Production Performance of Perforation Clusters during Multistage Fracturing in Shale Gas Reservoirs

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ABSTRACT: Gas production from each perforation cluster has an obvious difference along with the horizontal wellbore in shale gas reservoirs. Some special perforation clusters evenly do not produce any gas, which means that those perforation clusters are not fractured. In shale gas reservoirs, only when the shale gas section was fractured with equal volumes of fracturing fluids, gas can be produced evenly. In this study, a stress theory around the perforation tunnel considering the stress around the wellbore and an induced stress by leaking of the fluid and the tunnel is presented. The results show that (1) fractures will quickly be created at two of the three perforation clusters and then the fracture of the cluster initiates. (2) The rate through each cluster is different, and the fracture volume created will have a big difference. (3) The fracture distribution between three perforation clusters are different, thus shale gas production also will be different. The theory and the method presented in this paper, can be used for different reservoirs besides shale gas reservoirs, thus it can be applied and referred widely.

1. INTRODUCTION

Multi-stage horizontal well fracturing has been applied to shale gas reservoirs with extreme success throughout the world, and it is regarded as a thumb technology for those unconventional reservoirs such as shale. In recent years, most horizontal wells employed cased and cemented completion methods. Along the horizontal lateral, more than 20 stages are divided evenly, and 2–6 perforation clusters are included in each stage. The horizontal well will be fractured from toe to hoe stage-by-stage with bridge slug. Production evaluation data have confirmed that two-thirds of gas production comes from one-third of perforation clusters, and almost one-third of all perforation clusters is not contributing to production.1–6 This brings up an urgent problem of how to increase the efficiency of perforation clusters.7,8

From the statistics results of six shale gas fields in America, it can be seen that almost one-third of perforation clusters is not flowing with gas, and even 6% perforation clusters are still not flowing for the best stages in Barnett shale (Figure 1). For a single well, it is also testified that perforation clusters have a distinguishing difference in attributing the gas production for the whole well, and only several perforation clusters produce more than 80% of the total gas volume (Figures 2 and 3).

During multistage fracturing of shale gas horizontal wells, it can be found that there are almost no gas-producing perforation clusters in each horizontal section, and the gas production distribution in each horizontal section is uneven, and there is no complex fracture network near the horizontal...
wellbore after fracturing.\textsuperscript{9,10} During the hydraulic fracturing, perforation parameters, including the perforation entry friction and the fracture pressure at the perforation, will affect the fracture morphology and fracture propagation and also affect the perforation efficiency.\textsuperscript{11} Through the field logging data of Marcellus shale gas wells, Bunker and Cardella\textsuperscript{12} found that the high-gas-producing perforation clusters are mostly concentrated in the external position in the fracturing stage of horizontal wells. Sookprasoon\textsuperscript{13} studied the distributed actual sensing data during fracturing construction. The distribution of a fracturing fluid and a proppant in each perforation cluster was roughly estimated and analyzed. It was found that in a horizontal section of 10 clusters, about 30% of the dominant cluster was distributed with the fracturing fluid and the proppant, and in the other 9 clusters the dominant clusters are evenly distributed up to 70% of the fracturing fluid and proppant. In order to improve the perforation efficiency and the fracturing effect, a limited entry perforation technique has been widely used in multi-layer hydraulic fracturing, and it also provides ideas for multi-stage fracturing of shale gas horizontal wells.\textsuperscript{9,14}

Many researchers have used different methods to study how to improve the perforation efficiency of multi-staged fractured horizontal wells. Cheng\textsuperscript{15} studied the influence of the perforation cluster number and cluster spacing on the production performance of shale gas-fractured horizontal wells. Peirce and Bumger\textsuperscript{16} proposed that the negative effect of stress interference can be reduced by adopting a specific perforation cluster distribution, and multiple fractures can be evenly expanded. However, in the actual hydraulic fracturing, it is very difficult to implement the perforation cluster distribution according to a specific location due to multiple geological and engineering factors. Daneshy\textsuperscript{17} proposed a dynamic interaction theory between multiple fractures in the formation. Lecampion\textsuperscript{19} revealed the influence of the stress shadow effect and perforation friction on the propagation of multiple fractures and believed that a certain perforation pressure drop can inhibit the stress interference between different fractures. Zhao\textsuperscript{20} proposed a reasonable calculation method of perforation friction. This method considers the influence of the perforation friction on the uniform propagation of multiple fractures, and based on this calculation method optimizes the perforation engineering parameters of fracturing horizontal wells. The actual fracturing data show that the optimized perforation parameters can make multiple fractures, and the cracks develop evenly. Huang\textsuperscript{21} established a coupled finite-element model, which takes into account the interaction between fractures and the perforation friction that can simulate the expansion of multiple hydraulic fractures and optimize the flow distribution in each perforation cluster. Li\textsuperscript{22} used the coupled three-dimensional finite-element model to describe the complex relationship between rock deformation, fracture propagation, and fluid flow and developed a new pore pressure element for calculating the local perforation pressure drop, which was integrated into the coupled three-dimensional finite-element model. It can automatically partition the inflow rate of the fracturing fluid in multiple fractures and optimize the perforation parameters.

The production variability in different stages or perforation clusters will be caused by the heterogeneity of shale gas reservoirs’ petrophysical and geomechanical characteristics. Besides these factors, the operation factors such as the perforation parameters will also impact the fracture extension and the ultimate production yield.

Additionally, the fracture pressure and the related mechanical problems at the perforation and the effect of perforation parameters on the perforation efficiency have not been fully studied and discussed in previous work. Therefore, it is still necessary to study the fracture pressure at the perforation and establish relevant mechanical models, so that more fracturing fluid can enter each cluster of shale reservoir and improve the perforation efficiency and gas production of each horizontal section.\textsuperscript{23}

In this paper, according to the theory of stress distribution around a horizontal wellbore, the initiation breakdown pressure of perforations is discussed, and an example is applied to illustrate that the perforation parameters will affect the cluster efficiency severely.
2. Model for Prediction of Stress around the Perforation Tunnel. The breakdown of perforation will be mainly affected by the stress around the perforation tunnel. The local stress includes the stress concentration around the wellbore and induced stress caused by perforating and leaking the fluid, so the calculation of stress will be discussed.

2.1. Stress Distribution around the Horizontal Wellbore. The horizontal wellbore azimuth and the coordinate system are illustrated in Figure 4. In formation, three principal stresses are assumed to be aligned with the axes of the coordinate system. The wellbore has a deviation angle from the vertical axes and an azimuth angle with the minimum horizontal stress direction. In this condition, there are two steps to transform the \((x, y, z)\) coordinate system to the wellbore system as follows.

(1) rotating around the \(z\) axis with an angle \(\beta\),
(2) rotating around the \(y\) axis with an angle of 90°.

The stress around the horizontal wellbore caused by the initial formation stress concentration can be calculated in the Cartesian coordinate system as follows:

\[
\begin{align*}
\sigma_x &= \frac{\sigma_{\text{Hmin}} \cos^2 \beta + \sigma_{\text{Hmax}} \sin^2 \beta}{2} + \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right) \cos 2\theta \\
&+ \tau_x \left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right) \sin 2\theta + \frac{R^2}{r^2} \tau_y \\
\sigma_y &= \frac{\sigma_y - \sigma_x}{2} \left(1 - \frac{R^2}{r^2} - \frac{3R^4}{r^4}\right) \cos 2\theta \\
&- \tau_y \left(1 + \frac{3R^4}{r^4}\right) \sin 2\theta - \frac{R^2}{r^2} \tau_x \\
\sigma_\theta &= \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{R^2}{r^2} - \frac{3R^4}{r^4}\right) \sin 2\theta + \frac{R^2}{r^2} \tau_y \\
\tau_\theta &= \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \cos 2\theta + \tau_x \left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \\
\tau_{\phi x} &= \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{R^2}{r^2} - \frac{3R^4}{r^4}\right) \sin 2\theta + \tau_y \left(1 - \frac{R^2}{r^2} - \frac{3R^4}{r^4}\right) \\
\tau_{\phi y} &= \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \cos 2\theta + \tau_x \left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)
\end{align*}
\]

Based on the elasticity solution by Kirsch and other authors, such as Bradley, Peska, and Zoback, the stress distribution is given below in polar coordinates.

In the polar coordinate system, the stress around the horizontal wellbore will be as given below.

\[
\begin{align*}
\sigma_\phi &= \frac{\sigma_x + \sigma_y}{2} \left(1 - \frac{R^2}{r^2} - \frac{3R^4}{r^4}\right) \sin 2\theta + \frac{R^2}{r^2} \tau_y \\
\tau_\phi &= \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \cos 2\theta + \tau_x \left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \\
\tau_{\phi x} &= \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{R^2}{r^2} - \frac{3R^4}{r^4}\right) \sin 2\theta + \tau_y \left(1 - \frac{R^2}{r^2} - \frac{3R^4}{r^4}\right) \\
\tau_{\phi y} &= \frac{\sigma_x - \sigma_y}{2} \left(1 - \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right) \cos 2\theta + \tau_x \left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)
\end{align*}
\]

2.2. Stress Induced by the Perforation Tunnel. After the wellbore is cased and perforated, the stress will be concentrated around the perforation tunnel again. The perforation tunnel is normally much smaller than the diameter of the wellbore and can be assumed that it is a cylindrical open hole, which is subjected to remote stresses equal to the local stresses around the perforation tunnel.
stresses caused by the borehole in the formation (Figure 5). Then, the stress at the wall of the perforation tunnel will be calculated using the Kirsch elasticity equation, eq 3

\[
\begin{align*}
\sigma_{yr} &= \sigma_0 + \sigma_{\text{fracturing}} - 2(\sigma_{\text{fracturing}} - \sigma_0) \cos 2\theta_r - 4\tau_0\sin 2\theta_r - P_w \\
\sigma_{yp} &= \sigma_0 + \sigma_{\text{fracturing}} + 2(\sigma_{\text{fracturing}} - \sigma_0) \cos 2\theta_p + 4\tau_0\sin 2\theta_p \\
\tau_{\text{fracturing}} &= \tau_{fracturing} \\
\tau_{\text{fracturing}} &= 2(\tau_{\text{fracturing}} - \tau_{\text{fracturing}})
\end{align*}
\]

(3)

2.3. Stress Induced by Leak Off of the Fracturing Fluid. When the bottom-hole fluid pressure increases, the fracturing fluid will leak off into formation around the wellbore. For this phenomenon, Lubinski considered rock as a porous elastic medium, in which the fluid can flow according to Darcy’s law.

Below are the boundary conditions \( \sigma_r = -P_w, r = 0 \), and \( \sigma_r = 0 \), \( r = \infty \).

The stress induced by the radial flow of the fluid in any position of the rock formation can be formulated as follows

\[
\begin{align*}
\sigma_r &= -\frac{\alpha (1 - \nu)}{1 - \nu} \int_0^1 \phi r \left[ \sigma_0 (\xi) \frac{d\xi}{r} + \phi P_r (r) \right] \\
\sigma_\theta &= -\frac{\alpha (1 - \nu)}{1 - \nu} \int_0^1 \phi r \left[ \sigma_0 (\xi) \frac{d\xi}{r} + P_r (r) \right] + \phi P_r (r) \\
\sigma_z &= -\frac{\alpha (1 - \nu)}{1 - \nu} \left( \phi P_r (r) \right)
\end{align*}
\]

At the wellbore, the stress induced by the fracturing fluid is

\[
\begin{align*}
\sigma_r &= \phi (P - P) \\
\sigma_\theta &= \sigma_z = \frac{-\alpha (1 - \nu)}{1 - \nu} \left( \phi (P - P) \right)
\end{align*}
\]

(5)

2.4. Total Stress around the Perforation Tunnel. Considering the stress concentration around the wellbore, the pumping pressure, and poroelastic phenomena of the fracturing fluid flowing into formation, the total stress around the perforation tunnel can be combined as below

\[
\begin{align*}
\sigma_{yr} &= \sigma_0 + \sigma_{\text{fracturing}} - 2(\sigma_{\text{fracturing}} - \sigma_0) \cos 2\theta_r - 4\tau_0\sin 2\theta_r - P_w \\
\sigma_{yp} &= \sigma_0 + \sigma_{\text{fracturing}} + 2(\sigma_{\text{fracturing}} - \sigma_0) \cos 2\theta_p + 4\tau_0\sin 2\theta_p \\
\tau_{\text{fracturing}} &= \tau_{fracturing} \\
\tau_{\text{fracturing}} &= 2(\tau_{fracturing} - \tau_{fracturing}) \\
\tau_{fracturing} &= \tau_{fracturing} = 0
\end{align*}
\]

(6)

3. RESULTS AND DISCUSSION

For multistage fracturing of the horizontal well, several perforation clusters will be included in one stage. In order to create a fracture network with a similar stimulated reservoir volume, all of these perforation clusters should be stimulated and pass with a similar fracturing fluid volume. In fact, it is difficult to fulfill this aim, and the number of opening perforations is different between perforation clusters.

3.1. Model Validation. In order to verify the accuracy of the model, this paper’s method solutions were compared to the production profiles in the horizontal well of MG121 by the production log. The parameters of the horizontal well in the shale gas reservoir are shown in Table 1. The comparison results showed a high consistency, as shown in Figure 6.

3.2. Influencing Factors’ Analysis. The horizontal well of CQ11 is another example in the Fuling shale gas reservoir to demonstrate the difficulty in activating all perforation numbers and clusters in one fracturing stage. Along the lateral of the horizontal well, there is stress variation between clusters. The vertical stress changes a little, but the horizontal minimum stress varies from 64.78 to 70.63 MPa, and the horizontal maximum stress changes from 77.19 to 82.94 MPa; the details are listed in Tables 2 and 3.

Table 1. Parameters of Multistage Fracturing in the Horizontal Well of MG121

| Parameter                           | Value |
|------------------------------------|-------|
| Injection rate (m³/min)            | 12    |
| Young’s modulus (MPa)              | 26 000|
| Perforation clusters               | 15    |
| Poisson’s ratio (°)                | 0.19  |
| Perforation per cluster            | 9     |
| Tensile strength (MPa)             | 5.63  |
| Perforation phasing (°)            | 50    |
| Perforation diameter (mm)          | 2.5   |
| Perforation density (/m)           | 10    |

Table 2. Parameters of Multistage Fracturing in the Horizontal Well of CQ11

| Parameter                           | Value |
|------------------------------------|-------|
| Injection rate (m³/min)            | 12    |
| Young’s modulus (MPa)              | 35 000|
| Perforation clusters               | 3     |
| Poisson’s ratio (°)                | 0.25  |
| Perforation per cluster            | 9     |
| Tensile strength (MPa)             | 5.63  |
| Perforation phasing (°)            | 60    |
| Perforation diameter (mm)          | 2.5   |
| Perforation density (/m)           | 6     |

Table 3. Stress Parameters of Clusters in CQ11

| Cluster | TVD (m) | Formation pressure (MPa) | \( \sigma_r \) (MPa) | \( \sigma_{\text{fracturing}} \) (MPa) | \( \sigma_{\text{fracturing}} \) (MPa) |
|---------|---------|-------------------------|---------------------|------------------------------------|-------------------------------------|
| no. 1   | 3631.08 | 53.39                   | 88.82               | 66.53                               | 78.85                               |
| no. 2   | 3630.47 | 53.38                   | 88.79               | 70.63                               | 82.94                               |
| no. 3   | 3630.17 | 53.38                   | 88.79               | 70.63                               | 82.94                               |

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Figure 7. Fracture initiating pressures and pumping rates at each cluster.

Figure 8. Comparison of perforations accepting the fluid at each cluster.

Figure 9. Comparison of clusters after breakdown.
It is assumed that the perforation angle with $x$ of the wellbore coordinate is zero, which is an ideal condition. According to the above equations, the initial pressure to breakdown perforation and create fractures can be calculated in the position of each cluster. Figure 6 shows the bottom-hole pressures and the corresponding total pump rates required to initiate fractures at three perforation clusters. Fractures will quickly be created at the horizontal heel end and finger and then the fracture of the cluster is initiated at cluster no. 2.

Even though clusters start accepting the fluid at the rates shown in Figure 7, all of the perforations are not active in fact. When the first fracture starts at cluster no. 3 at 65 MPa, only the holes on the top and bottom of the casing are accepting the fluid (Figure 8). There are nine shots with 60° phasing in the length of 1.5 m. When the second initiation occurs at cluster no. 1 at 66 MPa, fractures also initiate at top and bottom positions. However, as shown in Figure 8, the injecting fluid mostly passes through cluster no. 3. After the bottom hole pressure attains 73 MPa, cluster no. 2 will be active, and the injection profile is shown in Figure 9; clusters no. 3 and 1 are

### Table 4. Adjusted Parameters for Perforation Clusters

| perforation cluster no. 1 | perforation cluster no. 2 | perforation cluster no. 3 |
|---------------------------|---------------------------|---------------------------|
| perforation per cluster   | 7                         | 9                         | 5                         |
| perforation phasing (°)   | 90                        | 60                        | 120                       |
| perforation density (/m)  | 5                         | 6                         | 5                         |
| perforation diameter (mm) | 2.5                       | 2.5                       | 2.5                       |

Figure 10. Comparison of stimulated volume between three clusters.

Figure 11. Comparison of the stimulated volume between three clusters after adjustment.
now fully active, but the rate through each cluster is different, then the fracture volume created will have a big difference.

In this condition, the stimulated volume is simulated by use of Meyer software, and the fracture network is shown in Figure 10. Obviously, the fracture distribution between three perforation clusters is different, thus shale gas production will also be different. Because the gas-producing rate for each cluster will depend on the appropriate reservoir volume stimulated by hydraulic fracturing.

In order to produce gas from each perforation cluster evenly, the stimulated volume should be similar, which means that the fracturing fluid volume entering each cluster should be the same. This can be obtained by adjusting the perforation parameters, such as increasing the perforation numbers in the higher stress section and decreasing the perforation numbers in the lower stress part. The adjusted parameters are listed in Table 4.

Through the above perforation parameters, the discrete fracture network (DFN) model is run again, and the fracture map is seen in Figure 11. The stimulated reservoir volume in each cluster is similar, so the gas rate will be almost equal.

4. CONCLUSIONS

(1) Stress theory around the perforation tunnel is presented, considering the stress around the wellbore and the induced stress by leaking of the fluid and the tunnel. According to the above theory, the breakdown pressure of different perforations can be calculated, and the performance of each perforation can be predicted.

(2) In order to stimulate the reservoir between each perforation cluster evenly, perforation parameters should be adjusted, and the stimulated reservoir volume is simulated by the DFN fracture model. Each cluster produces gas with similar rates when different perforation clusters are fractured evenly.

(3) Fractures will be quickly created at two of the three perforation clusters and then the fracture of the cluster initiates. The rate through each cluster is different, and the fracture volume created will have a big difference. The fracture distribution between three perforation clusters is different, thus shale gas production will also be different.

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Notes
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■ ABBREVIATIONS

| Symbol | Description                                      | Unit |
|--------|--------------------------------------------------|------|
| σx, σy, σz | normal stress component in the (x, y, z) coordinate system | MPa  |
| τxy, τyz, τzx | shear stress component in the (x, y, z) coordinate system | MPa  |
| σHmin, σHmax, σr | horizontal maximum, minimum, and vertical stress | MPa  |
| β | angle between the horizontal wellbore and the horizontal minimum stress, rad | |
| σr, σθ, σϕ | shear stress in the plane of θ − z, r − θ, r − z, MPa | |
| ρ | angle between any point with the x axis, rad | |
| Rw, ρr, ρθ, ρϕ | normal stress around the perforation tunnel, MPa | |
| tRθp, tRϕp, tRzp | shear stress around the perforation tunnel, MPa | |
| θp | angle around the perforation tunnel, rad | |
| α | biot poroelastic constant, α = 1 − C′/C′′ | |
| θ | rock compressive factor | |
| Cm | rock solid compressive factor | |
| ν | Poisson’s ratio | |
| ψ | porosity of rock | |
| pfi(r) | net pressure Pfi(r) = Pr − P0, MPa | |
| pi(r) | initial formation pressure, MPa | |
| p(r) | formation pressure at radius r, MPa | |

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