EFFECT OF PERFORATION PARAMETERS ON THE PRODUCTIVITY OF GEOTHERMAL WELLS

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ABSTRACT

In 2016 Pásztor and Schultz¹ published a new method for calculating the perforation design’s effect on the inflow of hydrocarbon wells. According to their results the different perforation parameters have a considerable impact on the productivity. As the PVT properties of the thermal water (density, formation volume factor and viscosity) differ from the oil’s, the behavior of their flow is also different. Because of this difference we investigated the effect of the perforation design on the inflow of geothermal wells, with the method of Pásztor and Schultz.

INTRODUCTION

Geological background

Natural conditions in Hungary are very favorable for geothermal energy production and use. The terrestrial heat flow is rather high (~0.09 W/m²) and the geothermal gradient is higher than the continental average (~0.05 °C/m). Pannonian sediments are multilayered, composed of sandy, shaly, and silty beds. The lower Pannonian sediments are mostly impermeable; the upper Pannonian and Quaternary formations contain vast porous, permeable sand and sandstone beds. Their individual sandy layers are up to 30 m thick. They don’t extend very far horizontally, but their sand lenses connect to form a hydraulically unified system. This Upper Pannonian aquifer has an area of 40,000 km², an average thickness of 200-300 m, a bulk porosity of 20-30%, and a permeability of 500-1,500 mD. The hot water reservoir has an almost uniform hydrostatic pressure distribution, although local recharge or discharge can slightly modify this pattern.

It has been proved that significant numbers of the geothermal wells in Hungary produce from many different aquifer-layers using many drilling sites.

Perforation design

Steel casings are set to prevent ground water contamination and the fracturing of subsurface layers during the drilling of a well. If the reservoir rock can withstand the stress resulting from the pressure differential which develops during the production, then the reservoir fluid can be produced from the open hole. This is the so called open hole completion. However, in most cases the reservoir cannot

DOI: 10.26649/musci.2017.002
tolerate large stresses; therefore the use of a production casing - which must be perforated - is inevitable. In this case, the produced fluid flows through the perforation channels before entering the well. This is why the investigation of the effect of perforation parameters on a given well’s productivity is very important. Perforations are created with an instrument usually referred to as a perforating gun, which is filled with explosives. After positioning and activating the gun at the desired depth, holes are punched in the casing or liner of a well. The amount of explosive which can be used in the perforating gun is limited. Thus the volume of the perforation channels is limited as well.

The parameters of the perforation geometry are presented in Figure 1. The parameters with their notations used in this study are the following: perforation channel length (L_p), radius of the perforation channel (r_p), radius of the crushed zone (r_c), shot density (n_s), and phase angle (Θ). The crushed zone, a thin layer around the perforation channel with decreased permeability, is formed during the perforating process.

![Figure 1: Perforation parameters](http://www.halliburton.com/public/lp/contents/Books_and_Catalogs/web/TCPCatalog/2005TCPcatalog/PerforatingSolutions_catalog.pdf)

**Properties of the thermal water**

For these calculations, the density (ρ_w), viscosity (μ_w) and the formation volume factor (B_w) of the water had to be known. The reservoir pressure, temperature and the water salinity were assumed to be the following:

\[ p_r = 2900 \text{ psi} \]
\[ T_r = 635.67 \, ^\circ R \]
\[ S = 15 \text{ wt\%} \]

For the calculations the McCain^2,3 correlations were used:

\[ \mu_{w1} = A T_r^{\frac{B}{2}} \]  \hspace{1cm} (1)

\[ A = 109.574 - 8.40564 \times S + 0.313314 \times S^2 + 8.72213 \times 10^{-3} \times S^3 \]  \hspace{1cm} (2)
\[
B = 1.12166 - 2.63951 \times 10^{-2} \times S + 6.79461 \times 10^{-4} \times S^2 + 5.47119 \times 10^{-5} \times S^3 \\
- 1.55586 \times 10^{-6} \times S^4
\]  
(3)

\[
\frac{\mu_w}{\mu_{w1}} = 0.9994 + 4.0295 \times 10^{-5} \times p_r + 3.1062 \times 10^{-9} \times p_r^2
\]  
(4)

\[
\rho_w = 62.368 + 0.438603 \times S + 1.60074 \times 10^{-3} \times S^2
\]  
(5)

\[
B_w = (1 + \Delta V_{wp})(1 + \Delta V_{wt})
\]  
(6)

\[
\Delta V_{wp} = -1.0001 \times 10^{-2} + 1.33391 \times 10^{-4}T_r + 5.50654 \times 10^{-7}T_r^2
\]  
(7)

\[
\Delta V_{wt} = -1.95301 \times 10^{-9}p_rT_r - 1.72834 \times 10^{-3}p_r^2T_r - 3.58922 \times 10^{-7}p_r \\
- 2.25341 \times 10^6 - 10p_r^2
\]  
(8)

Where:

- \(\mu_{w1}\) viscosity of the water at 1 atm
- \(S\) - water salinity
- \(\mu_w\) - water viscosity at reservoir conditions

The results were as follows:

\[
\mu_{w1} = 0.587 \text{ cP}
\]

\[
\rho_w = 69.3 \frac{\text{lb}}{\text{ft}^3}
\]

\[
B_w = 1.06 \frac{\text{bbf}}{\text{STB}}
\]

THE CALCULATION MODEL

Base concept

The calculation model we used during the investigation divides the flow to the well into two sections. The reservoir fluids first flow perpendicular to the wellbore, then at some point the direction of the flow changes perpendicularly to the perforation channels. It is hard to say where the flow direction of a certain particle changes, but we can make an assumption about the “average” particle. The change of the flow direction can happen anywhere in the drainage volume of a perforation channel. Assuming normal distribution, the average particle will start to flow perpendicularly to the perforation channel at the distance from the centre of the wellbore which is half the drainage volume. The following figure represents the change of the flow direction.

![Figure 2: Change of the flow direction](image-url)
From the above-mentioned statements, it can be deduced that the final theoretical inflow performance relationship is the superposition of the perforation channels’ IPR and the IPR of the zone where the flow changes direction.

**IPR of the perforation channels**

By assuming that the skin is caused by the permeability decrement in the vicinity of the well

\[ S = \left( \frac{k}{k_s} - 1 \right) \ln \left( \frac{r_c}{r_w} \right) \]  

(9)

and by making the following changes:
- \( L_p \rightarrow h / h_p \),
- \( r_p \rightarrow r_w \),
- \( r_{pc} \rightarrow r_c \),
- \( k_c \rightarrow k_s \),
- \( r_c \rightarrow r_s \),

the turbulent and Darcy terms of a perforation channel’s inflow equation are:

\[ A_p = C_1 \times \frac{1}{L_p^2} \frac{1}{r_p} \frac{1}{r_{ep}} \]  

(10)

\[ B_p = C_2 \times \ln \left( \frac{0.472}{r_p} \frac{r_c}{r_p} \frac{1}{L_p} \left( \frac{r_{ep}}{r_p} \right)^{\frac{1-\alpha}{\alpha}} \right) \]  

(11)

Where:
- \( r_p \) - radius of the perforation channel,
- \( r_{ep} \) - radius of the perforation channel’s drainage area,
- \( L_p \) - length of the perforation channel,
- \( r_c \) - radius of the crushed zone,
- \( \alpha = \frac{k_c}{k} \),
- \( k_c \) - permeability of the crushed zone.

For the calculation of \( r_{ep} \) we must know the shape of the perforation channels’ drainage volume. When the phase angle is greater than 180°, the drainage volumes of the perforation channels restrict each other. The following figure shows the case of a 60° phase angle.

![Figure 3: Drainage area of perforation channels at their toe (Θ=60°)](image)
In the case of 180° and 360° phase angles the perforation channels limit each other’s drainage space only in the vertical direction. The horizontal boundary of their drainage space is where the flow direction will change from perpendicular to the wellbore’s axis to perpendicular to the perforation channels. The shape of these drainage volumes can be approximated as ellipsoids.

The radius of the perforation channel’s drainage area changes along and around the perforation channel because of its elliptical shape. In the calculations, an average value must be used for which the concept of “equivalent cylinder” is applied.

For Θ<180°:
The flow changes direction at the distance of \( r_{ewb} \) from the axis of the wellbore. The periphery of the ellipse at that distance (shape of the perforation channel’s drainage area on the plane which is perpendicular to the perforation channel) is:

\[
P_1 = \left( \frac{1}{ns} \right)^2 \left( \frac{360}{\theta} \right)^2 - \frac{360}{\theta} + 1 + \left( 2r_{ewb} \tan \left( \frac{\theta}{2} \right) \right)^2,
\]

\[
P_2 = 12 \left( r_{ewb} \tan \left( \frac{\theta}{2} \right) \left( \frac{1}{ns} \right) \left( \frac{360}{\theta} \right) \right)^2,
\]

\[
a_{ep} = \frac{P_1 + \sqrt{P_1^2 - P_2}}{6},
\]

\[
K_{ep} = \pi \left( \frac{3}{2} \left( a_{ep} + \frac{r_{ewb} \tan \left( \frac{\theta}{2} \right) \left( \frac{360}{\theta} \right) \left( \frac{1}{ns} \right)}{a_{ep} \sqrt{3}} \right) + \sqrt{\frac{r_{ewb} \tan \left( \frac{\theta}{2} \right) \left( \frac{360}{\theta} \right) \left( \frac{1}{ns} \right)}{\sqrt{3}}} \right),
\]

\[
r_{ep} = \frac{K_{ep}}{2\pi}.
\]

For Θ>120°:
As stated before, the shape of the perforation channels’ drainage space can be approximated as ellipsoids, with the axis lengths of \( \frac{L_p}{2} \), \( r_{ewb} \) and \( \frac{1}{2ns} \frac{360}{\theta} \). The area of an ellipsoid:

\[
A_{pdraim} = 4\pi \left( \frac{1}{2ns} \frac{360L_p}{\theta} \right)^{1.6} + \left( \frac{1}{2ns} \frac{360}{\theta} r_{ewb} \right)^{1.6} + \left( \frac{L_p}{2} r_{ewb} \right)^{1.6} \left( \frac{0.625}{3} \right),
\]

\[
r_{ep} = \frac{A_{pdraim}}{\pi L_p}.
\]

**IPR of the extended wellbore**

The flow changes direction from perpendicular to the axis of the well to perpendicular to the perforation channels between the wellbore and the end of the perforation channels. Until the point of direction change, the flow can be assumed to be like a flow to a well with an extended wellbore, with the radius of \( r_{ewb} \). The IPR equation of a well with this extended wellbore is the following:

\[
A_{ewb} = C_1 \times \frac{1}{r_{ep}^2} \left( \frac{1}{r_{ewb}} \right) A_{ewb},
\]

\[
B_{ewb} = C_2 \times \ln \left( \frac{r_{ewb}}{r_{ewb}} \right) + s_{ewb},
\]

\[
B_{ewb} = C_2 \times \frac{0.472 \left( \frac{r_{ewb}}{r_{ewb}} \right) + s_{ewb}}{h}.
\]
\[ \lambda_{ewb} = \frac{r_w}{r_{ewb}}, \]  
\[ S_{ewb} = \ln \left( \frac{r_w}{r_{ewb}} \right), \]  
(21)  
(22)  

In the case of \( \Theta < 180° \):

\[ r_{ewb} = \sqrt{\frac{r_w^2 + (L_p + r_w)^2}{2}}, \]  
(23)

For \( \Theta = 180° \):

\[ r_{ewb} = \frac{r_{dc}}{\sqrt{2}} = \frac{L_p}{\sqrt{2}} + \frac{L_p}{\sqrt{2} \pi} + \frac{2r_w}{\pi}, \]  
(24)

For \( \Theta = 360° \):

\[ r_{ewb} = \frac{L_p}{2} - \arctan \left( \frac{r_w}{L_p} \right) \frac{L_p}{2 \pi}, \]  
(25)

**Final form**

With the superposition of the previously explained effects, the final form:

- for oil production:

\[ p_r - p_{wfs} = A q_o^2 + B q_o, \]  
(26)  
\[ A = 5.359 \times 10^{-4} \frac{B^2 \rho}{k^{1.201}} \frac{1}{h^2} \left( \lambda_{ewb} + \lambda_p \right), \]  
(27)  
\[ B = 141.24 \times \frac{\mu_o \rho_o}{k} \times \frac{0.472 \left( \frac{r_w}{r_w} \right)}{h} + S_{ewb} + S_p, \]  
(28)

- for gas production:

\[ p_r^2 - p_{wfs}^2 = A q_g^2 + B q_g, \]  
(29)  
\[ A = 7.3628 \times 10^{-2} \frac{\gamma_T Z}{k^{1.201}} \frac{1}{h^2} \left( \lambda_{ewb} + \lambda_p \right), \]  
(30)  
\[ B = 1424 \times \frac{\mu_g T Z}{h} \times \frac{0.472 \left( \frac{r_w}{r_w} \right)}{h} + S_{ewb} + S_p, \]  
(31)

Where:

\[ \lambda_{ewb} = \frac{r_w}{r_{ewb}}, \]  
\[ S_{ewb} = \ln \left( \frac{r_w}{r_{ewb}} \right), \]  
\[ \frac{r_w}{r_{pe}} - \frac{r_w}{r_{ce}}, \]  
\[ \lambda_p = \frac{L_p^{2.5} S_p^2}{h}, \]  
\[ \frac{0.472 r_{pe}^2 \times \left( \frac{r_w}{r_{ce}} \right)^{1-u}}{r_{ce}}, \]  
\[ S_p = \frac{L_p^{2.5} S_p^2}{h}, \]  
(32)  
(33)  
(34)  
(35)

In the equations, \( r_{pe} \) and \( r_{ce} \) refer to the perforation channels’ radius and the radius of the crushed zone, modified according to Pasztor and Kosztin\(^4\).
EFFECT OF PERFORATION PARAMETERS ON PRODUCTIVITY

For the investigation three sensitivity tests were carried out. The following tables represent the base parameters, and the variable parameters, which were used during the calculations.

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<th>Perforation parameters</th>
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<th>Well parameters</th>
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<tbody>
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<td>r_e [ft]</td>
<td>P_r [psi]</td>
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<tr>
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<td>1000</td>
<td>2900</td>
</tr>
</tbody>
</table>

Table 1: Base parameters

Table 2: Variable parameters of the perforations

For the investigation of the effect of perforation parameters on the productivity the absolute open flow potential of the wells was calculated for each variable parameter value. The cases where the variable parameter was the perforation channels’ length are presented here. In the graphs, a dashed line represents the absolute open flow potential where there was open hole completion.

Figure 4: Effect of perforation channel length on productivity

Figure 5: Effect of shot density on productivity
CONCLUSION

The examination of the effect of perforation parameters on the productivity yielded very important results for perforation design optimization:

- The best perforation angles are 60° and 45° (with marginal difference).
- The perforation channel length has the greatest effect on the productivity and the perforation channel radius has the smallest. This result is very important because the volume of the perforation channel depends on the volume of the used explosive, which is limited, so increasing the perforation channel’s length must be the top priority.
- With a proper perforation design the productivity of a perforated well can be better than that of a well with an open hole completion.

REFERENCES

[1] Pasztor, A. & Schultz, V. “Analytical determination of the perforation design’s effect on the productivity” MOL Group Proffessional Journal 2016/1

