivity because of proppant settlement, proppant fines generation and migration in the fracture [10], proppant diagenesis [11], proppant embedment in softer rock, and proppant crushing in harder rock [12–13]. In addition, Fredd et al. [14] performed a series of experimental studies of hydraulic fracture conductivity and found that fracture displacement, size and distribution of asperities, and rock mechanical properties significantly impact fracture conductivity. Vincent [15] suggested that the assumption of uniform proppant distribution within narrower fractures with hundreds or thousands of feet in length may not be reasonable. It is important to investigate the impact of proppant distribution on well performance of shale gas reservoirs.

Although the plug-and-perf operation method has been extensively applied in shale reservoirs, achieving uniform proppant distribution among all perforation clusters for each fracturing stage is challenging [16]. Cipolla et al. [17] have shown that about 40% of the perforation clusters were not contributing to gas recovery. Also, Miller et al. [18] reported that only 1/3 of perforation clusters contributes to 2/3 of gas production in some shale basins based on production logs more than 100 horizontal shale wells from six shale basins. Daneshy [19] investigated the proppant distribution between different perforation clusters within single stage in the plug-and-perf operation and reported that there is uneven proppant distribution among perforation clusters and most proppant likely enter the last perforation cluster. The amount of proppant entered the last cluster near the toe is almost four times the proppant amount in the first cluster toward the heel. This is because proppant grains with higher density and larger size and mass than fracturing fluid cannot easily change direction and enter the perforations uniformly. In addition, Crespo et al. [16] observed the phenomenon of uneven proppant distribution within three perforation clusters through conducting a large-scale experimental study to mimic the plug-and-perf operation, and it will be more severe in cases with higher proppant density and smaller flow rates. Bokane et al. [20] used computational fluid dynamics (CFD) technique to simulate proppant transport in different perforation clusters within a single stage and to understand the phenomena of uneven proppant distribution within perforations. However, the impact of uneven proppant distribution between different clusters within a single stage on ultimate gas recovery has not been evaluated quantitatively. Additionally, most reservoir modeling works in the literature assume uniform proppant distribution among perforation clusters within a single stage. Hence, a detailed study for investigation of the impact of uneven proppant distribution between different clusters on well performance in shale gas production is still significantly necessary.

In this paper, numerical reservoir simulation approach was validated by field production data from Marcellus shale using a numerical reservoir simulator considering gas desorption and stress-dependent fracture conductivity effects. The simulator was used to model gas production with various proppant distribution profiles. In our previous work [21], we had set up a reservoir model assuming four clusters per stage with fracture conductivity ratio of 1:1.5:2.5:4 and found that the impact of uneven proppant distribution on well performance is significant. In this paper, we extended the original work to perform a thorough sensitivity study to investigate the effect of uneven proppant distribution between different clusters within one stage on well performance based on typical field data from Marcellus shale. Six uncertainty parameters such as matrix permeability, fracture height, fracture half-length, fracture conductivity, cluster spacing and initial reservoir pressure, are considered. The results of this work can provide a better understanding of the impact of proppant distribution on shale gas production.

2. Methodology

2.1. Numerical modeling of shale gas reservoir

In this work, a numerical reservoir simulator of CMG-IMEX [22] is used to model multiple hydraulic fractures and gas production in Marcellus shale reservoirs. In our simulation model, bi-wing hydraulic fractures are explicitly modeled using local grid refinement (LGR) with logarithmic cell spacing, which can accurately model gas flow from shale matrix to hydraulic fractures. A no-flow boundary condition is used for the reservoir model. Non-Darcy flow is considered for which the non-Darcy Beta factor, used in the Forchheimer number, is determined using a correlation proposed by Evans and Civan [23]. This approach has been extensively used to model transient gas flow in hydraulically fractured shale gas reservoirs [24–28]. In the simulation model, the gas desorption effect is modeled using the classic Langmuir isotherm with two fitting parameters of Langmuir pressure and Langmuir volume [29], which is based on the assumption that there is a dynamic equilibrium at constant temperature and pressure between the adsorbed and free gas. When modeling geomechanics in hydraulic fractures, i.e., stress-dependent fracture conductivity, a specific compaction table is used to account for decreasing conductivities of propped fractures with the increase in closure stress or decrease in pressure. The compaction table is assigned in the simulator to cells describing propped hydraulic fractures. The stress-dependent fracture conductivity curves used in the following simulation studies are generated based on experimental measurements for stiff shale samples by Alramahi and Sundberg [30], which were discussed in our previous work [31].

2.2. Validation of numerical model

Once a numerical reservoir model including multiple hydraulic fractures is built, it requires validation with field production data to ensure the reliability of simulation results. After validation, it