論 文

Effects of perforation schemes and non-Darcy flow on hydraulically-fractured gas well performances

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Abstract: Limiting a perforation interval has been proposed as a means to improve hydraulic fracture configurations. This technique, however, may cause productivity impairment, as widely recognized for non-fractured wells. To examine how severe the impairment is for fractured wells, simulation case studies are performed.

Unless non-Darcy flow prevails, limited completion does not impair the fractured-well productivity severely ; thus, the limiting perforation technique can be applied to oil wells without excessive concern. Even in non-Darcy flow situations, the productivity impairment due to limited completion is not significant for wells with long-and wide-enough fractures. If the fracture configuration is not improved, on the contrary, the productivity impairment can be significant under non-Darcy flow conditions. In such a case, re-perforating the remaining interval is a viable option to reduce the degree of productivity impairment. It is important to assign flow rates evenly over the production interval for mitigating the effects of non-Darcy flow.

Keywords: fracturing, partial completion, non-Darcy flow, productivity, simulation

1. Introduction

Due to a combination of near-wellbore tortuosity and simultaneous propagation of multiple fractures, proppant placement has proved to be extremely difficult in the Minami-Nagaoka gas field.¹⁾ The fracturing treatments executed in this field experienced extremely high net pressures (on the order of 4,000 psi) and ended with premature screen-outs (only 20% of the designed quantity was placed in the reservoir). Similar problems are observed in many fields worldwide.^{2~4)} The resultant fracture is short and narrow, and because of the

low proppant concentration the fracture conductivity is vulnerable to large drawdown.¹⁾

When hydraulic fracturing is hard to implement, several remedial means can be adopted, which include (but not limited to) applying proppant slugs,⁵⁾ utilizing high fluid viscosity,^{6~7)} orienting perforation to a preferred fracture plane,⁸⁾ and limiting the length of perforation intervals.⁴⁾ These methods are believed to mitigate the near-wellbore tortuosity and the creation of multiple fractures, and to improve the fracture configuration (longer and wider fractures with higher proppant concentrations).

Improved fracture configurations, however, do not necessarily imply improved productivity. For instance, highly viscous fluid may leave a considerable amount of gel residue in the created fracture and reduce the fracture conductivity (consequently aggravate the well

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productivity). Among such possible reverse-effects, limited perforation length is examined in this study. From a production point of view, limited completion appears to be daring. It has been long recognized that the limited entry causes considerable reduction in productivity⁹⁾ for non-fractured wells. Symbolically, this reduction is expressed by the pseudo skin that accounts for pressure losses due to convergence of fluid around the limited perforation. For fractured wells, this subject has not been well examined. For gas wells, in addition, non-Darcy flow is pronounced due to the increased velocity toward the limited entry and could be an additional factor that may reduce productivity.

Thus, there arise the following questions: (1) how severe is the productivity impairment due to the limited completion for a fractured gas well, (2) can improved fractures alleviate the productivity impairment, and (3) is it worth considering re-perforation after the fracturing operation. To answer these questions, simulation case studies are performed. Although a part of the model settings is prepared for the Minami-Nagaoka gas field, the conclusions drawn in this study are rather general.

2. Problem definition and assumptions

Of interest in this study are fractured gas well performances with different perforation schemes under non-Darcy flow conditions. Formation and fracture properties of the Minami-Nagaoka gas field are used for case studies. Basic properties are listed in Table 1. Single-phase gas flow is assumed in a reservoir, the boundary of which is far enough from the well so that it has no effect on pressure behavior during a production period of 100 days.

Without application of remedial means, the resultant fracture is short and the conductivity is low (Fig. 1), as observed in the Minami-Nagaoka gas field. As a base case, the fracture configurations, obtained through history matching¹⁾ against actual pressure behavior during fracturing and production, are em-

Table 1 Basic properties for case studies.

formation thickness, h	120 ft
initial pressure, p_i	7645 psi
matrix porosity, ϕ	0.1
rock compressibility, c_f	6.34×10^{-6} psi ⁻¹
matrix permeability (horizontal), k_h	0.2 md
matrix permeability (vertical), k_v	0.0008 md
specific gravity of gas	0.85
formation temperature	350°F

Fig. 1 Fracture configurations: (top) without remedial means and (bottom) with remedial means.

ayed; the fracture length (x_f) of 64 ft and the fracture conductivity (k_{fw}) of 4 % of the laboratory measured data for monolayer proppants.

With remedial means applied, the fracture configuration could be improved (Fig. 1). In this study, perforation lengths (h_p) of 1/6 and 1/3 of the formation thickness are considered.

As for an improved fracture configuration, x_f of 162 ft and the conductivity of 50% of the measured data are assumed, based on a preliminary design.^a

3. Method of solution

As early as 1901, Forchheimer (as cited in Refs. 10 through 17) observed that flow rate was not proportional to the pressure drop for high-velocity flow. Since then, there have been several discussions on the physical reasons for the onset of nonlinearity, including turbulence,¹⁰⁾ inertial forces,¹¹⁾ microscopic viscous forces,¹²⁾ and microscopic inertial forces.¹³⁾ Despite these controversial outcomes in physics, non-Darcy flow has been successfully expressed, in practice, by adding an extra term to Darcy's law for a pressure gradient ($\Delta p/\Delta L$), which takes into account the high-velocity flow :

$$\Delta p/\Delta L = \mu v/k + \beta \rho v^2, \quad (1)$$

where μ is the fluid viscosity, ρ the fluid density, v the fluid velocity, k the permeability, and β the non-Darcy coefficient.

A number of correlations have been proposed for β , which are summarized in Refs. 14 and 15. In this study, Cook correlation,¹⁶⁾ which is used in Ref. 1 and yields satisfactory results, is employed for fractures. Although the effects of non-Darcy flow are likely insignificant within matrix (which turns out to be true as shown in the following sections), Firoozabadi and Katz correlation (Eq. 7 in Ref. 14) is employed for matrix.

To deal with non-Darcy flow in a simple manner, the non-Darcy factor¹⁷⁾ F_{ND} is introduced :

$$F_{ND} = k_{ND}/k = 1/(1 + \beta \rho v k/\mu), \quad (2)$$

where k_{ND} is the permeability required in Darcy's law to provide correct values under non-Darcy flow conditions. F_{ND} is a measure of the degree of non-Darcy flow : F_{ND} of unity corresponds to Darcy flow and as F_{ND} decreases, the degree of non-Darcy flow increases.

In addition to the effects of non-Darcy flow, stress-sensitive fracture conductivity complicates the analysis. The effective stress (σ_e) on proppants is expressed as

$$\sigma_e = \sigma_h + p_{net} - p_f, \quad (3)$$

where σ_h is the minimum horizontal stress, p_{net} is the net fracturing pressure, and p_f is the fluid pressure in the fracture during production. $\sigma_h + p_{net}$ of 13,000 psi is assumed, based on the previous experience.¹⁾ Since p_f decreases during production, σ_e increases, resulting in a decreasing fracture conductivity. The relationship between $k_f w$ and σ_e for monolayer proppants is measured in laboratory, which is modified to be adequate for the actual pressure behavior,¹⁾ as shown in Fig. 2.

Due to the complexity attributed to non-Darcy flow and stress-sensitive fracture conductivity, no analytical solution is available and a numerical simulation model has been developed, following the work of Holditch and Morse,¹⁷⁾ who proposed a single-phase, two-dimensional, finite-difference scheme. Extensions added in the present model are three dimensionalization and wellbore hydraulics to simulate partial completions. The model itself is based on Darcy's law. The effects of non-Darcy flow can be included in the solution by using k_{ND} instead of k in Darcy's law. The per-

Fig. 2 Fracture conductivity with monolayer proppants.

^a internal study done by Pinnacle Technology Inc. for Teikoku Oil Co., Ltd.

meability assigned in grid blocks for a fracture is adjusted based on σ_e so that the sensitivity of fracture conductivity to closure stress can be simulated with the numerical model. Details of the numerical schemes are documented in Ref. 17 and will not be covered here.

3.1 Model verification

The simulation model is verified against established solutions. Because of the symmetry of the system, only a quarter of the x - y extent need be modeled. The perforation intervals considered in this study are located in the center of the formation and symmetric in the z (vertical) direction. In a strict sense, pressure-dependent fluid properties are not exactly symmetric in the z direction due to the pressure gradient. However, the deviation is negligible because of the low fluid density; it turns out to be enough to model only a lower half of the formation.

In the course of the verification process, simulation sensitivity to gridding and time stepping is examined, and proper grid and timestep sizes are determined. The results shown below (and in the subsequent sections) are obtained with the $28 \times 28 \times 5$ grid system, providing fine breakup near the wellbore and along the fracture (aligned in the x direction), and with automatic time stepping ranged from 0.0001 day to 1.0 day.

Fig. 3 compares the model results with the Cinco *et al.* solutions¹⁸⁾ for a well with finite-conductivity fractures. A good match between the two is observed for different values of dimensionless fracture conductivity $C_{FD}(=k_f w/kx_f)$. Fig. 4 compares the model results with the Streltsova solutions⁹⁾ for a well with limited flow entry. A good match between the two is observed for different values of dimensionless completion length $h_{pD}(=h_p/h)$ and permeability anisotropy k_v/k_h . The model accuracy for non-Darcy flow is verified by the same manner as in Ref. 17. Although the verification can be done only for individual aspects separately, the model appears to be applicable to a fractured well with partial completion under non-Darcy

Fig. 3 Model verification against the Cinco *et al.* solution for a well with a finite-conductivity fracture.

Fig. 4 Model verification against the Streltsova solution for a well with limited flow entry.

flow conditions.

4. Results

Investigated in this section are the effects of perforation schemes (Fig. 5), non-Darcy flow (Fig. 6), and fracture configurations (Fig. 7) on productivity, and the effectiveness of re-perforation (Fig. 8) to mitigate the productivity impairment.

4.1 Darcy flow case

To investigate solely the effect of perforation schemes on productivity, Darcy flow is assumed for the moment. Fig. 5 shows the pressure behavior for different perforation schemes. For comparison, also shown are pre-treatment (no fracture) well performances. Without fractures, limited completion aggra-

Fig. 5 Pressure behavior for different perforation schemes with or without 64 ft fractures under Darcy flow conditions: (left) $q=1.866$ MMscf/D and (right) $q=3.732$ MMscf/D.

Fig. 6 Pressure behavior for different perforation schemes with or without 64 ft fractures under non-Darcy flow conditions: (left) $q=1.866$ MMscf/D and (right) $q=3.732$ MMscf/D.

vates the productivity severely, and economic production cannot be maintained with $h_{pD}=1/6$ and $h_{pD}=1/3$. With full completion ($h_{pD}=1$), drawdown pressures after 100-day production are 2056 psia and 4201 psia for production rates (q) of 1.866 MMscf/D and 3.732 MMscf/D, respectively. These values are used as benchmarks to evaluate productivity improvement under Darcy flow conditions.

With 64 ft fractures created, the productivity is improved; in particular, limited completions yield the pressure performances similar to the

full completion case and turn out to be feasible options. In contrast to the no fracture case, h_{pD} values do not affect the productivity severely. Fig. 9 shows the productivity improvement, defined by the ratio of the benchmark value to the drawdown pressure after 100-day production. Little difference is observed among the three completion schemes.

Once fractures are created, productivity impairment due to limited completion becomes negligible under Darcy flow conditions. Thus, when the target formation contains only

Fig. 7 Pressure behavior for different perforation schemes with 162 ft or 64 ft fractures under non-Darcy flow conditions: (left) $q=1.866$ MMscf/D and (right) $q=3.732$ MMscf/D.

Fig. 8 64 ft fracture performances with or without re-perforation under non-Darcy flow conditions: (left) $q=1.866$ MMscf/D and (right) $q=3.732$ MMscf/D.

liquid, one can apply the limited completion scheme without excessive concern.

4.2 Non-Darcy flow case

When the target formation contains gas, non-Darcy flow likely takes place in particular along high conductivity fractures. Fig. 6 shows the pressure behavior for different perforation schemes under non-Darcy flow conditions. Although non-Darcy flow is considered even in a matrix formation, the no-fracture case does not yield much difference from the Darcy flow case. With full completion, drawdown pres-

ures after 100-day production are 2066 psia and 4260 psia for $q=1.866$ MMscf/D and $q=3.732$ MMscf/D, respectively. These values are used as benchmarks to evaluate productivity improvement under non-Darcy flow conditions (sections 4.2, 4.3, and 4.4).

With 64 ft fractures created, the productivity is improved compared with the no fracture case. Unlike the Darcy flow case, the magnitude of improvement is a strong function of perforation schemes. As also shown in Fig. 9, the productivity improvement is blurred as the

Fig. 9 Productivity improvement after 100-day production: (left) $q=1.866$ MMscf/D and (right) $q=3.732$ MMscf/D.

completion length decreases. This becomes severer when the production rate is high. For $q=1.866$ MMscf/D, the fractured well with h_{pD} of $1/6$ yields somewhat higher productivity than the non-fractured well with h_{pD} of 1 (Fig. 6). For $q=3.732$ MMscf/D, the opposite is true; the fractured well with h_{pD} of $1/6$ cannot maintain a desired production rate for 100 days (thus, no bar is shown in Fig. 9), while the non-fractured well with h_{pD} of 1 can (Fig. 6).

When the attempts (including limited perforation) to improve the fracture configuration do not properly function and the operation ends up short and narrow multiple fractures, one may encounter productivity impairment due to the limited completion.

4.3 Improved fracture configuration

The purpose of the limited completion is to mitigate near-wellbore tortuosity and multiple-fracture propagation and to create longer and wider fractures. Assumed in this scenario are fracture length of 162 ft and fracture conductivity of 50% of laboratory-measured values.

Fig. 7 shows the pressure behavior for different perforation schemes with longer and wider fractures. For comparison, also shown are 64 ft fracture performances. The productivity is largely improved compared with the previous case (64 ft fractures). In particular, limited completions ($h_{pD}=1/6$ and $h_{pD}=1/3$) benefit

significantly from the improved fracture configuration. As shown in Fig. 9, the productivity improvement is not much sensitive to the completion length.

When long and wide fractures are successfully created, the productivity impairment due to the limited entry becomes insignificant. The degree of improvement in this scenario is higher than that of the short and narrow fractures with full completion (Fig. 9); thus, limiting a perforation interval is worth attempting for the purpose of improved fracturing operation.

4.4 Effectiveness of re-perforation

In the previous two sections, two scenarios are considered: failure (section 4.2) and success (section 4.3). When the fracture-configuration improvement is achieved, productivity is also improved regardless of the completion scheme (section 4.3); thus limited completion appears to be attractive. The risk inherent in this scheme is that when no improvement in fracture configurations is achieved the fractured-well productivity can be lower than the fully completed non-fractured well productivity (section 4.2). To cope with this risk, one may consider re-perforating the well after unsuccessful fracture operations.

Fig. 8 compares the 64 ft fracture performances with and without re-perforation. In this

scenario, no luck is considered; no additional hole perforated communicates with the created fractures. For $h_{pD}=1/3$ case, for instance, one third of the completed interval is connected with the fractures and the remaining two thirds are open only to the matrix formation. Even with this severe setting, the productivity is improved by the re-perforation operation. As also seen in Fig. 9, re-perforation recovers the well productivity to the level similar to the full-completion productivity ($h_{pD}=1$ in the non-Darcy flow case).

Thus, it is worth considering re-perforation if the fracturing operation fails and does not create long- and wide-enough fractures. In a fracturing design stage, one can estimate how long and how wide are enough by performing a case study similar to the one described in section 4.3.

These results encourage us to include the limited completion scheme in a set of remedial means against the near-wellbore tortuosity and the propagation of multiple fractures. This scheme provides potential of success and does not leave fatal results; an unsuccessful operation can be fixed later.

5. Discussion

To deepen our understanding on the fractured well performances presented in the previous sections, details of the simulation results are examined. In this section, h_{pD} of $1/3$, q of 3.732 MMscf/D, and x_f of 64 ft are considered.

5.1 Pressure profiles

Pressure profiles after 100-day production within the top and bottom layers are shown in Fig. 10 through Fig. 12. Perforation schemes and fracture configurations are also shown schematically (The vertical-to-horizontal scale is not exact). Under Darcy flow conditions, pressure profiles are obtained as shown in Fig. 10. Although the top layer is perforated and the bottom layer is not, the pressure profiles along the fracture is not much different from each other, which is attributed to the high fracture conductivity. This is not the case for non-

Darcy flow conditions. As shown in Fig. 11, the pressure gradient in the top layer is much steeper than that in the bottom layer due to the effect of non-Darcy flow.

Additional perforations after the fracturing operation alleviate the steep pressure gradient as shown in Fig. 12. This is because the flow rates (thus, the flow velocities) assigned in the two top layers are reduced by virtue of the additional contributing layers. Fig. 13 shows the production rates of individual layers. The

Fig. 10 Pressure profiles for a well with 64 ft fractures under Darcy flow conditions: (top) top layer and (bottom) bottom layer.

Fig. 11 Pressure profiles for a well with 64 ft fractures under non-Darcy flow conditions: (top) top layer and (bottom) bottom layer.

flow rates after 100-day production of the two top layers (1 and 2) are about halved by performing re-perforation in the three bottom layers (3, 4, and 5). It is important not to assign a high flow rate to a certain layer for mitigating the effects of non-Darcy flow.

5.2 Non-Darcy flow within fractures

By comparing the results in sections 4.1 and 4.2, it is revealed that the effects of non-Darcy flow are significant on the pressure performances. Fig. 14 shows the profile of F_{ND} along the fracture in the top and bottom layers after 100

Fig. 12 Pressure profiles for a re-perforated well with 64 ft fractures under non-Darcy flow conditions: (top) top layer and (bottom) bottom layer.

-day production. (The profile in the second top layer is similar to that in the top layer and is not shown.) In the top layer, F_{ND} in the x direction near the wellbore is 0.027, which indicates that the pressure gradient is 37 times the value under Darcy flow conditions. In the bottom layer, despite no production, substantial non-Darcy flow in the x direction can be seen in the middle portion of the fracture. F_{ND} values in the z direction are far below unity, implying that a large amount of gas flows upward (toward the perforated layers 1 and 2) along the fracture.

Performing re-perforation in the remaining three layers affects the profile of F_{ND} as shown in Fig. 15. In the bottom layer, due to the production, F_{ND} in the x direction decreases compared with the previous case. In exchange, F_{ND} in the top layer becomes higher. Near the wellbore, F_{ND} in the x direction in the top layer is 0.067, indicating that the pressure gradient is 2/5 of the previous case. In the z direction, F_{ND} values become much higher than the previous. This is because the flow rates assigned in the two top layers are reduced by producing from the other three layers, resulting in reduction of upward gas flow along the fracture.

6. Conclusions

1. Unless non-Darcy flow prevails, limited completion can be applied to improve the

Fig. 13 Production rates of individual layers: (left) without re-perforation and (right) with re-perforation.

Fig. 14 Non-Darcy factor along the 64 ft fracture without re-perforation: (left) x direction and (right) z direction.

Fig. 15 Non-Darcy factor along the 64 ft fracture with re-perforation: (left) x direction and (right) z direction.

- fracture configuration without excessive concern about productivity impairment.
2. Even in non-Darcy flow situations, the productivity impairment due to limited completion is not significant for wells with long- and wide-enough fractures.
3. When non-Darcy flow prevails and the fracture configuration is not improved enough, limited completion may impair the productivity.
4. Performing re-perforation can mitigate the productivity impairment even if the perforated holes do not communicate with

the fractures.

5. Assigning flow rates evenly over the production interval is important to mitigate the effects of non-Darcy flow.

Nomenclature

- C_{fD} : dimensionless fracture conductivity, $k_f w / k x_f$
- F_{ND} : non-Darcy factor, defined by Eq. (2)
- h : thickness, L
- h_p : perforation length, L
- h_{pD} : dimensionless completion length, h_p / h
- k : formation permeability, L^2

- k_f : fracture permeability, L^2
 p_f : fluid pressure in the fracture, m/Lt^2
 p_{net} : net fracturing pressure, m/Lt^2
 q : flow rate, L^3/t
 v : fluid velocity, L/t
 w : fracture width, L
 x_f : fracture length, L
 β : non-Darcy coefficient, $1/L$
 μ : fluid viscosity, m/Lt
 ρ : fluid density, m/L^3
 σ_e : effective stress on proppants, defined by Eq. (3), m/Lt^2
 σ_h : minimum horizontal stress, m/Lt^2

SI Metric Conversion Factors

- $cp \times 1.0^*$ $E-03 = Pa \cdot s$
 $ft \times 3.048^*$ $E-01 = m$
 $MMscf \times 2.831685$ $E+4 = m^3$
 $md \times 9.869233$ $E-04 = \mu m^2$
 $psi \times 6.894757$ $E+00 = kPa$
 $(^{\circ}F - 32)/1.8 = ^{\circ}C$

* Conversion factors are exact.

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要 旨

水圧破碎を施したガス井挙動に対する 穿孔手法と非ダルシー流の影響

佐藤光三・武田秀明

水圧破碎で形成されるフラクチャーの形状を改善するための一手法として、穿孔区間の制限が提唱されている。しかしながら、通常の坑井で広く認識されているように、この手法は生産性の低下を招きうる。フラクチャーの形成された坑井で、この低下がどの程度のもの

であるかを把握するために、シミュレーションによるケーススタディーを実施した。

本研究により、以下の点が明らかとなった。すなわち、非ダルシー流が支配的でない限り、部分仕上げはフラクチャー坑井の生産性を著しくは低下させず、したがって、油井に対しては穿孔制限をすることに問題はない。また、フラクチャーが十分に長く広ければ、非ダルシー流であっても部分仕上げによる生産性低下はさほど大きくない。しかしながら、フラクチャー形状の改善が達成されない場合、穿孔制限は非ダルシー流の下で顕著な生産性低下を招きうる。そのような場合に取らうる対処法としては、未穿孔区間への再穿孔が有効である。非ダルシー流の影響を緩和するためには、生産区間全体にわたる流量の均等化が重要である。