Analytical IPR Equation for Perforated Wells

Ádám Pásztor
Vera Schultz

Petroleum Engineering Department
University of Miskolc

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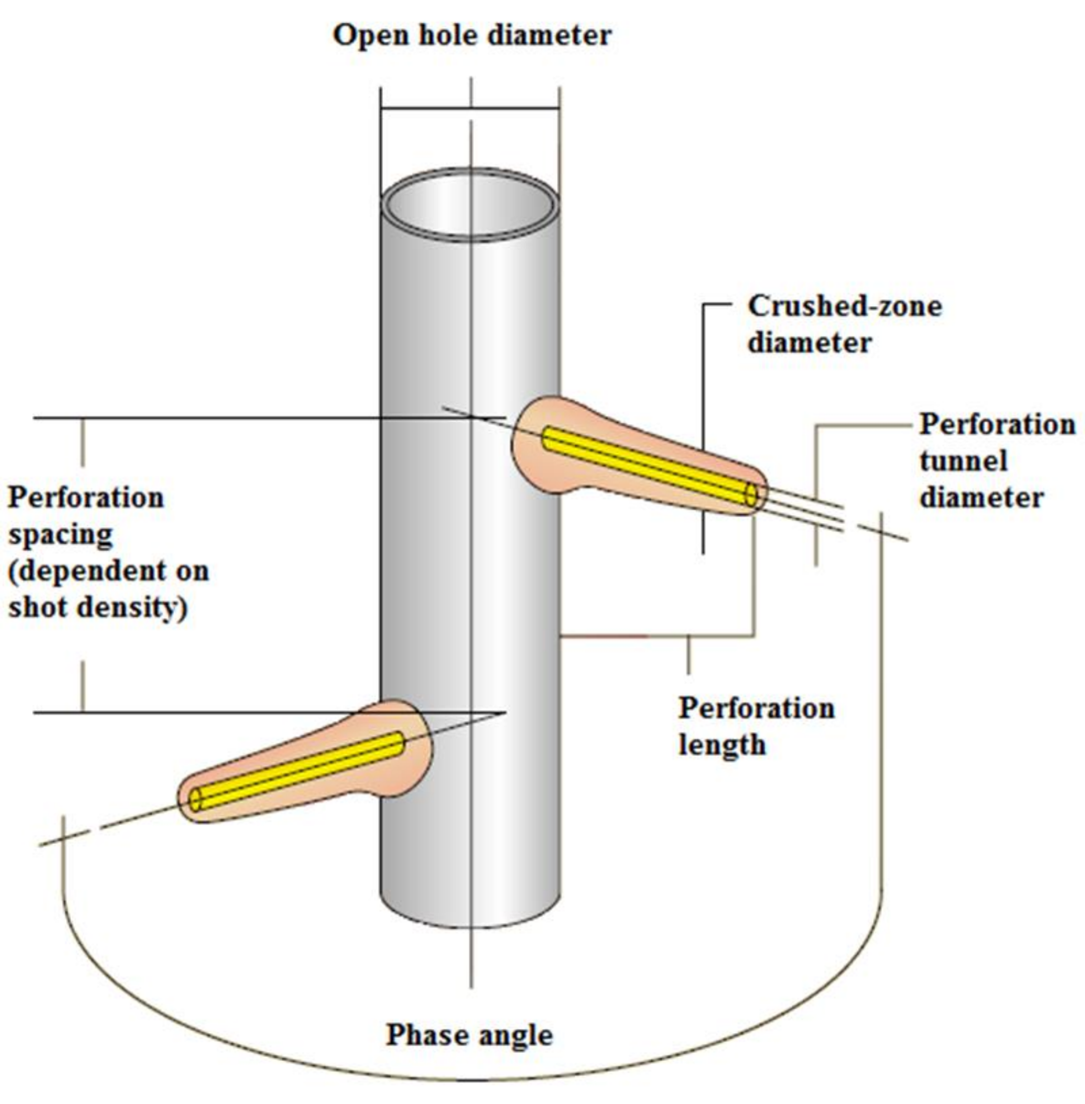
Perforation parameters



Open hole radius	r_w
Perforation tunnel radius	r_p
Crushed zone radius	r_c
Perforation length	L_p
Phase angle	Θ
Shot density	ns
$k_{crushed}/k_{res}$	α

Main questions of the perforation design

- <u>Which perforation parameter has the most importance?</u>
  - Volume of explosive is limited
  - L_p, r_w and ns are not independent from each other
- <u>Which phase angle (Θ) to chose?</u>

Methods for pressure drop calculation

Method by McLeod:

(McLeod O.H. Jr. 1983)

- Assumes that perforations are small wells and uses the Jones method for pressure drop calculation

Method by Karakas and Tariq:

(Karakas M. & Tariq S.M. 1988)

- Semi-analytical solution for perforation skin calculation

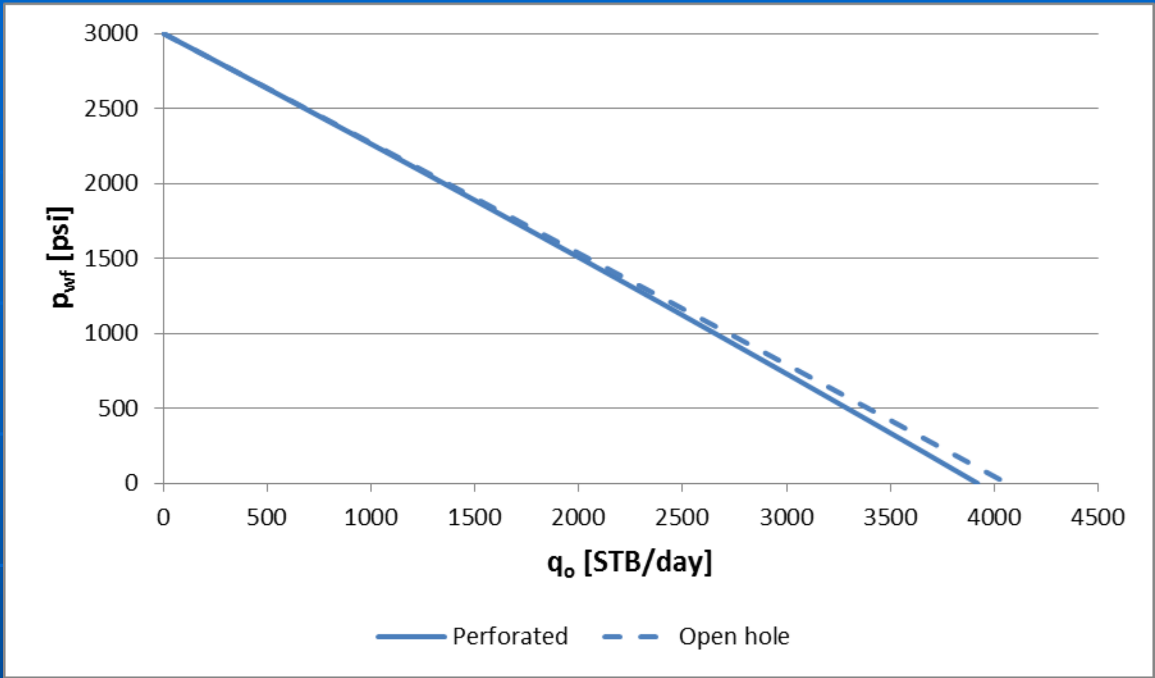
Investigation with theoretical wells!

Data of theoretical wells

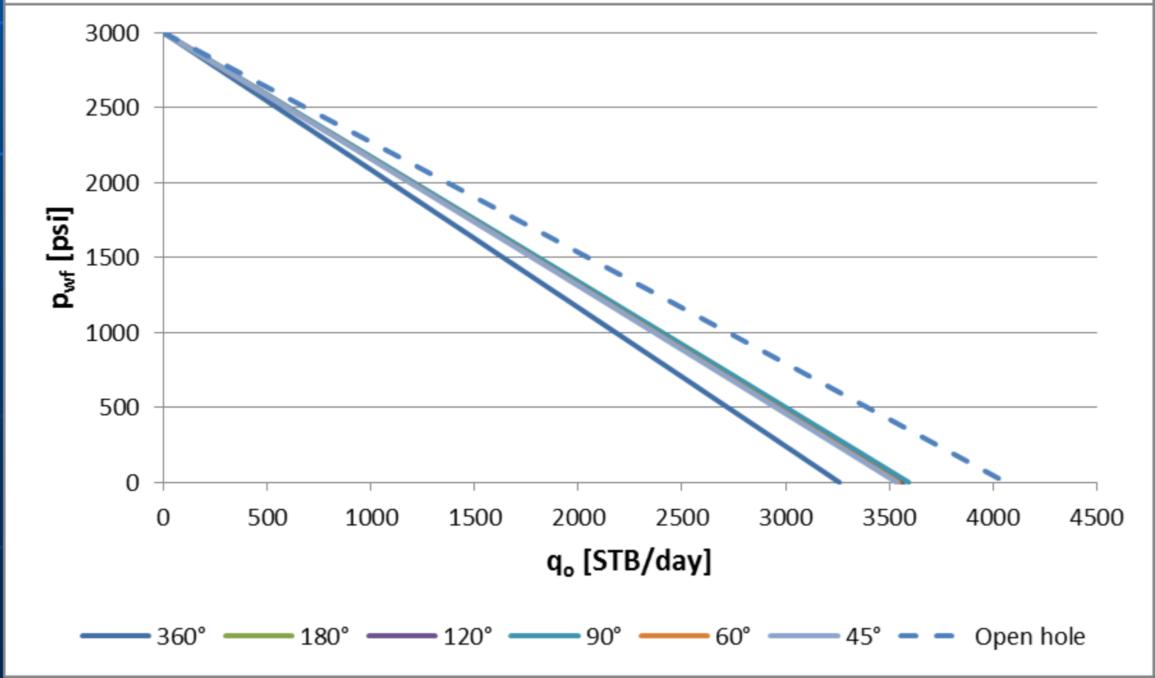
Perforation parameters						
L_p [ft]	ns [spf]	α	h_p [ft]	θ [°]	r_p [ft]	r_c [ft]
1	5	0.3	25	0	0.015	0.056667
Reservoir parameters					**Well parameters**	
k [mD]	r_e [ft]	P_r [psi]	k_H [mD]	k_V [mD]	r_w [ft]	h [ft]
50	1000	3000	50	5	0.292	25
Oil Properties			**Gas Properties**			
API density	μ_o [cP]	B_o [bbl/STB]	T [R°]	z	μ_o [cP]	γ_g
45.375	0.751	1.16	630	1	0.01933	0.64

Oil production

McLeod:

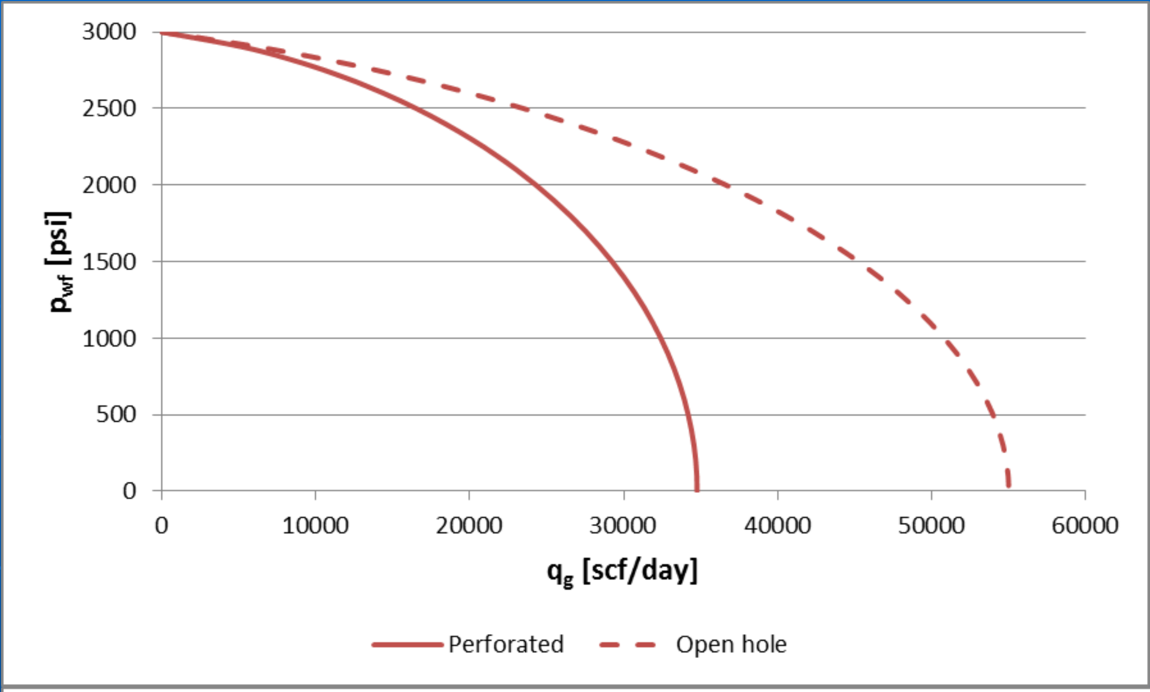


Karakas & Tariq :

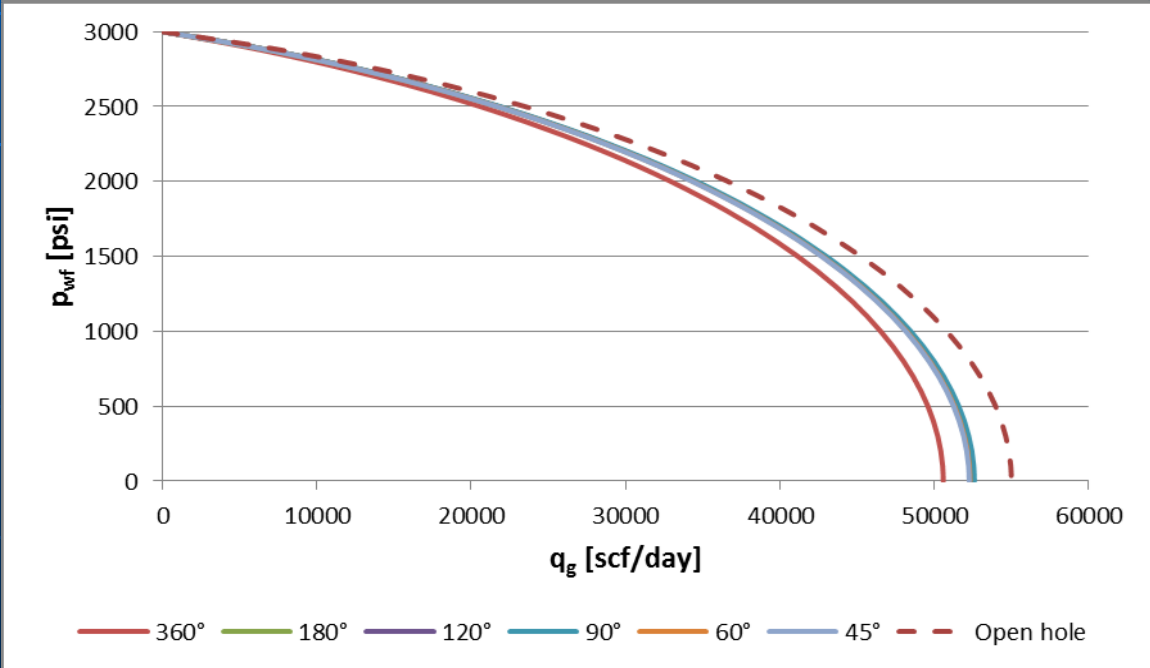


Gas production

McLeod:



Karakas & Tariq :



Conclusion of the investigation:

- The method of McLeod does not take the phase angle into consideration
- According to the method of Karakas and Tariq:
  - The perforation design has no effect on the non-Darcy term
  - The best phase angle is 90° (not explained)

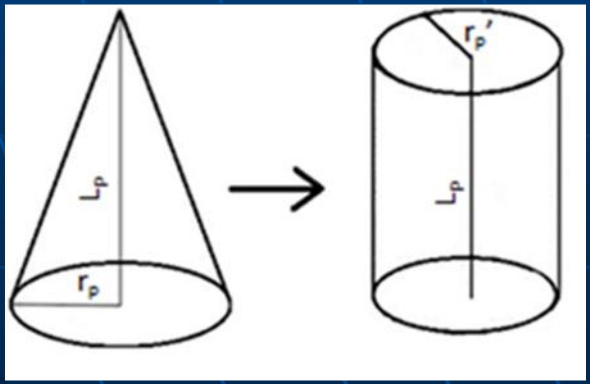
Criteria for a new IPR equation:

- It should have a purely analytical derivation.
- The phase angle must be taken into consideration.
- It must modify both the non-Darcy and Darcy terms.

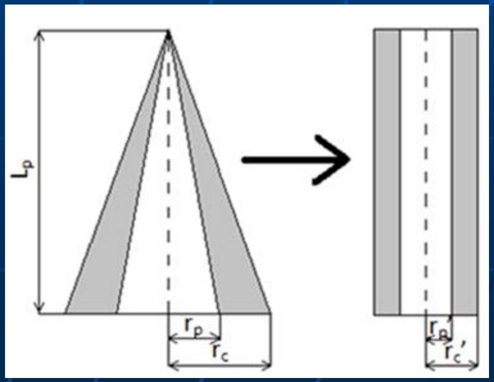
Analytical IPR equation – Base concept

- The flow is separated into two sections:
  - Flow perpendicular to the axis of the well
  - Flow perpendicular to the axis of the perforation channels
- The perforations are assumed to be small wells .
- Modification of the radius of the perforation channels and the crushed zone (Pásztor Á. & Kosztin B. 2015).

Modification of r_p:

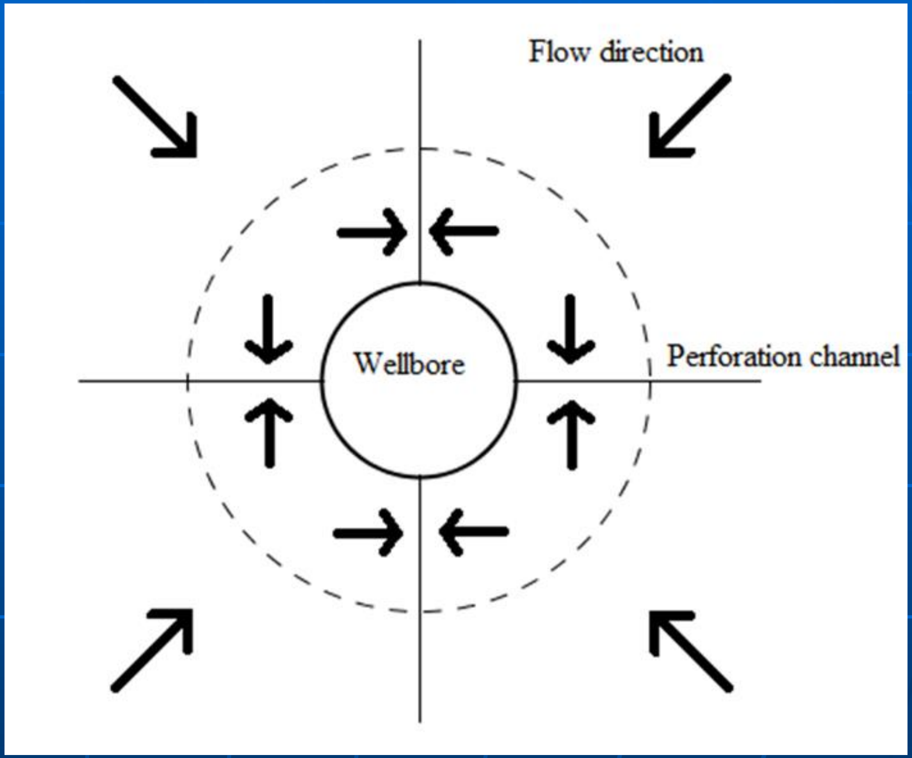


Modification of r_c:

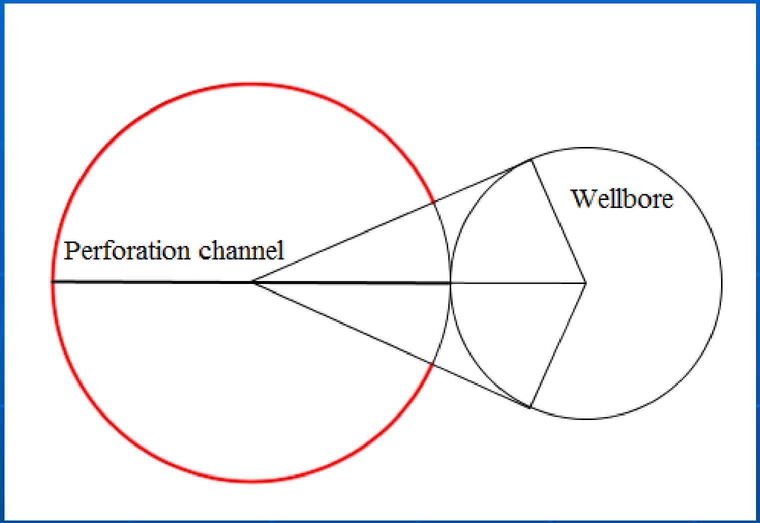


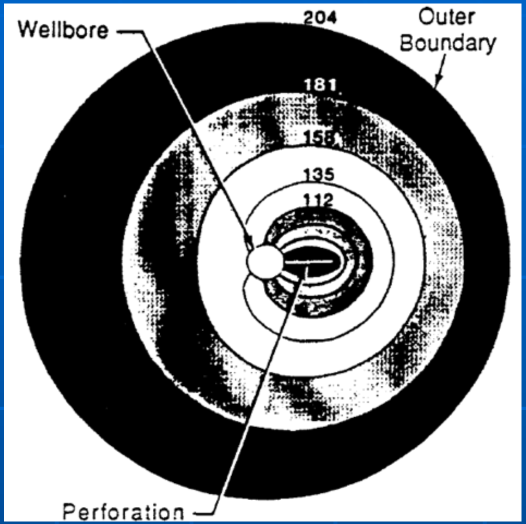
Extended wellbore radius

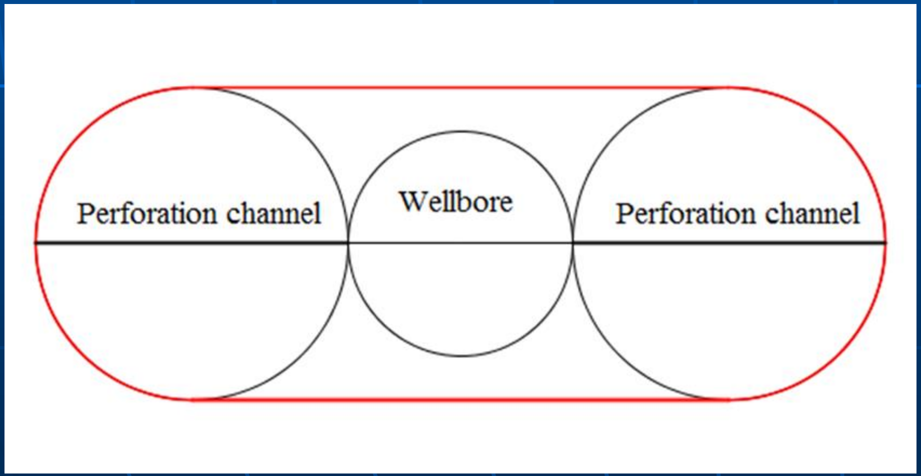
- The distance from the axis of the well at which the flow changes direction can be assumed as the radius of an extended wellbore.
- The flow direction of an average particle changes at the distance from the axis of the well where the volume of the drainage area is halved.

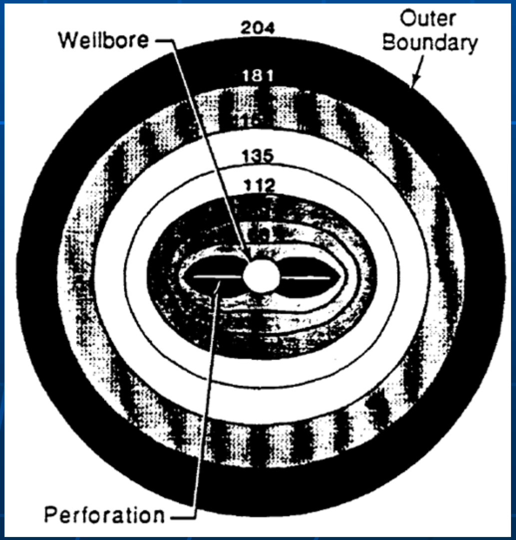


Extended wellbore radius for Θ=360°, 180°









(After Karakas M. & Tariq S.M. 1988)

IPR of a perforation channel

$$A = C_1 \times \frac{1}{h_p^2}(\frac{1}{r_w} - \frac{1}{r_e}) \longrightarrow A_p = C_1 \times \frac{\frac{1}{r_p} - \frac{1}{r_{ep}}}{L_p^2}$$

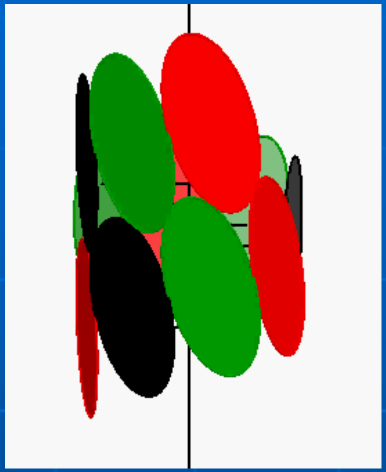
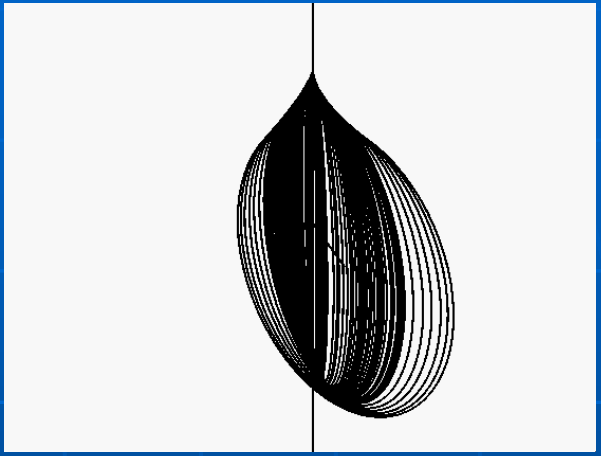
$$B = C_2 \times \frac{\ln\left(0.472\left(\frac{r_e}{r_w}\right)\right) + S}{h} \longrightarrow B_p = C_2 \times \frac{\ln\left(0.472\frac{r_{ep}}{r_p} \times \left(\frac{r_c}{r_p}\right)^{\frac{1-\alpha}{\alpha}}\right)}{L_p}$$

A and B parameters from the IPR equation of Jones et al. (Jones L.G. et al. 1967)

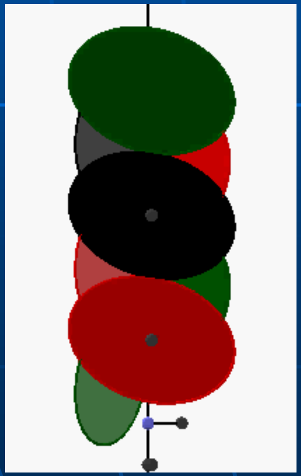
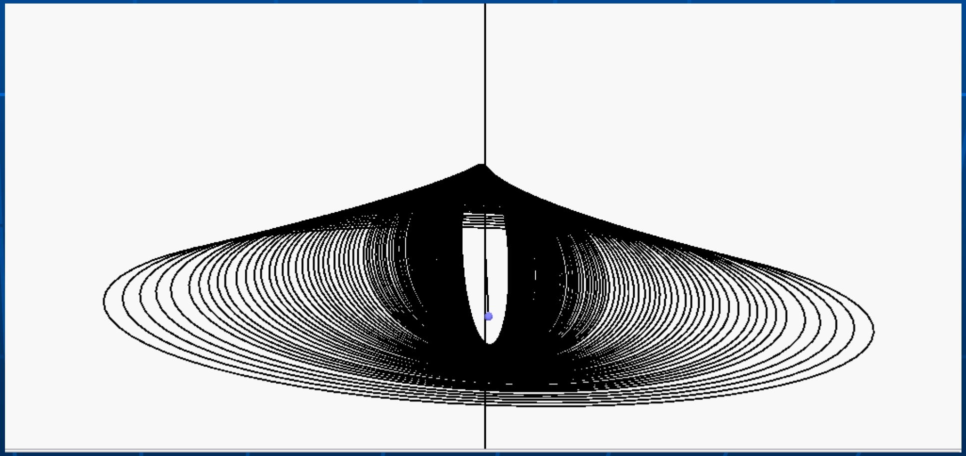
r_{ep} is the radius of a cylinder which has the same length as the perforations and the same area as the perforation channel's drainage space

Shape of the perforation channels' drainage space

Θ=45°

Θ=120°

Final form of the analytical IPR equation

$$p_r^{(2)} - p_{wf}^{(2)} = q^2 A + qB$$

$$S_p = \frac{ln\left(0.472\frac{r_{ep}}{r'_{pe}} \times \left(\frac{r'_{ce}}{r'_{pe}}\right)^{\frac{1-\alpha}{\alpha}}\right)}{L_p n s h_p} \times h$$

$$A = C_1 \times \frac{1}{h_p^2}\left(\frac{1}{r_w}\right)(\lambda_{ewb}+\lambda_p)$$

$$S_{ewb} = ln\left(\frac{r_w}{r_{ewb}}\right)$$

$$B = C_2 \times \frac{ln\left(0.472\left(\frac{r_e}{r_w}\right)\right) + S_{ewb} + S_p}{h}$$

$$\lambda_p = \frac{\frac{r_w}{r'_{pe}} - \frac{r_w}{r_{ep}}}{L_p^2 n s^2} \qquad \lambda_{ewb} = \frac{r_w}{r_{ewb}}$$

For oil production:

$$C_1 = 5.359 \times 10^{-4}\frac{B_o^2 \rho}{k^{1.201}}$$

$$C_2 = 141.24 \times \frac{\mu_o B_o}{k}$$

For gas production:

$$C_1 = 7.3628 \times 10^{-2}\frac{\gamma_g T z}{k^{1.201}}$$

$$C_2 = 1424 \times \frac{\mu_g T z}{h}$$

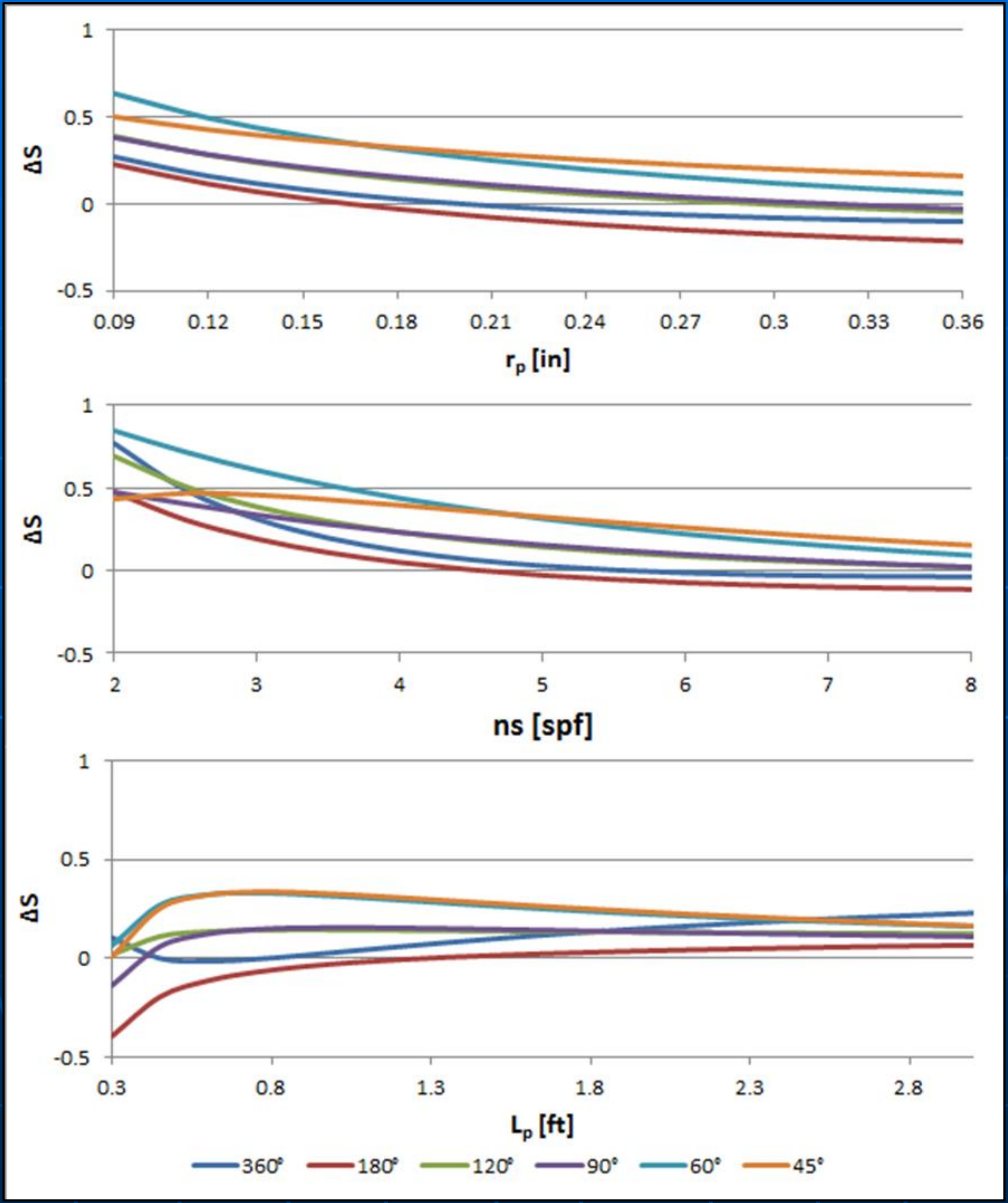
Analysis of the analytical equation’s behavior

- Comparison of the rate independent skin factors
- IPR curves of the theoretical wells
- Impact of perforation parameters on the productivity

Parameters of the sensitivity tests:

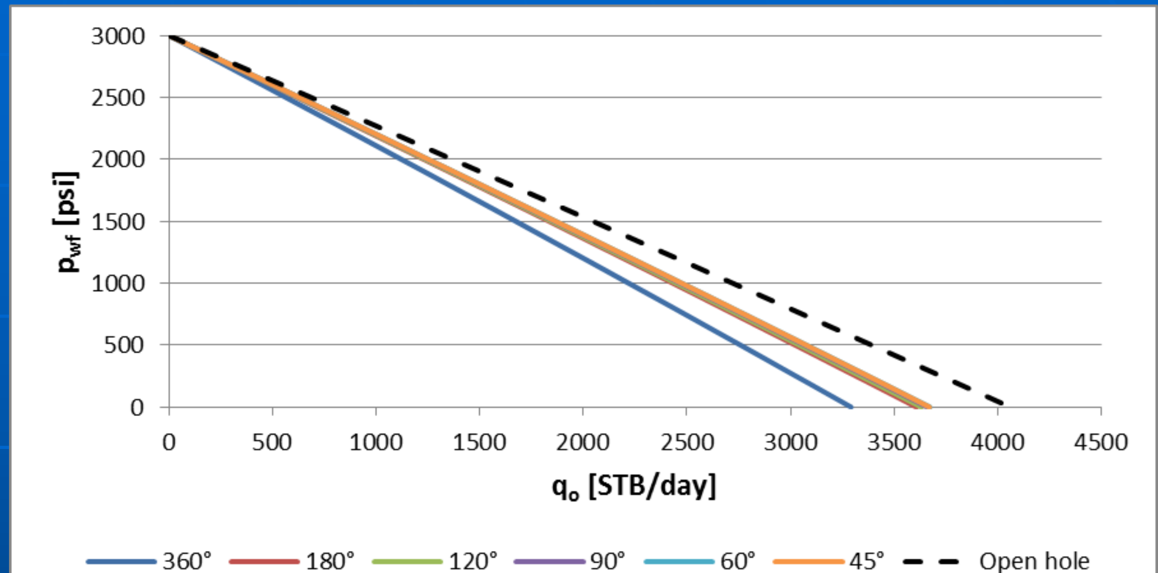
Variable	**Starting value**	**End value**
Shot density (ns) [spf]	2	8
Perforation length (L_p) [ft]	0.3	3
Perforation channel radius (r_p) [in]	0.09	0.36

Comparison of the rate independent skin factors

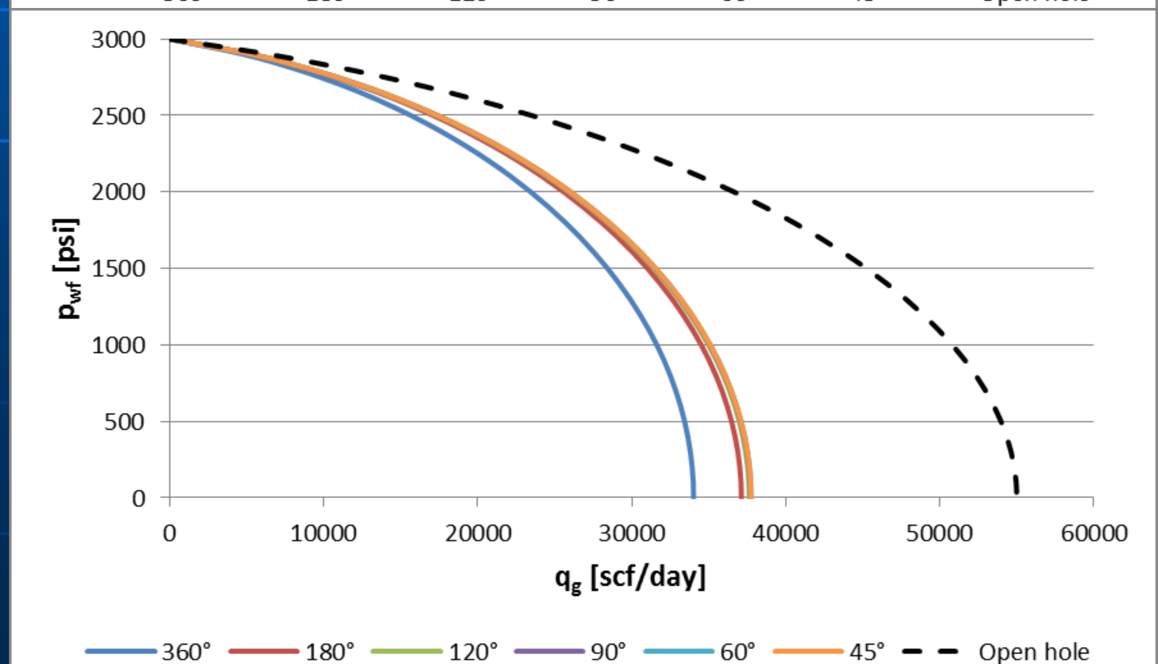


IPR curves of the theoretical wells

Oil production:

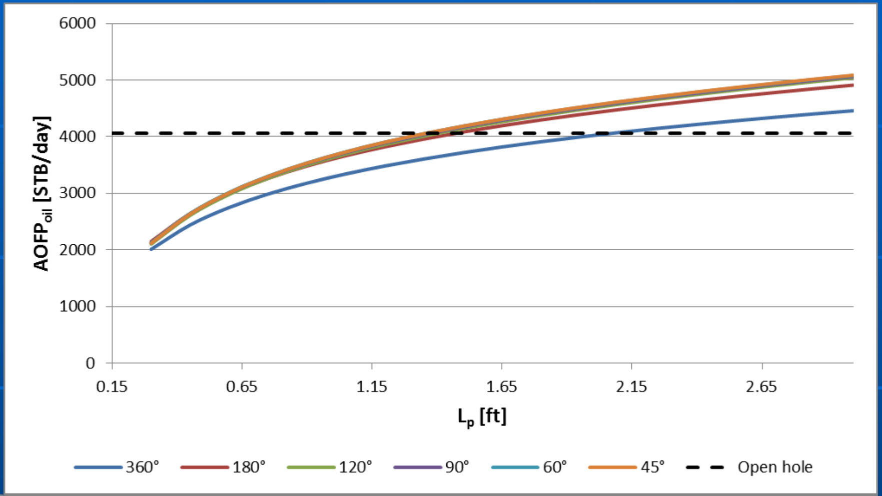


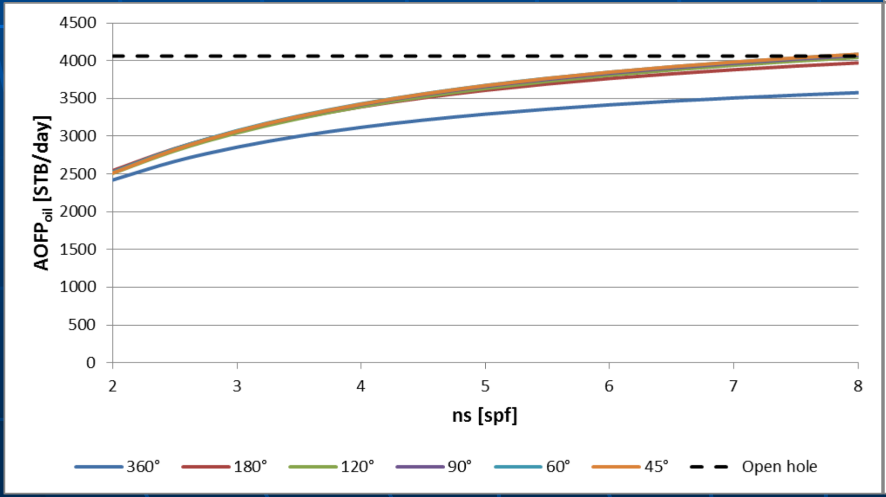
Gas production:

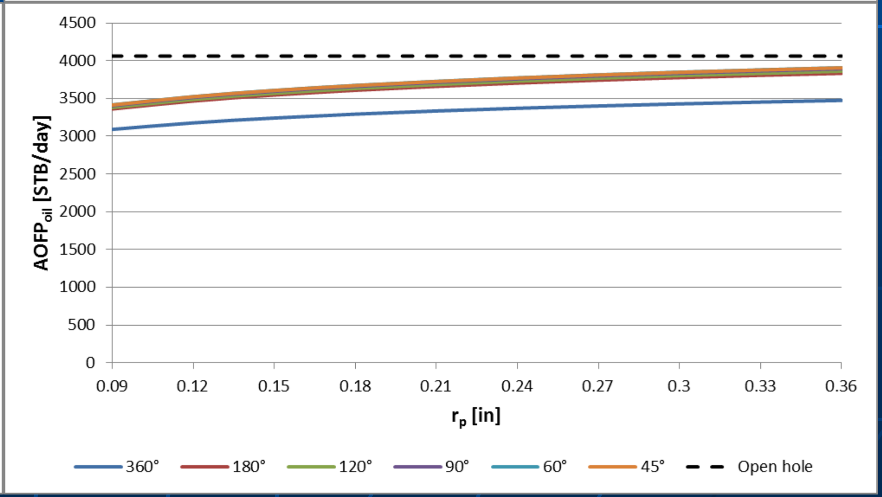


Impact of perforation parameters on the productivity

Oil production

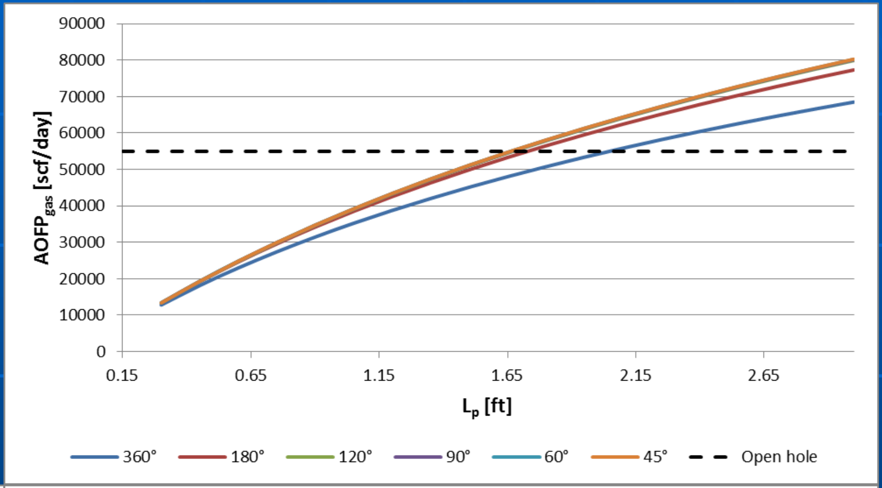


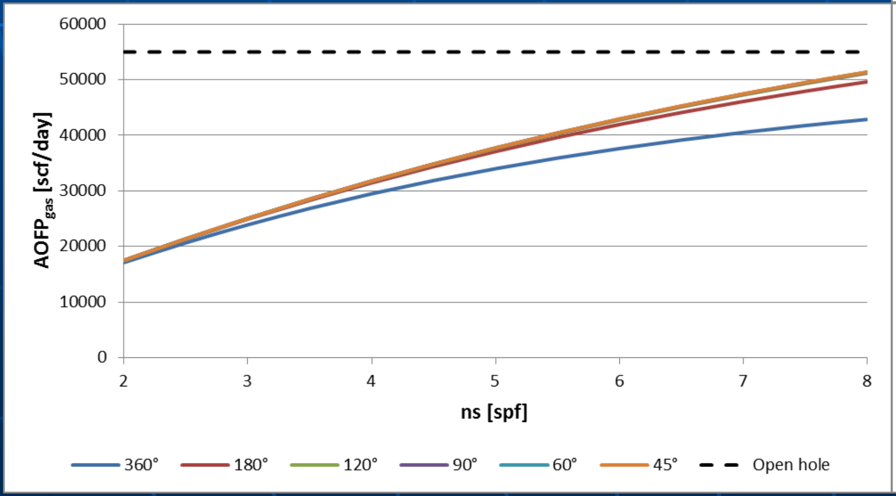


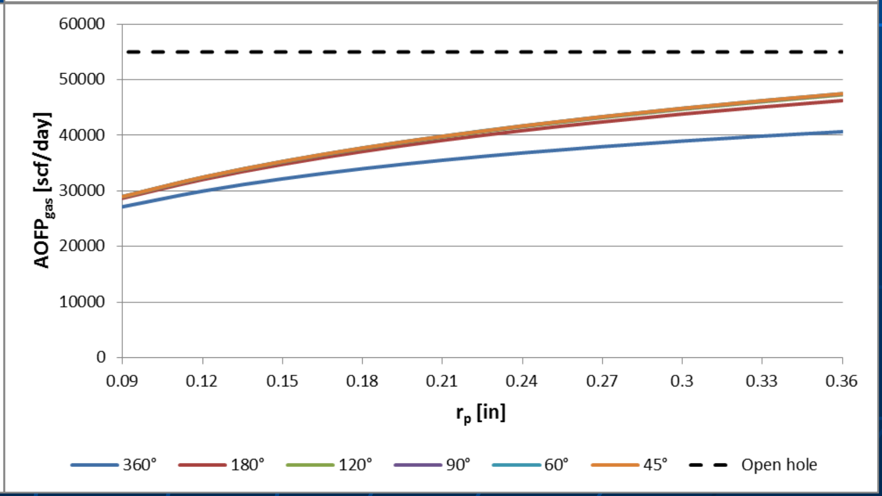


Impact of perforation parameters on the productivity

Gas production







Conclusion

- All the previously set criteria are met.
- The analytical equation describes the results of Karakas and Tariq well.
- The best perforation angle is 45°.
- The perforation channel length has the greatest effect on the productivity and the perforation channel radius has the smallest.
- With a proper perforation design the productivity of a perforated well can be better than a well with an open hole completion.
- In case of gas production it is more difficult to achieve a better productivity than in the case of open hole completed wells due to the rate dependent skin.

References

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- Karakas, M., and Tariq, S. M.: ”Semi-analytical Productivity Models for Models for Perforated Completions,” paper SPE 18247 presented at the 63rd Annual Technical Conference and Exhibition of the SPE held in Huston, TX, October 2-5, 1988.

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Thank you for your kind attention!
Questions?