Optimization of Perforated Completions for Horizontal Wells in High-Permeability, Thin Oil Zone
Hassi R’mel Oil Rim, Algeria

By
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OUTLINE

- Introduction
- Statement of the problem
- Objectives of the Study
- Methodology
- Geological and Reservoir Characterization
- Sensitivity Analysis on Perforated Completions
- Performance of Inverted High Angle Completion Case Study: HRZ-09
- Conclusions and Recommendations
INTRODUCTION

- The success of Horizontal well technology is mainly due to the advantages that horizontal wells offer such as: productivity improvement, coning reduction and sand problems attenuation.

- Very often, either for geological reasons or for production purposes, the wells need to be cased and perforated. It is important in this case to know how much of the horizontal length should be perforated and where to locate the perforations.

- In this respect, minimizing the horizontal section to be perforated for an optimization purpose is justified.
A considerable number of studies have been done on how to optimize the perforated completions for horizontal wells; but very few of them took into consideration the reservoir heterogeneity as well as coning problems.

Probably one the most important work directly related to this topic is the one developed by Goods and Wilkinson. They have presented an analytical solution for the performance of partially completed horizontal well.
According to their model, the inflow performance of a well is related to the long-time behavior of constant rate pressure. So, they derived a formula that expresses the inflow performance of a partially open horizontal well as follows:

\[
J_h = \frac{7.08 \times 10^{-3} k_h h}{\mu_o \beta_o (P_{ID} + S_{m}^*)} \quad \text{(STB/D – PSI)}
\]

Where:
- \(P_{ID}\) : Dimensionless Inflow Pressure.
- \(S_{m}^*\) : Skin Factor.
Goods and Wilkinson’s model limitations:

1. It considers the reservoir as Homogeneous.
2. It does not consider the gas and water coning effects.

So in this study, a numerical solution was developed to optimize the perforated completions in a heterogeneous reservoir laying between a large gas cup and active aquifer (Double coning problem).
In thin oil zones with high permeability, horizontal wells are used to minimize water and or gas coning; so that, an inappropriate perforated completion scheme may actually exacerbate the problem at the downstream end of the well.

In addition, the productivity of horizontal wells producing from such reservoir may be severely restricted by frictional pressure losses within the perforation section of the well.

Hence, in thin oil zones, optimizing the perforated completion in horizontal wells will substantially improve the oil recovery, alleviate gas and water coning, and so that minimize the investment cost.
OBJECTIVES OF THE STUDY

1. Investigate the effect of the most relevant reservoir parameters on horizontal well performance for different perforation alternatives.

2. Generate correlation curves that can be used to optimize the perforated completions for Horizontal wells.

3. Find out the optimum perforation scheme for horizontal wells in Hassi R’mel Oil Rim.

4. Study the performance of the Inverted High Angle completion in Hassi R’mel Oil Rim (Case study: HRZ-09).
METHODOLOGY

- Reservoir Characterization of the A-Sand reservoir of Hassi R’mel Oil Rim using the sedimentary subdivision and the best approaches to estimate the petrophysical properties. Hence, the most accurate geological model to be introduced in the simulator.

- A single well simulation model was built to investigate the effect of perforation length and its distribution, reservoir permeability, vertical anisotropy and areal anisotropy on horizontal well performance.
A second single well model was involved in a real case where the performance of the well HRZ09, for different perforation schemes, was a concern. To cover this part, three points have to be developed:

- History matching
- Comparative study based on well performance
- Comparative study based on Economic Analysis
RESERVOIR CHARACTERIZATION

- Introduction
- Statement of the problem
- Objectives of the Study
- Methodology

- Geological and Reservoir Characterization
  - Sensitivity Analysis on Perforated Completions
  - Performance of Inverted High Angle Completion Case Study : HRZ-09
  - Conclusions and Recommendations
Cases where core and log analysis data were available, the priority for porosity and permeability determination was given to core analysis.

The permeability for the non-cored sections were estimated from the curve fitting of the permeability-porosity relationship.

**Effective Formation:**

- Cut-off porosity = 4%
- Cut-off Shale content = 35%
- Cut-off Water Saturation = 55%
- Cut-off Permeability = 1md
PETROPHYSICAL (RESERVOIR) CHARACTERIZATION

- Shale Content, $V_{Sh}$:
  
  \[ V_{Sh} = I_{Sh} \left( 2^{21Sh} - 1 \right) \]  
  (Older Rock)

- Effective Porosity:
  
  \[ \phi = 0.707 \sqrt{\phi_{NC}^2 + \phi_{Dc}^2} \quad \Rightarrow \quad \phi_e = \phi(1-V_{sh}) \]

- Water Saturation:
  
  \[ S_W = \frac{aR_w}{2\phi^m} \left[ -\frac{V_{Sh}}{R_{Sh}} + \left( \frac{V_{Sh}}{R_{Sh}} \right)^2 + \frac{4\phi^m}{aR_wR_l} \right]^{0.5} \]  
  (Vsh > 10%)

RESERVOIR CHARACTERIZATION
Porosity-Permeability Correlation

\[ \ln k = 0.401(\phi) - 2.594 \]

\[ R^2 = 0.7739 \]
# RESULTS OF THE PETROPHYSICAL CHARACTERIZATION

## HR-189

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SENSITIVITY ANALYSIS
ON PERFORATED COMPLETIONS

- Introduction
- Statement of the problem
- Objectives of the Study
- Methodology
- Geological and Reservoir Characterization

- Sensitivity Analysis on Perforated Completions
- Performance of Inverted High Angle Completion
  Case Study: HRZ-09
- Conclusions and Recommendations
A parametric study is conducted to analyze the effect of the most relevant reservoir parameters on horizontal well performance for different Perforation Schemes. This in High-permeability thin Oil zone. These parameters are:

- Perforation length and its Distribution
- Reservoir Permeability
- Vertical anisotropy Ratio
- Horizontal anisotropy Ratio
To perform this study, a single-horizontal well model is needed. For this simulation model, a 3-D regular Cartesian grid was built.

- Number of blocks in X-direction: 15
- Number of blocks in Y-direction: 15
- Number of blocks in Z-direction: 14
- Total number of blocks: \(15 \times 15 \times 14 = 3150\)
Once the single well simulation model was built, the sensitivity analysis can be performed for different perforation alternatives. All the simulation runs were done for 12 years forecast.

Assuming that the well is completed with a fully cemented and perforated liner, and the horizontal wellbore has 500m long, seven (07) perforation schemes were proposed for this study. These are:
Case 1: $L_p = 500m$ (100%)
The Proposed Perforation schemes

Case 2 : $L_p = 400m$ (80%)

$L = 500m$

Heel  Toe
The Proposed Perforation schemes

Case 3: \( L_p = 300 \text{m} \ (60\%) \)

\( L = 500 \text{m} \)
The Proposed Perforation schemes

Case 4: \( L_p = 200m \) (40%)

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SENSITIVITY ANALYSIS
The Proposed Perforation schemes

Case 5: \( L_p = 100 \text{m} \) (20%)
The Proposed Perforation schemes

Case 6: $L_p = 300m$ UD (60%)
The Proposed Perforation schemes

Case 7: $L_p = 200m$ TE (40%)

$L = 500m$

SENSITIVITY ANALYSIS
1. Base Case (Perforation Length and Distribution Effect):

All the reservoir parameters are kept unchanged; and they took values that match those of Hassi R’mel Oil rim. These are:

- $K = 500 \text{md}$
- $K_v/K_h = 0.01$
- $K_y/K_x = 1$
- $Q_o = 100 \text{ SM}^3/\text{D}$
Base Case
Perforation Length and its Distribution Effect

Plot of Oil Recovery Versus Time For different perforation scenarios

- Lp=100%
- Lp=80%
- Lp=60%
- Lp=40%
- Lp=20%
- Lp=60% UD
- Lp=40% TE
Base Case

Perforation Length and its Distribution Effect

Plot of Gas-Oil Ratio Versus Time For different perforation scenarios

- Lp=100%
- Lp=80%
- Lp=60%
- Lp=40%
- Lp=20%
- Lp=60% UD
- Lp=40% TE
Base Case
Perforation Length and its Distribution Effect

Perforation Distribution Effect

Plot of Oil Recovery versus time for the comparison between case 3 and case 6

- Lp=60% CP
- Lp=60% UD

Plot of Gas-Oil Ratio versus time for the comparison between case 3 and case 6

- Lp=60% CP
- Lp=60% UD

SENSITIVITY ANALYSIS
Perforation Distribution Effect

Base Case

Perforation Length and its Distribution Effect

Plot of Oil Recovery versus Time for the comparison between case 4 and case 7

Plot of Gas-Oil Ratio versus Time for the comparison between case 4 and case 7
Base Case
Perforation Length and its Distribution Effect

Oil Recovery for the different perforation schemes proposed after 12 years production
- Base Case -

Perforation Schemes

- Lp=100%
- LP=80%CP
- LP=60%CP
- LP=40%HE
- LP=20%CP
- LP=60%UD
- LP=40%TE

Oil Recovery, %

Best Case
Gas-Oil Ratio for the different perforation schemes proposed after 12 years production
- Base Case -
In case of continuous perforation, the higher the perforation length, the higher the oil recovery, and the higher the Gas-Oil ratio.

The perforation length can be reduced, and in many cases, without a substantial decrease in oil recovery. Moreover, lower values of perforation length lead to lower gas-oil ratios produced.

Hence, the perforation length has to be optimized with respect not only to oil recovery, but also to gas-oil ratio in order to guarantee the lowest investment cost in gas facilities.
The reservoir produces more efficiently when the perforation intervals are uniformly distributed along the wellbore rather than being continuously placed.

Case 6 (60% Uniformly Distributed Perforation) is the most favorable case of all the proposed perforation schemes since it guaranties:

- High Oil recovery and low Gas-oil ratio.
- Pressure and production rate stabilization.
- Coning reduction.
- Lowest investment cost (Maximum net Present Value).
2. Reservoir Permeability Effect

To investigate the effect of reservoir permeability on horizontal well performance for various completion alternatives, we considered five values of reservoir permeability:

- $K_1 = 1000 \text{ md}$
- $K_2 = 500 \text{ md}$
- $K_3 = 100 \text{ md}$
- $K_4 = 50 \text{ md}$
- $K_5 = 10 \text{ md}$
RESERVOIR PERMEABILITY EFFECT

\[ K_1 = 1000 \text{ md} \]

Horizontal well performance for the different perforation schemes
RESERVOIR PERMEABILITY EFFECT

Effect of Perforation Length on well performance for different Reservoir Permeability values after 12 years
Effect of Reservoir Permeability on well performance for different perforation scenarios after 12 years
The higher the reservoir permeability, the higher the oil recovery for any perforated completion alternative.

In case of a thin oil rim sandwiched between a large gas-cap and an active aquifer, lower values of reservoir permeability yield higher gas-oil ratio in comparison to the case of higher permeability values.

Hence, high reservoir permeability values (K>50md) are more favorable in such case (thin oil rim).
3. Vertical Anisotropy Effect

Four (04) vertical anisotropy ratios were examined:

- \((K_v/K_h)_1 = 1\)
- \((K_v/K_h)_2 = 0.1\)
- \((K_v/K_h)_3 = 0.01\)
- \((K_v/K_h)_4 = 0.001\)
VERTICAL ANISOTROPY EFFECT

\[(K_v/K_h)_1 = 1\]

Horizontal well performance for the different perforation schemes

**SENSITIVITY ANALYSIS**

**Plot of Oil Recovery Versus Time For different perforation scenarios**

**Plot of Gas-Oil Ratio Versus Time For different perforation scenarios**
Effect of Perforation Length on well performance for different Vertical Anisotropy values after 12 years

VERTICAL ANISOTROPY EFFECT

Effect of Perforation Length on well performance for different Vertical Anisotropy values after 12 years
Effect of **Vertical Anisotropy** on well performance for different perforation scenarios after 12 years.
In case of a thin oil rim trapped between a large gas-cap and an active aquifer, the higher the vertical anisotropy ratio, the lower the oil recovery for any perforation scenario.

Hence, in this case, low anisotropy ratios are preferable not only to get higher oil recovery but also to come out with the least amount of gas produced.
4. Horizontal Anisotropy Effect

Four (04) values of horizontal anisotropy were considered to investigate its effect on horizontal well performance for different perforation alternatives. These are:

- \((Ky/Kx)_1 = 10\)
- \((Ky/Kx)_2 = 5\)
- \((Ky/Kx)_3 = 1\)
- \((Ky/Kx)_4 = 0.1\)
HORIZONTAL ANISOTROPY EFFECT

\[(K_y/K_x)_1 = 10\]

Horizontal well performance for the different perforation schemes

SENSITIVITY ANALYSIS
Effect of Perforation Length on well performance for different Horizontal Anisotropy values after 12 years

SENSITIVITY ANALYSIS
Effect of **Horizontal Anisotropy** on well performance for different perforation scenarios after 12 years
For all the perforated completion schemes, the higher the horizontal anisotropy \((K_y/K_x)\), the higher the oil recovery.

This is because the well is drilled in X-direction. However, if the well was drilled in Y-direction, the opposite trend would be got.
Conclusion of The Sensitivity Analysis

All the plots generated in this parametric study are very useful to optimize perforated completions for horizontal wells in Hassi R’mel Oil Rim, and to predict their performance within a wide range of reservoir permeability, vertical anisotropy and Horizontal anisotropy.
Performance of Inverted High Angle Completion
« Case Study : HRZ-09 »

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  Case Study : HRZ-09

- Conclusions and Recommendations
Total Oil Recovery = 7.4%

CASE STUDY

8-13 m

Oil Rim

GAS

K_{avg} = 500 md

WATER
All those factors made the necessity to develop this oil rim by implementing horizontal wells, in addition to vertical wells (Mixed Development Strategy), to improve the oil recovery in one hand, and to alleviate the water and gas coning problems in the other hand.

Among the areas where most horizontal wells have been drilled is the CTH2 area. This area will be our zone of interest in this study since the well HRZ-09 belongs to it.
HRZ-09 HISTORY

HRZ-09 (January 2002)

CASE STUDY
HRZ-09 ACTUAL PATH

HRZ09 Path

Distance to the East from the Well head, m

TVD, m

TopA

GOC

WOC

CASE STUDY
OBJECTIVE OF THE STUDY

• Because of the difficulty in locating the GOC and WOC contacts in the CTH2 area, there will probably be other horizontal wells that will take the same profile as that of HRZ-09.

• So, it is important to study the performance of this well and to investigate various perforation scenarios in case of inverted high angle profile.

• Hence, to come up with the best perforation scheme that guarantees the maximum oil recovery, the minimum gas-oil ratio, and consequently, the lowest investment cost.
To study the performance of the well HRZ-09 for different perforation schemes, a simulation modeling of this well is needed.

The model Grid, in this case, has to be refined in the vicinity of the well.

A history match is needed for wells that are inside the Model grid.
For this well model, an irregular Cartesian grid was built, and the Cartesian (X-Y-Z) coordinate are as follow:

- Number of blocks in X-direction: 31
- Number of blocks in Y-direction: 17
- Number of blocks in Z-direction: 14
- Total number of blocks: \(31 \times 17 \times 14 = 7378\)
1. Horizontal Section Perforation (Actual Case)
2. Slanted Section Perforation
THE PROPOSED
PERFORATION SCHEMES

3. Horizontal & Slanted Section Perforation
(Double Perforation Scheme)
In this section, the focus will be on selecting the best perforation scheme of the three proposed.

The selection will be based on well performance, especially oil recovery and gas-oil ratio, as well as economic analysis of the three perforation alternatives.
Comparative Study
Based on well Performance

Comparative Plot of Oil Recovery versus Time for the Three Perforation Schemes

- Slanted Section
- Horizontal Section (Actual Case)
- Slanted & Horizontal Sections (Double Perforation Case)

Oil Recovery,%

Time, Years

0 2 4 6 8 10 12 14
Comparative Study
Based on well Performance

Comparative Plot of Gas-Oil ratio versus Time for the Three perforation Schemes

- Slanted portion
- Horizontal Section (Actual Case)
- Slanted & Horizontal Sections (Double Perforation Case)
Hence, the actual case (base case) is the most favorable case according to well performance analysis. This result has to be confirmed by an economic analysis on the three perforation schemes.
The economic analysis in this study is based on the calculation of the Net Present Value (NPV) for each perforation scenario. This parameter, NPV, provides a convenient measure to select the best perforation alternative. The optimum case is the one that corresponds to the maximum NPV.
Comparative Study
Based On Economic Analysis

NPV:

\[ NPV = \sum_{i=1}^{n} (CF_i) \times R_i \]

Where:

\( (CF)_i \): Cash Flow in the Year \( i \)

\( R_i \): Discount Rate in the Year \( i \)

\[ R_i = \frac{1}{(1 + \tau)^{i-1}} \]

\( \tau \): Rate of Interest
Comparative Study
Based On Economic Analysis

Knowing that in Hassi R’mel Oil Rim:

- Perforation Cost, $C_p = 1,300 \$/meter
- Cost of Fluid Transport, $T = 1.2 \$/bbl
- Drilling Cost, $C_D = 5 \text{ MM}\$

And assuming that:

- Oil Price = 25 \$/bbl
- Rate of Interest, $\tau = 12\%$
### Comparative Study Based On Economic Analysis

#### 1. Horizontal Section perforation (Actual Case)

**NPV = 21.05MM$**

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<th>Year Number ($i$)</th>
<th>Year</th>
<th>$Npi$ (M.Barrels)</th>
<th>Income $l_i$ (MM$)</th>
<th>Drilling Cost</th>
<th>Transport Cost</th>
<th>Cash Flow (MM$)</th>
<th>Discount Rate $R_i$</th>
<th>(NPV)$_i$ (MM$)</th>
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<td><strong>21.05</strong></td>
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CASE STUDY
Comparative Study Based On Economic Analysis

2. Slanted Section perforation

\[ NPV = 14.61 \text{MM}$\]

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<th>Year Number, $i$</th>
<th>Year</th>
<th>$N Pi$ M.Barrels</th>
<th>Income $I_i$ (MM$)$</th>
<th>Drilling Cost</th>
<th>Transport Cost</th>
<th>Cash Flow (MM$)$</th>
<th>Discount Rate, $R_i$</th>
<th>$(NPV)_i$ (MM$)$</th>
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<td>2003</td>
<td>171.92</td>
<td>4.30</td>
<td>5.1</td>
<td>0.21</td>
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Comparative Study Based On Economic Analysis

3. Horizontal & Slanted Sections perforation

NPV = 21.37MM$

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<th>Transport Cost</th>
<th>Cash Flow (MMS)</th>
<th>Discount Rate, $R_i$</th>
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Comparative Study
Based On Economic Analysis

Comparative histogram of the three perforation schemes:
Oil Price = 25 $/bbl

NPV, MM$

Horizontal Section: 21.05
Slanted Section: 14.61
Slanted & Horizontal Sections: 21.37

CASE STUDY
The simulation results indicate that there is no extra-recovery to be expected from the double perforation scheme. Besides, such perforation scheme leads to higher Gas-Oil Ratio to be produced in comparison to the Horizontal section perforation (actual case). Thus, the best perforation scheme is the one that corresponds to the actual case.
The Economic analysis performed on the three perforation scenarios has confirmed the above conclusion, which means that the maximum net present value (NPV) will correspond to the actual case if we take into account the investment cost in gas facilities.

Although the well HRZ-09 took an inverted high angle profile accidentally, this profile has brought several advantages, such as:
• Allow the exact location of Gas-Oil and Water-Oil contacts, so that, the horizontal drain can be placed at a desired depth.

• Explore the entire oil column and find out the high quality sand of this column prior to placing the horizontal drain. Thus, it serves as a Pilot Hole.

• Alleviate the water and gas coning problems.
CONCLUSIONS AND RECOMMENDATIONS

- Introduction
- Statement of the problem
- Objectives of the Study
- Methodology
- Geological and Reservoir Characterization
- Sensitivity Analysis on Perforated Completions
- Performance of Inverted High Angle Completion
  Case Study: HRZ-09

Conclusions and Recommendations
Based on the entire study, the following conclusions can be drawn:

1. The perforation length can be reduced, and in many cases, without a substantial decrease in oil recovery. Moreover, lower values of perforation length lead to lower gas-oil ratios produced.

2. Hence, the perforation length has to be optimized with respect not only to oil recovery, but also to gas-oil ratio. This to guarantee the lowest investment cost in gas facilities.
CONCLUSIONS
(Continued)

3. The reservoir produces more efficiently when the perforation intervals are uniformly distributed along the wellbore rather than being continuously placed.

4. The correlation curves developed in the parametric study can be used to optimize the perforation scheme for horizontal wells in Hassi R’mel Oil Rim, especially CTH2 area.
5. In Hassi R’mel Oil Rim, the optimum perforation scheme for horizontal well is the case that corresponds to 60% uniformly distributed perforation.

6. Although the well HRZ-09 took an inverted high angle profile accidentally, this profile has brought several advantages.