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Optimized Design for Horizontal Well Perforated Casing and Slotted Liner Completions

Chen Chaofeng, Liu Xihe, Ruan Dong, Xie Zhiyi, Meng Qingyang, Wu Yue, Wang Xunian

Exploration Division, Xinjiang Oilfield Company, China Petroleum, Karamay, Xinjiang 834000, China

Abstract: Well completion is the process of creating an effective flow path between the reservoir and the wellbore. An effective completion must maintain the mechanical integrity of the wellbore while ensuring fluid flow within the well. This paper outlines a method for optimizing horizontal well design, using a skin factor model suitable for all types of completions, including those affected by formation damage and turbulence. Various completion methods in horizontal wells, such as slotted liners, perforated liners, perforations, casing, or gravel packing, are employed to enhance wellbore stability and prevent sand production. However, compared to open-hole completions, these methods generally result in lower well productivity, manifested as a positive skin factor. This is due to the convergence of flow towards perforation holes and slotted liners, which increases the fluid velocity near the wellbore. Additionally, any region with reduced permeability (due to drilling, completion, or other processes causing formation damage) amplifies the fluid flow convergence effect, resulting in a significant skin factor. The model presented in this paper considers the combined effects of completion-related formation damage, such as compaction zones and turbulence caused by perforation or slotted liner blockages, and the interactions between these effects. This paper also discusses how to select perforated casing and slotted liner completion types using the skin factor model. The selection process takes into account key parameters, including formation permeability, permeability anisotropy, fluid properties, formation damage, and rock mechanical properties. Additionally, the paper provides types of completions that can provide production parameters for the model. The application of the slotted liner or perforated liner completion model demonstrates that the skin factor variation can reach up to 40%, depending on the properties of the perforation holes and slotted liners. Case studies show that optimizing completion performance can

improve well productivity with minimal or no additional investment, while maintaining the mechanical strength of the liner.

Keywords: Horizontal Wells, Perforated Casing Completion, Slotted Liner Completion, Optimization Design, Analytical Model

1. Introduction

Optimizing well completion to improve the inflow dynamics of horizontal wells is a complex, practical, and challenging task. It requires engineers to predict skin factors under different conditions and to propose recommendations that minimize the skin factor, thereby maximizing well productivity. Key factors to consider in the optimization design of horizontal well completions include formation interactions, perforation damage effects, and the convergence flow effects of perforation holes and slotted liners.

There have been many reports on perforated casing completion models for vertical and horizontal wells, which can be used to predict well productivity. These models are generally divided into two categories: numerical models ^[1-3] and semi-analytical models ^[4-5]. Numerical models require the development of finite difference models, finite element models, or Green's function (fundamental function) models, along with advanced computer programs to solve complex flow problems. These models can provide accurate solutions under various conditions, but they require solving large matrices and typically involve longer computational times compared to analytical models.

Analytical and semi-analytical models are widely used in field practices due to their simplicity and ease of understanding the relationships between different parameters influencing well productivity. These models address complex flow issues through simplified assumptions and are sometimes calibrated with numerical simulation results.

Furui et al. (2005) ^[6] proposed a mathematically rigorous general skin factor equation. This equation incorporates the skin factor (which is unrelated to production), the turbulence conversion factor f_t , and the Forchheimer number F_o (where $f_t \cdot F_o$ is the skin factor related to production). According to their model, the skin factor for any completion type can be expressed as:

$$s_i = s_{0i} + f_t \cdot F_{o,w} \quad (1)$$

Where the subscript i represents the completion type.

The Forchheimer number is similar to the Reynolds number and is defined as:

$$F_{o,w} = \beta \frac{\rho k}{\mu} \left(\frac{q}{2\pi r_w L} \right) \quad (2)$$

Alternatively, expressed using field application units:

$$F_{o,w} = 1.64 \times 10^{-16} \beta \frac{\rho k}{\mu} \left(\frac{q}{r_w L} \right) \quad (3)$$

In these equations, the geometric factor 2π is included in the constant term.

2. Perforation Hole Characteristics in Horizontal Wells

In horizontal well completions, the main difference between vertical and horizontal perforations is the permeability anisotropy and the effect of perforation orientation on inflow dynamics. The perforation skin model developed by Furui et al. in 2002 ^[7] suggests that perforations should be aligned parallel to the direction of minimum permeability, as this minimizes the perforation skin factor (maximizing well productivity).

For most horizontal wells, this means that the perforations should be vertical to the wellbore and extend both upward and downward. An orientation of 180° is considered optimal, as all perforations are aligned with the direction of minimum permeability at this phase angle.

Therefore, in anisotropic formations, multi-directional perforation techniques (such as 60° , 90° , or 120°) are generally not recommended, as they differ from the approach used in homogeneous formations. However, if the perforation density is sufficiently high, multi-directional perforation can achieve a skin factor as low as that of 180° phase perforation. In some cases, multi-directional perforation may even be more advantageous than 180° phase perforation, as the skin factor in the former is independent of perforation orientation, and the perforating gun does not need to be as precisely positioned.

The choice of perforation flow orientation in horizontal wells depends on the degree of anisotropy in the formation. In highly anisotropic formations, all perforations should align with the direction of minimum permeability to achieve maximum productivity. A phase angle of 180° is generally the best choice. On the other hand, for formations with lower anisotropy, multi-directional phase adjustments can provide higher productivity than 0° and 180° phase perforations, similar to the approach used in vertical well perforations.

2.1 Minimizing Formation Damage Effects in Perforated Casing Completions

Figure 1 illustrates the process flow for minimizing formation damage effects in perforated casing completions. The key is to perforate along the direction of the minimum damage radius $r_s(\alpha)$. Formation damage caused by the loss of drilling mud is distributed elliptically in anisotropic formations. Previous studies ^[7,8] assumed that the minimum damage penetration depth is parallel to the direction of minimum permeability (vertical direction). By extending the perforation holes towards the top and bottom of the wellbore, the damaged zone can be crossed, minimizing formation damage. This represents a significant advantage of perforated casing completions compared to open-hole and slotted liner completions.

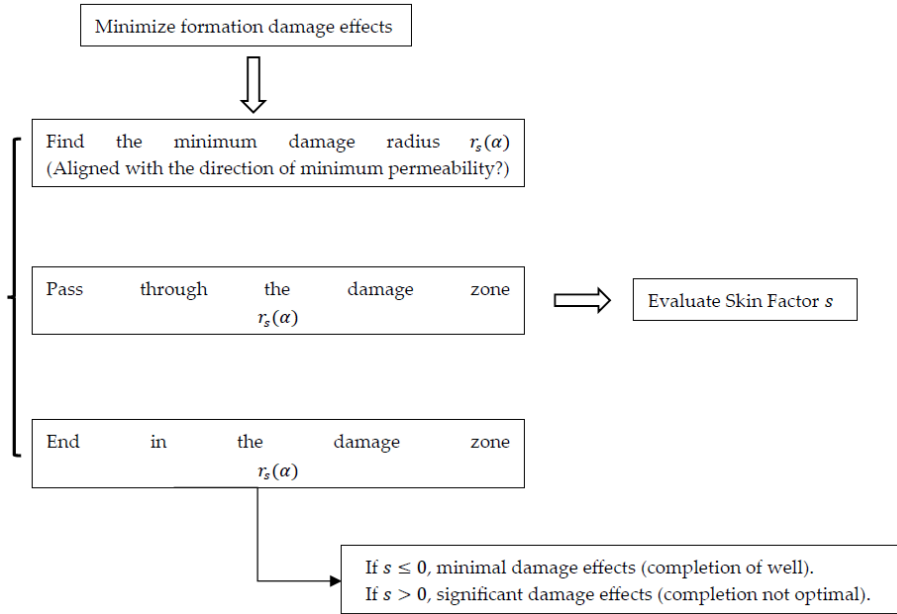


Figure 1. Flowchart for Minimizing Formation Damage Effects

Although the perforations terminate within the damaged zone, the formation damage effect is smaller compared to open-hole completions. The skin factor for perforations terminating in the damage zone (ignoring compaction effects^[6]) is given by:

$$s_p = s_{fo} + \frac{k}{k_s} s_{op} + \beta_s \cdot f_t \cdot p \cdot F_o, w \quad (4)$$

2.2 Minimizing Compaction Effects in Perforated Wells

The compaction zone around the perforations is a region of reduced permeability caused by the perforation process. Figure 2 illustrates the process flow for minimizing compaction effects in perforated casing wells. According to the research by Furui et al.^[6], the compaction effect when perforations pass through the compaction zone can be represented as:

$$s_p = s_{op} + hDe \left(\frac{k}{k_{cz}} - 1 \right) \ln \left(\frac{r_{cz}}{r_p} \right) \quad (5)$$

When perforations terminate in the compaction zone:

$$s_p = s_{fo} + \frac{k}{k_s} s_{op} + hDe \left(\frac{k}{k_{cz}} - \frac{k}{k_s} \right) \ln \left(\frac{r_{cz}}{r_p} \right) \quad (6)$$

Where:

s_{op} is the perforation skin factor accounting for formation damage, calculated using effective perforation length and wellbore radius (Karakas and Tariq, 1991; Furui et al.,^[6]).

The dimensionless perforation spacing hDe is defined as follows:

For phase angles of 0° and 180° :

$$hDe = hl_p \left(\frac{k_x}{k_z} \right) \sin^2 \alpha + \left(\frac{k_x}{k_z} \right) \cos^2 \alpha \quad (7)$$

For multi-directional perforation:

$$hDe = hl_p \left(\frac{k_y k_z}{k_x} \right)^{0.5} \quad (8)$$

In these equations, the x-axis is assumed to be parallel to the horizontal well, and the y-axis and z-axis are perpendicular to the wellbore. The compaction effect is directly proportional to the perforation spacing $h(= 1/np)$ and inversely proportional to the perforation length l_p . The longer the perforation and the higher the perforation density, the smaller the radial flow region around the perforation. Fluid flow in this case approximates two-dimensional flow, similar to fracturing wells. In such a scenario, the damage zone can be neglected, and the results discussed by Karakas and Tariq (1991) ^[9] in vertical wells are similar.

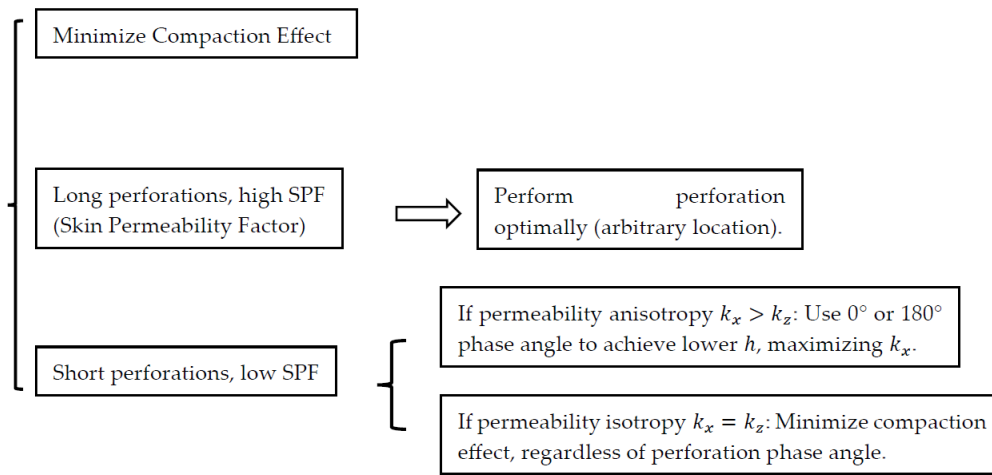


Figure 2. Process Flow for Minimizing Compaction Effect

When the perforation length and hole density are insufficient, the compaction zone significantly reduces the perforation productivity. However, if the perforation is in a highly anisotropic formation, using 0° and 180° phase angles for perforation placement can help minimize the compaction effect. For example, assuming $k/k_{cz} = 10$, $r_{cz}/r_p = 3$, $k_x = k_y = 0.01 \mu m^2$, $k_z = 0.001 \mu m^2$, $h = 304.8$ mm, and $l_p = 152.4$ mm, no formation damage occurs.

For multi-directional perforation, the skin factor due to the compaction effect can be calculated using the following formula:

$$hDe = h \cdot l_p \left(\frac{k_y k_z}{k_x} \right)^{0.5} = 1 \cdot 0.5 \cdot \left(\frac{10}{10} \right)^{0.5} = 1.12 \quad (9)$$

$$s_{cz} = hDe \left(\frac{k}{k_{cz}} - 1 \right) \ln \frac{r_{cz}}{r_p} = 1.12 (10 - 1) \ln 3 = 11.07 \quad (10)$$

For perforations at 0° and 180° phase angles along the vertical direction, the compaction skin factor can be reduced by approximately 40%. Aligning the perforation direction with the direction of minimum permeability increases the effective perforation length, thereby reducing the skin factor.

3. Performance of Slotted Liner (Perforated Liner)

In most cases, the wellbore of horizontal wells in sandstone reservoirs is prone to collapse or partial collapse, making open-hole completions unfeasible. To protect the wellbore, open-hole pre-liner completions are widely used. Based on previous research, the skin factor equation for slotted liners (Furui, 2005) has been derived. This equation takes into account convergence flow, slotted liner blockage, as well as the effects of formation damage and turbulence.

In this study, it is assumed that the formation collapses and tightly adheres to the liner. If the formation is sufficiently hard to form a gap around the liner, the convergence flow effect can be neglected, which also holds true in the presence of formation damage. In this case, the skin factor is the same as for open-hole completions, and the convergence flow in the slotted liner can be ignored.

According to prior research (Furui, 2005), the skin factor equation for slotted liners consists of three components: the skin factor caused by slotted liner blockage (represented by linear flow within the slotted liner, denoted by subscript l), the skin factor caused by convergence flow (denoted by subscript r), and the formation damage skin factor s_{fo} . Therefore, the skin factor equation can be written as:

$$s_{SL} = s_{fo} + s_{0SL,l} + \frac{k}{k_s} s_{0SL,r} + (f_{t,SL,l} + \beta_s f_{t,SL,r}) F_{o,w} \quad (13)$$

Where s_{fo} is derived from the general Hawkins formula for homogeneous media (Hawkins, 1956) or the generalized Hawkins formula for heterogeneous media (Furui et al., 2005). The dimensionless skin factor for convergence flow $s_{0SL,r}$ and $f_{t,SL,r}$ increase due to severe permeability reduction k/k_s (where β_s is a function of permeability).

For low-production wells/injection wells ($F_{o,w} < 0.1$) and formations where severe permeability reduction is not observed ($k_s/k \approx 1$), the total skin factor is given by:

$$s_{SL} = s_{0SL,r} \quad (\text{Slotted Liner Open}) \quad (14)$$

$$s_{SL} = s_{0SL,l} + s_{0SL,r} \quad (\text{Slotted Liner Blocked}) \quad (15)$$

Assuming that the skin factor due to convergence flow $s_{0SL,r}$ is approximately 1, and the skin factor caused by slotted liner blockage $s_{0SL,l}$ is approximately 5, the total skin factor for an open slotted liner is relatively small ($s_{SL} = 1$), while the total skin factor for a blocked slotted liner is moderate ($s_{SL} = 6$).

For some damaged formations ($k_s/k > 1$), the skin factor becomes:

$$s_{SL} = s_{fo} + \frac{k}{k_s} s_{0SL,r} \quad (\text{Slotted Liner Open}) \quad (16)$$

Assuming $k_s/k = 0.2$, $r_s/r_w = 2$, the total liner skin factor is 7.8, while the skin factor for an open-hole completion in the same formation is 2.8. To reduce the damage effects in liner completions, it is necessary to optimize the slotted liner design and provide the permissible slotted area, which is determined by the mechanical properties of the liner, resulting in $s_{0SL,r} \approx 0$. Measures such as formation damage removal (e.g., acidizing) can

also restore permeability in damaged formations. For blocked slotted liners, the total skin factor under the given formation conditions is 12.8.

For high-production wells ($F_o, w > 0.1$), additional skin factors due to turbulence effects must be considered. This effect is more significant in gas wells. Assuming the turbulence conversion factor due to convergence flow is $f_{t,SL,r} = 20$, and the turbulence skin factor due to slotted liner blockage is $f_{t,SL,l} = 200$, with $F_o, w = 1$, the total skin factor for an undamaged formation with an open slotted liner is:

$$s_{SL} = s_{0SL,r} + f_{t,SL,r} F_o, w = 1 + 20 \times 0.1 = 3 \quad (17)$$

For a closed slotted liner:

$$s_{SL} = s_{0SL,l} + s_{0SL,r} + (f_{t,SL,l} + f_{t,SL,r}) F_o, w = 5 + 1 + (200 + 20) \times 0.1 = 28 \quad (18)$$

Clearly, the turbulence effect in liner completions is substantial, especially when the slotted liner is blocked. When there is formation damage, the skin factor increases. The total skin factor for an open slotted liner is 21.4, and for a blocked slotted liner, the total skin factor is 46.4 (assuming $\beta_s/\beta \approx 6.8$). In the earlier example, the formation damage effects and turbulence effects in liner completions are significant. For formations with severe permeability damage, a perforated casing completion is more suitable, as the perforations can penetrate the damaged zone and create a flow path through the damaged area, reducing the impact of formation damage.

4. Case Study — Slotted Liner Design

In the development of heavy oil reservoirs in the North Slope of Alaska, a methodology was applied to analyze the effectiveness of existing completion designs and hardware. The current completion design is used for horizontal and multi-branch wells, with each branch equipped with a non-sand control slotted liner. The reservoir consists of unconsolidated fine-grained sandstone with unconfined compressive strength ranging from 0.345 to 13.8 MPa, and at a reservoir temperature of 41.6°C, the reservoir fluid has an API gravity of 16° to 20°. Sand production management (limited sand control) is employed as the preferred sand control strategy (Burton et al., 1998). Oil fields and wells in the same region have shown increased productivity and higher economic benefits through sand production management rather than traditional sand control techniques.

Considering the potential collapse between the slotted liner and the open hole, it is assumed that the slotted liner is unobstructed, allowing solids to flow out with the formation fluid. The initial design used a 114.3 mm liner with slotted openings of 6.35 mm × 63.5 mm arranged in a staggered pattern, with a slotted density of approximately 52 slots per meter, covering 5.9% of the flow area. By analyzing the convergence flow towards the slotted liner, the optimized slotted liner type and density were determined to provide a low skin factor and high flow efficiency.

The skin factor model discussed in this paper was applied to calculate the required slotted liner width to avoid blockage from convergence flow, thereby optimizing the slotted liner design. By altering the shape and density of the slots, the convergence flow skin factor was

significantly reduced. When the slotted width was reduced from 6.35 mm to 3.175 mm and the slot density was increased from 52 to 104 slots per meter, the convergence flow skin factor decreased from 1.3 to 0.6. This reduction in the skin factor was applied to the inflow dynamic equation, which calculated the improvement in well flow efficiency (WFE) as $Q_{now}/Q_{original}$. The simulation also determined the sensitivity of WFE to permeability damage. This simulation helps expand the applicability of the wellbore, including near-wellbore flow stimulation (unconsolidated wellbore) and restrictive flow (formation damage and collapse). Assuming that the permeability of the collapsed zone is equal to the reservoir permeability, the new design reduced the convergence flow skin factor by 50%. In all cases studied, the non-Darcy flow skin effects in the heavy oil reservoir were not significant.

The calculations show that, under the above completion conditions, improving the slotted liner structure by maintaining more and narrower slots increases well flow efficiency by 0% to 8%. The improvement depends on the permeability of the collapsed zone around the slotted liner. Slotted liner manufacturers are more concerned with the feasibility and cost of the new liner (which improves slotted structure and density). They are willing to produce optimized designs without increasing investment, as the new design maintains the same flow area as the original design, ensuring mechanical integrity. As a result, manufacturers adopt optimized slotted spacing and density to improve well flow efficiency and achieve a lower skin factor. The new slotted liner design was applied in the field without mechanical failure.

5. Conclusions

This paper introduces the process of optimizing horizontal well completions using an accurate skin factor analytical model. It discusses several key parameters that influence horizontal well completion performance, such as reservoir permeability, permeability anisotropy, fluid properties, formation damage effects, and rock mechanical properties. The paper demonstrates the process of optimizing slotted liner designs for horizontal wells through case studies. The main conclusions of this study are:

1. Perforated casing completions are suitable for damaged formations with severe permeability reduction, even when all perforations terminate within the damaged zone. The formation damage effect of perforated casing completions is lower than that of open-hole and slotted liner completions when effective perforation is used ($s_{0p} < 0$).
2. The compaction effect around perforations should not be neglected, especially when perforation length and density are insufficient. However, perforating with a 0° or 180° phase angle aligned with the direction of minimum permeability can reduce the skin factor in anisotropic formations.
3. Slotted liner blockage generates a substantial skin factor in high-production wells.
4. Permeability damage around perforations increases the convergence flow skin factor, unless the formation is sufficiently hard to create a gap around the liner.
5. The skin factor model presented in this paper was applied to optimize the slotted liner design for heavy oil reservoirs in the North Slope of Alaska. The new slotted liner design reduced the convergence flow skin factor by 50%.

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