MODEL FOR DETERMINING TOTAL SKIN IN HORIZONTAL WELLS COMPLETED WITH SLOTTED LINERS

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ABSTRACT
The installation of slotted liners in horizontal wells controls formation sand production and prevents damage to installed downhole and surface facilities. Howbeit, while mitigating sand production, slotted liners also create skin problems when formation fines plug the slots, causing flow convergence and turbulence. These problems create additional pressure drop around the wellbore and, thus, reduction in production. A new analytical skin model is developed to account for the total skin slotted liners that incorporates distance between slots. Moreover, the effects of skin on flow rate, slot penetration ratio, slot width, distance between slots, wellbore radius, and slot length were also investigated. Results from this model show good agreement when validated with existing models. With an application illustrated in this paper, this model can be used in the optimization of slotted liner designs.

KEYWORDS
Skin; horizontal wells; slotted liner; distance between slots; fines plugging

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1. INTRODUCTION

Horizontal wells can be completed as open hole with slotted liners, liners with external casing packer and cemented and perforated liners. Open-hole completion is used for stable consolidated formations that will not collapse when the well is put on production. Consequently, sanding, water and gas coning tendencies are common, since this completion design allows no contingency for shutting off unwanted production. As a result, slotted liners are installed to provide necessary obstruction to sand production (Tang et al., 2006).

Liners can equally help in the mitigation of sand production when appropriate slot width sizes are selected during production. Although, liners are very useful in sand control, they create pressure drop due to flow convergence around slots during production which is measured through skin (Zhang et al., 2014). Mahmoudi et al (2016a) studied criteria for slotted liner design for heavy oil thermal production and conducted several large-scale sand retention tests to refine the criteria used for slotted liner design. Fattahpour et al (2020) investigated the parameters that influence sand control performance such as particle size distribution, flow rates, slotted opening size and slot density. Their work gives us an improved understanding of the role of slot width and slot density in sand control for thermal heavy oil production applications. Mahmoudi et al (2016b) developed a model based on slot width, slot density and spatial distributions of slots, and near liner permeability. This model incorporates spatial plugging of slots and is validated using experimental sand retention data. However, no good match was obtained between experimental data and analytical model for narrow slots and high flow rate wells.

Skin is a dimensionless factor calculated to evaluate the production efficiency of a well by comparing actual condition against theoretical or ideal condition. The concept of skin has been interpreted in a wide sense to account mathematically for any deviation of flow and pressure field in the near-well vicinity from the perfect radial flow to the wellbore (Furui et al., 2005). Skin can be caused by some factors like formation damage, partial completion, well deviation, non-darcy effects, and drainage shape and position of well in the reservoir (Yildiz, 2008). The development of horizontal wells has further complicated the concept of skin because the impact of skin factor on the overall productivity depends greatly on well configuration and reservoir geometry (Furui et al., 2005). This creates the need to investigate different skin factor models in slotted liners in horizontal wells to understand which one can better predict skin in horizontal wells. In this work, an analytical model for calculating skin in horizontal wells completed with slotted liners is developed to effectively account for the skin factor.

2. METHODOLOGY

The analytical model was developed under the following assumptions:
a) The flow is horizontal and, thus, effect of gravity is negligible;
b) Flow path is non-tortuous;
c) Radius of liner equals to wellbore radius;
d) Reservoir is isotropic;
e) The slots are symmetrically arranged on the horizontal liners;
f) Flow rate is high enough to create turbulent flow.

2.1 Rate independent skin, SRI and Turbulence scale factor, $T_f$

Following the above assumptions, Darcy law is appropriate to describe a system in laminar flow as:

$$\frac{\delta p}{\delta x} = \frac{q\mu}{kA(x)}$$  \hspace{1cm} (1)

Where $q$ is flowrate (bbl/d), $k$ is permeability (mD), $\mu$ is viscosity (cp), $p$ is pressure (psia), $A$ is open flow area as a function of flow path coordinate, $x$. However, at high velocities, flow is non-laminar and must be accounted for as a deviation from Darcy flow. To account for non-Darcy flow, a deviation factor is incorporated into Equation (1) as:
Where $\beta$ is turbulence factor, $\rho$ is density, and $\beta \rho \left( \frac{q}{A(x)} \right)^2$ is Forchheimer’s number and can be expressed in oilfield units as:

$$N_F = \frac{\beta \rho k}{\mu} \left( \frac{q}{2\pi \nu L} \right)$$  \hspace{1cm} (3)

From Equations (1) and (2), the difference between the Darcy flow and non-Darcy flow is the presence of turbulent factor $\beta \rho \left( \frac{q}{A(x)} \right)^2$, which accounts for the extra pressure drop due to turbulence. The change in pressure drop between Darcy and non-Darcy can be expressed mathematically as (Furui et al., 2005):

$$\Delta P_s = \int_{x_0}^{x_1} \frac{q \mu}{kA(x)} \, dx + \int_{x_0}^{x_1} \beta \rho \left( \frac{q}{A(x)} \right)^2 \, dx - \int_{x_0}^{x_1} \frac{q \mu}{kA(x')} \, dx'$$  \hspace{1cm} (4)

Where $\Delta P_s$ is change in pressure due to skin (psi), $\beta$ is turbulence factor, $\rho$ is density (lb/cuft). Total pressure drop due to skin can be calculated as (Hawkins, 1956):

$$\frac{q \mu}{2\pi L S} = \frac{q \mu}{k} \left( \int_{x_0}^{x_1} \frac{dx}{A} - \int_{x_0'}^{x_1'} \frac{dx'}{A} \right) +$$

$$\beta \rho q^2 \int_{x_0}^{x_1} \frac{dx}{A^2}$$  \hspace{1cm} (5)

Simplifying equation 5, the skin factor can be expressed as:

$$S = 2\pi L \left( \int_{x_0}^{x_1} A^{-1} \, dx - \int_{x_0'}^{x_1'} A^{-1} \, dx' \right) +$$

$$+ \left( \frac{\beta \rho k}{\mu} \right) (2\pi L q) \int_{x_0}^{x_1} A^{-2} \, dx$$  \hspace{1cm} (6)

Incorporating Forchheimer’s number into equation (6), and converting the flow area $A$ and flow path coordinate $x$ as dimensionless parameters, total skin can be expressed as:

$$S_T = \left( \int_{x_{D_0}}^{x_{D_1}} A_D^{-1} \, dx_D - \int_{x_{D_0}'}^{x_{D_1}'} A_D^{-1} \, dx'_D \right) +$$

$$+ \left( \int_{x_{D_0}}^{x_{D_1}} A_D^{-2} \, dx_D \right) N_F$$  \hspace{1cm} (7)

Hence, in a compact form, the total skin equation (7) can be expressed as:

$$S_T = S_{RI} + T_I N_F$$  \hspace{1cm} (8)

Where:

$$S_{RI} = \int_{x_{D_0}}^{x_{D_1}} A_D^{-1} \, dx_D - \int_{x_{D_0}'}^{x_{D_1}'} A_D^{-1} \, dx'_D$$  \hspace{1cm} (9)

and

$$T_I = \int_{x_{D_0}}^{x_{D_1}} A_D^{-2} \, dx_D$$  \hspace{1cm} (10)

$S_{RI}$ is rate independent skin, $T_I$ is turbulence scale factor, and $A_D$ is dimensionless area. If the permeability in actual conditions varies due to formation damage, then, in a dimensionless form; rate-independent skin and turbulence scale factor can be estimated using:

$$S_{RI} = \int_{x_{D_0}}^{x_{D_1}} K_D^{-1} A_D^{-1} \, dx_D - \int_{x_{D_0}'}^{x_{D_1}'} A_D^{-1} \, dx'_D$$  \hspace{1cm} (11)

and

$$T_I = \int_{x_{D_0}}^{x_{D_1}} \beta_D A_D^{-2} \, dx_D$$  \hspace{1cm} (12)

### 2.2 Modeling of skin factor in slotted liner

Modeling skin factor in slotted liners requires accounting for linear flow inside slots and radial flow caused by multiple slots on the liner. These factors are functions of variables such as flow area, distance between slots, slot width, slot length, slot penetration ratio, length of liner and number of slots around the circumference of the liner. Figure 1 is a schematic of slotted liner showing the slot width (ft), slot length (ft), distance between slots (ft), number of slots around circumference (slots) and wellbore radius (ft).

When slots are arranged symmetrically, linear flow into slots occurs. Thus, the flow area for linear flow into the liner can be estimated using:

$$A = n_s \ell_{sl} w_s \ell_s$$  \hspace{1cm} (13)

Where $n_s$ is number of slots per unit, $w_s$ is slot width, $L$ is length of liner (ft), and $\lambda_s$ is the slot penetration ratio. The number of slots around the circumference of a liner can be determined by using:
Where \( w_s \) is slot width (ft), \( d_s \) is distance between slots (ft), and \( r_w \) is wellbore radius (ft). Substituting equation (14) into (13) gives:

\[
A = n_s \times \frac{2\pi r_w}{w_s + d_s} \times w_s \times L \times \lambda_s
\]

(15)

Defining dimensionless slot width as \( w_{sD} = \frac{w_s}{r_w} \), the dimensionless flow area can be calculated as:

\[
A_D = n_s \times \frac{2\pi r_w}{w_s + d_s} \times w_{sD} \times L \times \lambda_s \times \frac{1}{2\pi r_w L}
\]

(16)

Simplifying equation (16), the dimensionless flow area can be expressed as:

\[
A_D = n_s \frac{w_{sD} \lambda_s}{d_s + w_s}
\]

(17)

Defining dimensionless thickness of liner \( h_{sD} \) as \( h_{sD} = \frac{h_s}{r_w} \), and assuming \( k_1 \) to be permeability and \( \beta \) to be turbulent factor inside the slots in linear flow, the flow area of liner is integrated into rate independent skin factor and expressed as:

\[
S_{RII} = \int_{x_{D1}}^{x_{D2}} \frac{dA_D}{k_D A_D} = \int_0^{L_{D1}} \left[ \frac{k}{n_s w_{sD} \lambda_s} \right] dx_D = \frac{(W_{sD} + d_s)}{(n_s w_{sD} \lambda_s)} \left( \frac{k}{k_D} \right) h_{sD}
\]

(18)

and turbulence scale factor as:

\[
T_{II} = \int_{x_{D1}}^{x_{D2}} \frac{\beta_D dx_D}{A^2} = \left( \frac{w_{sD} + d_s}{n_s w_{sD} \lambda_s} \right)^2 \left( \frac{\beta_D}{\beta} \right) h_{sD}
\]

(19)

### 2.3 Radial flow caused by multiple slots on the liner

Like linear flow, radial flow also occurs in completions with multiple slotted liners. The area of liner for radial flow was calculated considering the number of slots around the circumference. Using equation (13), the area of liner for radial flow can be estimated as:

\[
A = n_s \times \frac{2\pi r_w}{w_s + d_s} \times L \times \lambda_s \times \frac{1}{2\pi r_w L}
\]

However, for radial flow, the dimensionless thickness is defined as:

\[
h_D = h_1 r_D + h_2
\]

(22)

Where \( h_1 = 2(1 - \lambda) \), and \( h_2 = l_{sD} \).

Integrating Equation (21) with respect to the dimensionless radius gives:

\[
\int_{r_{D1}}^{r_{D2}} \frac{dr_D}{A_D} = \frac{(W_{sD} + d_s)}{n_s w_{sD} \lambda_s} \int_{r_{D1}}^{r_{D2}} \frac{dr_D}{r_D h_D}
\]

(23)

Integrating the right hand of equation (23) and substituting for \( h_D \) gives:

\[
\int_{r_{D1}}^{r_{D2}} \frac{dr_D}{r_D h_D} = \frac{W_{sD} / 2n_s}{r_D (h_1 r_D + h_2)} = \frac{1}{h_2} \left[ \ln \left( \frac{h_1}{h_1 + h_2 / r_D} \right) \right]^{W_{sD} / 2n_s}_{r_D / 2n_s} = \left( \frac{1 - \lambda + 2 l_{sD} / W_{sD}}{1 - \lambda + n_s l_{sD} / W_{sD}} \right)
\]

(24)

Hence, the rate-independent skin for radial flow becomes:
Also, for radial flow area, turbulence scale factor becomes:

\[
T_f = \int_{r_d}^{r_0} \frac{dr}{A_D} = \frac{w_a + d_a}{n_a r_a \pi} \times \left[ \frac{1}{I_{SD}} \ln \left( \frac{1 - \lambda + 2 l_{SD}/w_{SD}}{1 - \lambda + n_d l_{SD}/w_{SD}} \right) \right]
\]  
(26)

Therefore, the total skin factor for slotted liners can be expressed as:

\[
S_{SLT} = S_{RIT} + T_{IT}
\]  
(27)

Where \( S_{SLT} \) is total skin for slotted liners, \( S_{RIT} \) is total rate-independent skin, and \( T_{IT} \) is total turbulence scale factor.

3. RESULTS AND DISCUSSION

Results obtained from the models are presented and discussed in this section. Figure 2 shows the effect of flow rate on skin factor for different wellbore radii in slotted liner. As can be seen in Figure 2, skin is directly proportional to flow rate and inversely proportional to wellbore radius. This frequently is experienced in high flow rate oil and gas wells as an extra pressure drop generated by the turbulence associated with high flow rates (Furui et al., 2005). The smaller the wellbore radius, the higher the skin and vice-versa.

Figure 3 shows the effect of different slot widths on skin. From Figure 3, one can observe that a linear relationship exists between skin and various sizes of slot widths. Smaller slot widths give higher skin values if compared to bigger slot widths; this is attributed to flow convergence around the slots. However, one can observe that there is an optimum slot width, which is 0.002 ft, beyond which skin cannot be reduced further but only high level of skin is obtained (Yujia et al., 2020).

In Figure 4, the effects of distance between slots are investigated. Figure 4 shows that the skin factor tends to decrease as the distance between slots decreases. Hence, more pressure drop would need to be overcome due to flow convergence of fluid from formation caused by fewer slots on the liner. Apparently, larger slot distances lead to partial plugging of slots as the formation fluid finds its way to the wellbore at a higher pressure (Furui et al., 2005). This can cause increased pressure drop due to partial plugging (skin).
The effect of various penetration ratios on skin for slotted liners is shown in Figure 5. As the slot penetration ratio increases from 1.5 to 3, there is a decrease in skin at the same flow rate. Obviously, slot penetration ratios have substantial influence on skin factor, and low slot penetration ratio can lead to high skin factor (Furui et al., 2005).

3.1 Validation

A validation was carried out with existing models, as shown in Figure 6, to investigate the accuracy of the model developed. Figure 6 is a comparative plot of skin factor against wellbore radius between the model developed in this work and other works. As one can observe in Figure 6, all models gave a skin factor value of zero between 1.5 and 0.8ft wellbore radius. From below 0.8ft wellbore radius up until a wellbore radius of about 0.2ft, the model validation is in good agreement. The level of agreement is also depicted in the relative error analysis in Table 1, with a mean relative error of 14.59%.

3.2 Applications

This section shows how the model developed in this work can be applied in slotted liner
completions. Table 2 shows the data used for illustrating the application.

Suppose that a slotted liner data shown in Table 2 is installed in an isotropic formation of \( k = 150 \text{ md} \), \( \beta = 1.687 \times 10^8 \), oil density= 53 lb/ft, oil viscosity= 2.5 cp, then, the number of slots per foot can be calculated as:

\[
S_n = \frac{A_s}{w_f L_r} = \frac{(2 \times \pi \times 0.5) \times 0.0147}{0.003 \times 0.3} = 51 \text{ slots/ft} \quad (28)
\]

The number of slots around a circumference of the liner is obtained as:

\[
n = \frac{w_f L}{2 \pi A_s}
\]

Table 2 shows the data used for illustrating the application.

| Wellbore radius(ft) | Furui et al., 2007 = \( A \) | This model = \( B \) | \( \frac{|B - A|}{A} \times 100 \) |
|---------------------|-----------------------------|-----------------|-----------------|
| 0.2                 | 17.74201                    | 12.60179        | 28.972          |
| 0.3                 | 10.41403                    | 8.182192        | 21.431          |
| 0.5                 | 6.433042                    | 4.982309        | 22.551          |
| 0.8                 | 0                           | 0               | 0               |
| 1.5                 | 0                           | 0               | 0               |

\[
\sum_{i=1}^{n} \frac{(B - A)}{A} = 72.954
\]
The slot unit length in inches is calculated as:

\[ L_{us} = \frac{12}{(N_s/M_s)} = \frac{12}{(51/12)} = 2.8in, \quad (30) \]

The slot penetration ratio is given as:

\[ \lambda = \frac{L_s}{L_u} = \frac{3.6}{2.8} = 1.3 \quad (31) \]

The dimensionless slot length can be calculated as:

\[ L_{sd} = \frac{L_s}{r_w} = \frac{0.3}{0.5} = 0.6, \quad (32) \]

While dimensionless slot width is obtained as:

\[ w_{sd} = \frac{W_s}{r_w} = \frac{0.003}{0.5} = 0.006 \quad (33) \]

Assuming that the slot arrangement is a single inline slot; number of slots per unit is 1, i.e: \( n_{Ps} = 1 \), and \( w_{sd} = w_{uD} \). Also, assuming the slots are filled with formation fines, the linear flow component through the plugged slot must be considered. The depth of partial plugging is assumed to be 0.15in, then, the dimensionless partial plugging depth can be estimated as:

\[ h_{sd} = \frac{t_s}{r_w} = \frac{0.15}{0.5} = 0.3 \quad (34) \]

Therefore, skin factor for linear flow will be:

\[ S_{Rli} = \left( \frac{w_s + d_s}{n_s w_s A_s} \right) t_{sd} = \left( \frac{0.003 + 0.259}{1 \times 0.003 \times 1.3} \right) \times 0.3 = 20.154 \quad (35) \]

Where \( S_{Rli} \) is skin for slotted liner due to linear flow, \( W_s \) is slot width, \( d_s \) is slot distance (spacing), number of slots per slot unit, and \( A_s \) is slot penetration. Turbulence scale factor for linear flow can also be calculated as:

\[ T_{fl} = \left( \frac{w_s + d_s}{n_s w_s A_s} \right)^2 t_{sd} = \left( \frac{0.003 + 0.259}{1 \times 0.003 \times 1.3} \right)^2 \times 0.3 = 135.925 \quad (36) \]

For the radial flow component of skin factor, the rate independent skin is estimated as:

\[ S_{Rir} = \frac{(w_s + d_s) r_{sd}}{n_s r_w A_R} \times \left[ \frac{1}{L_{sd}} \ln \left( \frac{1 - \lambda + 2L_{sd}/w_{sd}}{1 - \lambda + n_{sd} L_{sd}/w_{sd}} \right) \right] = \left( \frac{0.003 + 0.259}{1 \times 0.003 \times 1.3} \right) \times \left( \frac{1 - 1.3 + 2 \times 0.6}{1 - 1.3 + 0.006} = 0.089 \quad (37) \right. \]

and the turbulence scale factor as:

\[ T_{fr} = \left( \frac{w_s + d_s}{n_s r_w A_R} \right)^2 \times \left[ \frac{1 - L_{sd}/w_{sd}}{1 - L_{sd}/w_{sd}} \right] = \left( \frac{0.003 + 0.259}{1 \times 0.003 \times 1.3} \right)^2 \times \left[ \frac{1 - 1.3 + 0.006 / 0.259}{1 - 1.3 + 0.006} \right] + \frac{4}{1 - 1.3} \times \frac{2 \times 1}{0.006} - 4(1 - 1.3) - \frac{2 \times (1 - 1.3)}{1 - 1.3 \times 0.006} \right) \]

\[ = -3.3031 \quad (38) \]

The Forchheimer number is calculated using:

\[ N_F = 1.64 \times 10^{-16} \frac{\beta plk}{\mu} \left( \frac{q}{r_w} \right) \quad (39) \]

\[ N_F = 1.64 \times 10^{-16} \times \frac{1.667 \times 10^8 \times 53 \times 150}{0.5 \times 2.5 \times 2500} q = 0.00000007 q \quad (40) \]

Where \( \beta \) is turbulence factor, \( \rho \) is oil density in lb/ft\(^3\), \( k \) is permeability(mD), \( \mu \) viscosity (cp), \( q \)
flowrate (bbl/d), and L length (ft) at an oil production rate of 10000bbl/d. Substituting values gives Forchheimer’s number as:

\[ N_F = 0.00000007 \times 10000 = 0.0007 \]  
\[ (41) \]

For plugged slots, the total rate-independent skin factor is obtained by summing the rate-independent skin for linear and rate-independent skin for radial flows. As such, the total rate-independent skin factor for plugged slots becomes:

\[ S_{RIT} = S_R + S_{RIF} = 20.1 + 0.089 = 20.242 \]  
\[ (42) \]

Also, the total turbulence scale factor is obtained by summing both turbulence scale factors in radial and linear flows, which is calculated as:

\[ T_{IT} = T_R + T_{IF} = 1353.9350 + (-3.3031) = 1350.6219 \]  
\[ (43) \]

Hence, the total skin factor for plugged slots becomes:

\[ S_{SLT} = 20.242 + 1350.6219 \times 0.0007 = 21.1874 \]  
\[ (44) \]

For open slot, the total skin factor becomes:

\[ S_{SLT} = S_R + T_R = 0.089 + (-3.3031) \times 0.0007 = 0.0867 \]  
\[ (45) \]

4. CONCLUSION

This work presents a new analytical model developed for calculating total skin factor in horizontal wells completed with slotted liners. The model incorporates linear and radial flows into the slots for calculating the total skin in slotted liners. Various slot parameters that can affect flow due to their impact on skin were also investigated to show how each variable contributes to an improved performance of horizontal wells completed with slotted liners. The model was validated with an existing model and showed very good agreement. Moreover, the application of this model was also demonstrated in this work for professionals for ease of application in the industry.

NOMENCLATURE

\[ N_F = \text{Forchheimer’s number} \]
\[ T_{IT} = \text{Turbulence scale factor} \]
\[ S_{RIT} = \text{Rate-independent skin factor} \]
\[ S_{SLT} = \text{Total skin factor for slotted liner} \]
\[ r = \text{radial flow} \]
\[ l = \text{linear flow} \]
\[ r_0 = \text{dimensionless radius} \]
\[ A_0 = \text{dimensionless flow Area} \]
\[ l_s = \text{slot length} \]
\[ W_s = \text{slot width} \]
\[ Q = \text{flow rate (bbl/d)} \]
\[ \beta = \text{turbulence factor} \]
\[ \lambda = \text{penetration ratio} \]
\[ A_s = \text{open slot area of liner per foot (ft²/ft)} \]
\[ S_p = \text{number of slots per foot} \]
\[ M_s = \text{number of slots around circumference (slot)} \]
\[ l_{us} = \text{slot unit length (in)} \]
\[ W_{sd} = \text{dimensionless slot width} \]
\[ l_{usd} = \text{dimensionless slot length} \]
\[ n_{ps} = \text{number of slots per slot unit} \]
\[ d_s = \text{distance between slots(ft)} \]
\[ \rho = \text{density (lbs/cuft)} \]
\[ k = \text{permeability (Md)} \]
\[ \mu = \text{viscosity (cp)} \]
\[ x = \text{flow path(ft)} \]
\[ \Delta P = \text{change in pressure drop (psi)} \]
\[ S = \text{Skin factor} \]
\[ P = \text{Pressure (psi)} \]
\[ l = \text{Linear flow} \]
\[ \Delta P_s = \text{change in pressure due to skin (psi)} \]

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