Inflow Performance Relationship of Hydraulically Fractured Gas Wells with Non-Darcy Flow

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I. ABSTRACT

This paper presents a new inflow performance relationship for a hydraulically fractured well producing from a gas reservoir. In this study, we specifically address the effect of non-Darcy flow that occurs in the fracture. The inclusion of the non-Darcy phenomena is important due to high mobility of gas particularly in the fracture whose permeability is very high. Failure not to account for this effect will yield too optimistic well performance prediction, since the pressure losses (pressure drawdown) inside the fracture is underestimated.

In this work we generated analytical results of a hydraulically fractured gas well with non-Darcy flow for various different proppant sizes, gas properties, reservoir permeabilities, fracture-length to reservoir-radius ratio, and fracture conductivities. Sensitivity analyses have been performed for each of those parameters. Based on these results we developed a unique inflow performance relationship.

II. INTRODUCTION

Guppy et al.\(^1\) developed semianalytical and numerical (finite difference) models to analyze the unsteady flow behavior of finite conductivity fractures producing at high flow rates. The models also incorporate the effect of non-Darcy flow effect that occurs in the fracture. Several important conclusions from their work are: (i) the effect of non-Darcy in the fracture is to cause an apparent fracture conductivity significantly less than the true fracture conductivity; (ii) to describe the non-Darcy flow effect, two physical parameters are required: the dimensionless fracture conductivity and the dimensionless flow rate constant; (iii) developed correlation between flow rate constant, apparent fracture conductivity and true fracture conductivity were developed.

The correlation between flow rate constant, apparent fracture conductivity and true fracture conductivity is given by Eq. 1.\(^1\)

\[
\frac{[F_{cD}]}{[F_{cD}]_{app}} = 1 + 0.31(q_{DND})_f
\]  

The ranges of \(q_{DND}\) and \([F_{cD}]_f\) are given by the following:
1. For all values of \((q_{DND})\), that yields \([F_{cD}]_{app} \geq 2.0\, [F_{cD}]_f < 10\).
2. For all values of \((q_{DND})_f\) equal to 1 to 20, \(10 \leq [F_{cD}]_f \leq 100\).
3. For all values of \((q_{DND})_f\) less than or equal to 10, \(100 \leq [F_{cD}]_f \leq 500\).
Where:

\[ F_cD = \frac{k_f w_f}{k_x f} \] .................................................................(2)

\[ (q_{DND})_f = \frac{4.64 \times 10^{-16} k_f \beta M q_g}{w_f h \mu_i} \] ..............................................(3)

\[ \beta = \frac{(30.48 \times 10^6) \times b'}{(k_f)^a} \] .................................................................(4)

The constants \( a' \) and \( b' \) are given in Table 1.2

<table>
<thead>
<tr>
<th>Sand Size (mesh)</th>
<th>( a' )</th>
<th>( b' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 to 12</td>
<td>1.24</td>
<td>17423.61</td>
</tr>
<tr>
<td>10 to 20</td>
<td>1.34</td>
<td>27539.48</td>
</tr>
<tr>
<td>20 to 40</td>
<td>1.54</td>
<td>110470.39</td>
</tr>
<tr>
<td>40 to 60</td>
<td>1.60</td>
<td>69405.31</td>
</tr>
</tbody>
</table>

### III. DESCRIPTION OF MODEL

Eq. 1 implies that the hydraulic-fractured well response affected by non-Darcy flow can be modeled using the hydraulic-fractured well without non-Darcy flow as long as the apparent fracture conductivity is used. In this paper the development of inflow performance relationship (IPR) is based on that assumption.

The IPR is developed using constant rate solution of hydraulic fractured well from which the data at the start of the pseudosteady-state flow \( t_{DA} = 0.1 \) is used for the development. The results are then plotted in term of \( \frac{p_{wf}}{p_r} \) versus \( \frac{q_g}{q_{max}} \). The base case data in this study are shown in Table 2, and the results are plotted in Fig. 1.

<table>
<thead>
<tr>
<th>Table 2 – Base Case Data</th>
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<tbody>
<tr>
<td>Reservoir pressure, ( p_i )</td>
</tr>
<tr>
<td>Reservoir temperature, ( T )</td>
</tr>
<tr>
<td>Gas specific gravity</td>
</tr>
<tr>
<td>Proppant size</td>
</tr>
<tr>
<td>( L_f/X_e )</td>
</tr>
<tr>
<td>Fracture width</td>
</tr>
<tr>
<td>Reservoir permeability</td>
</tr>
</tbody>
</table>
Figure 1 – IPR plot of hydraulic fractured gas well using base case data for various dimensionless true fracture conductivity.

Fig. 1 shows that the pseudosteady-state solution for hydraulic fractured gas well can be be correlated by two parameters in the IPR plot: dimensionless pressure, \( \frac{p_{wf}}{p_r} \), and dimensionless rate, \( \frac{q_g}{q_{max}} \). All data for \( F_{cD}=0.1 \) to 1000 almost fit to single curve. The maximum variation of \( \frac{p_{wf}}{p_r} \) is 0.2. As seen from this figure, we may also divide the data into two groups: (i) \( F_{cD}=0.1 \) to 10 (denoted by solid symbols), and (ii) \( F_{cD} > 10 \) (denoted by open symbols).

III. SENSITIVITY ANALYSES

In this section, results are generated for various cases of proppant size, specific gravity of gas, reservoir permeability, and fracture half-length to reservoir radius. This sensitivity analysis is intended to see the effect of those parameters mentioned on the IPR as to whether the two dimensionless IPR parameters (\( \frac{p_{wf}}{p_r} \) and \( \frac{q_g}{q_{max}} \)) is enough to describe the pseudosteady-state performance of the hydraulic fractured gas wells.
The IPR plot for various proppant sizes, reservoir permeabilities, gas gravities and fracture half-length to reservoir radius ratio are shown in Fig. 2 to 5. The maximum variation of \( \frac{p_{wf}}{p_r} \) is 0.1 for sensitivity cases of proppant sizes, reservoir permeabilities, and fracture half-length to reservoir radius ratio. The sensitivity case on gas gravity shows maximum variation of 0.2. Overall the variation is It shows that the effect of proppant size can be captured by the two IPR parameters \( \frac{p_{wf}}{p_r} \) and \( \frac{q_g}{q_{max}} \) and there is no need for additional parameter to take into account for this effect in the IPR plot.

\[ \frac{q_g}{q_{max}} = \left[ 1 - 0.0471033 \left( \frac{p_{wf}}{p_r} \right) ^{-1.47438 \left( \frac{p_{wf}}{p_r} \right) ^2 + 0.5214833 \left( \frac{p_{wf}}{p_r} \right) ^3} \right] ^{0.856745} \]  

\text{(5)}

IV. CORRELATION OF INFLOW PERFORMANCE RELATIONSHIP

All data generated for different parameters are plotted in Fig. 6. The range of those parameters are as follows: reservoir permeabilities are between 0.1 mD to 1000 mD, gas gravities are between 0.5 to 0.9, dimensionless fracture conductivities are between 0.1 to 1000, proppant sizes (mesh) are 10-20, 20-40, 40-60, and fracture half-length to reservoir radius ratios are between 0.25 to 0.75. Except for cases of very high permeability combined with very low fracture conductivity, the data can be reasonably well fitted with a single curve. The IPR correlation that best fit the data is:
Figure 3 – IPR plot of hydraulic fractured gas well for various reservoir permeability.

Figure 4 – IPR plot of hydraulic fractured gas well for various specific gas gravity.
Figure 5 – IPR plot of hydraulic fractured gas well for various fracture half-length to reservoir radius ratio.

Figure 5 – IPR plot of hydraulic fractured gas well for all cases.
V. CONCLUSIONS

Our conclusions are as follows:
1. The pseudosteady-state performance of a hydraulically fractured gas well where non-Darcy flow occurs in the propped fracture can be correlated by two IPR parameters. They are dimensionless pressure, \( p_{wf}/p_r \), and dimensionless flow rate, \( q_g/q_{max} \).
2. This work proposes a new inflow performance relationship correlation for a hydraulically fractured gas well with non-Darcy flow effect in the propped fracture. This IPR correlation is:

\[
\frac{q_g}{q_{max}} = \left[ 1 - 0.0471033 \left( \frac{p_{wf}}{p_r} \right) - 1.47438 \left( \frac{p_{wf}}{p_r} \right)^2 + 0.5214833 \left( \frac{p_{wf}}{p_r} \right)^3 \right]^{-0.856745}
\]

3. We observed that for very high reservoir permeability \( (k > 100) \) combined with very low fracture conductivity \( (F_{cD} < 1) \), the IPR show quite big difference from other cases. It indicates that one more additional parameter may be needed in the IPR plot to describe this behavior, which can be addressed in the future study.

NOMENCLATURE

\( F_{cD} \quad = \quad \text{dimensionless fracture conductivity} \)
\( h \quad = \quad \text{formation thickness, ft} \)
\( k \quad = \quad \text{reservoir permeability, md} \)
\( k_f \quad = \quad \text{fracture permeability, md} \)
\( L_f \quad = \quad \text{fracture length, ft} \)
\( M \quad = \quad \text{molecular weight of gas, lb/lb-mol} \)
\( p_r \quad = \quad \text{reservoir pressure, psia} \)
\( p_{wf} \quad = \quad \text{well flowing pressure, psia} \)
\( q_{max} \quad = \quad \text{maximum gas flowrate (AOF), Mscf/D} \)
\( q_g \quad = \quad \text{gas flow rate, Mscf/D} \)
\( w_f \quad = \quad \text{fracture width, ft} \)
\( x_f \quad = \quad \text{fracture half-length, ft} \)
\( x_e \quad = \quad \text{reservoir size, ft} \)
\( \beta \quad = \quad \text{beta factor, ft}^{-1} \)
\( \mu_i \quad = \quad \text{initial gas viscosity, cp} \)
REFERENCES


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