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Effects of perforation parameters on the productivity of hydrocarbon wells

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Abstract

It is essential to know the relationship between the inflow rate and the performance of a production well. It describes the flow rate at the bottom of the well in function of the applied pressure head. The process is influenced by the parameters of the producing well, the reservoir in production and the production fluid.

In a cased and perforated well, the reservoir fluid flow takes place through the perforation channels before it flows into the well. Thus the parameters of the perforation (penetration depth, phase angle, perforation interval, radius of perforation channels and the crushed zone), have a great effect on the relationship between the flow rate and the well performance. The very first examination on this phenomenon dates back to the mid 70's. Several equations have been developed to describe the pressure drop through the perforation. However, numerous assumptions are applied in the derivations of these equations, which result in significant loss of accuracy.

A new equation has been derived in this study by applying the most accepted methods, i.e. the equation of McLeod and the one of Tariq and Karakas. The complex method takes all of the perforation parameters and their effects into account to provide more accurate results. The effect of different perforation parameters on the productivity of oil and gas producing wells are also demonstrated.

1 Introduction

It is assumed that the primary function of the well is to connect the reservoir to the surface. The accurate physical description of a well is essential. For optimal production, the well design requires some complex engineering considerations. Optimal production yields maximum return on the investment.

1.1 Inflow Performance Relationship

The functional relationship between the production rate and the flowing bottom hole pressure is the Inflow Performance Relationship or IPR. Its pressure range is defined between the average reservoir and atmospheric pressure. The flow rate corresponding to the atmospheric flowing bottom hole pressure is called the absolute open flow potential (AOF), of the well.

Darcy's Law

The first equation that describes the fluid flow through a porous media was proposed by Henry Darcy.

$$q_o = \frac{7.08 \times 10^{-3} k_o h (p_r - p_{wfs})}{\mu_o B_o \left[\ln \left(\frac{r_e}{r_w} \right) - 0.75 + s_t \right]} \quad (1.1.)$$

Darcy's Law assumes laminar steady-state flow, therefore it is only valid at low filtration velocities. Correction must be applied at large filtration velocity, which is usually referred to as Forcheimer's equation.

1.1.1 Jones method

Jones, Blount and Gaze presented a new IPR equation which is based on the Forcheimer's equation ^[1.]:

For oil wells:

$$p_r - p_{wfs} = a q_o^2 + b q_o, \quad (1.2.)$$

$$a = \frac{2.30 \times 10^{-14} \times \beta B_o^2 \rho}{h^2 r_w}, \quad (1.3.)$$

$$b = \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + s_t \right]}{7.08 \times 10^{-3} \times k_o h}. \quad (1.4.)$$

For gas wells:

$$p_r^2 - p_{wfs}^2 = a q_g^2 + b q_g, \quad (1.5.)$$

$$a = \frac{3.16 \times 10^{-12} \times \beta \gamma_g T z}{h^2 r_w}, \quad (1.6.)$$

$$b = \frac{1.424 \times 10^3 \mu_g T z \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + s_t \right]}{k_g h}, \quad (1.7.)$$

where, “a” is the turbulent correction factor and “b” represents the Darcy flow term. If factor “a” vanishes then one gets Darcy's equation.

This method can be used for both oil- and gas wells and the measurement of the coefficients (a and b) can be performed by flow tests. The AOFp can be calculated by applying the quadratic formula:

$$AOFp = \frac{-b + \sqrt{b^2 + 4a \times p_r}}{2a} \quad (1.8.)$$

For gas wells p_r must be replaced with p_r^2 .

1.2 Skin factor

The skin factor (s) represents the pressure difference between the ideal and actual flowing wellbore pressure, i.e. the additional pressure loss in the near-wellbore region (Δp_s), due to the formation damage, and other flow restrictions at the inlet of the well (see Figure 1.1)

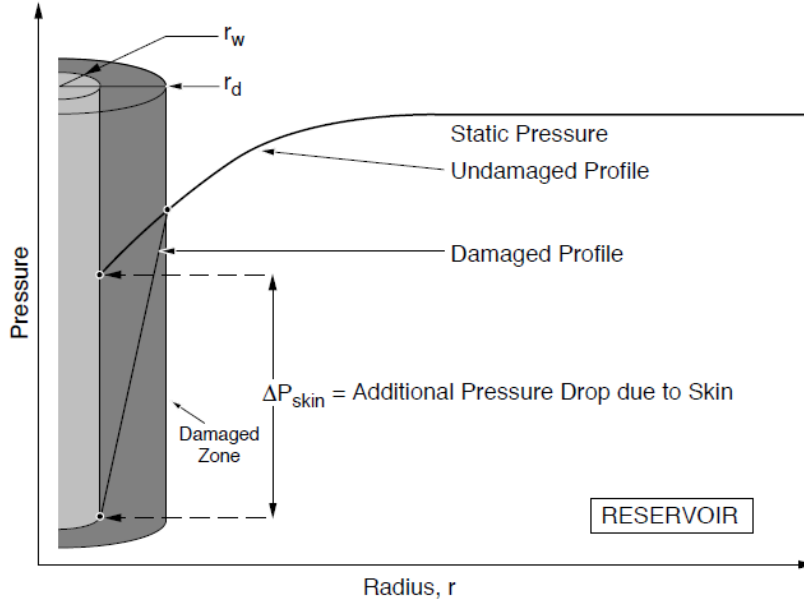


Figure 1.1 Pressure profile of damaged and undamaged vertical well

[Source: <http://blog.delphianballistics.com/2014/05/the-perforators-guide-to-formation-damage-part-1-measuring-formation-damage-as-total-skin/>]

The total skin is the composite of all non-ideal conditions which affect the flow into the wellbore, and it can be described with the following main components:

$$s_t = s_{dam} + s_{part} + s_{dev} + s_{perf} + s_{dperf} + s_{gravel} + \Sigma p_{pseudoskin} \quad (1.9.)$$

The last term on the right-hand side of Eq. (1.9) represents an array of pseudoskin factors. These effects are mostly mechanical, i.e. they are the results of obstructions or phase- and rate-dependent (S_{turb}) effects. Terms of Eq. (1.9) are the followings:

- S_t : Total skin factor (Horner skin),
- S_{dam} : Skin due to formation damage (positive). This component can be removed with matrix treatment.
- S_{part} : Skin due to limited perforation height (positive). This results from the well which is not perforated along the complete reservoir interval.
- S_{dev} : Skin due to wellbore deviation (negative). In case of high deviation angles, the well productivity increases in line with the increment of the open section to inflow.
- S_{perf} : Skin due to perforation channels (positive or negative). It depends on their size and phasing,
- S_{dperf} : Skin due to the reduced permeability of the crushed zone in the vicinity of perforations (positive). The uncertainty of corresponding parameters (permeability of the crushed zone, actual depth of perforation) is high, therefore the estimation of this component is difficult
- S_{garvel} : Skin due to the gravel pack (generally positive). Theoretically its value can be negative in case of increased effective wellbore radius (in underreamed, open hole, gravel packed wells).
- S_{turb} : Skin due to turbulent (non-Darcy) flow. This is instrumental in mainly gas wells (positive). This is the result of inadequate number of perforations which often generates flow convergence.

2 Perforation skin

Conductive tunnels are created by perforations to connect hydrocarbon reservoirs to the steel-cased wellbore which lead to the surface. However, this perforation process can significantly reduce the permeability of the rock nearby the perforation channels. In the previous chapter it was shown, that the damage and the perforation parameters – penetration depth, phase angle, perforation interval, radius of perforation channels – have significant effect on the pressure drop near the wellbore and therefore, on production. Thus, optimization of these parameters and mitigation of the induced damage are important aspects of the perforation process.

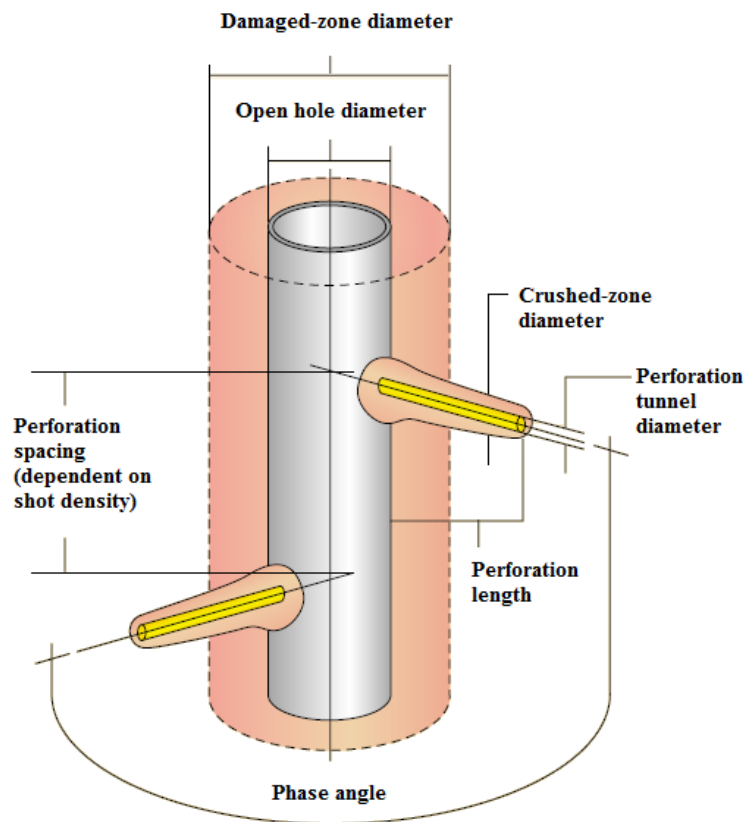


Figure 2.1: Perforation parameters

[Source: http://www.halliburton.com/public/lp/contents/Books_and_Catalogs/web/TCPCatalog/2005TCPcatalog/PerforatingSolutions_catalog.pdf]

The effect of perforation design on the fluid flow into the wellbore was investigated by several authors. The most widely applied methods were proposed by McLeod^[2.], and by Karakas and Tariq^[3.].

2.1 McLeod method

McLeod assumed that perforations are small wells in the reservoir and used the Jones method to calculate the pressure drop across them. He applied the following equations:

For oil wells:

$$p_{wfs} - p_{wf} = a \left(\frac{q}{n_s \times h_p} \right)^2 + b \left(\frac{q}{n_s \times h_p} \right), \quad (2.1.)$$

$$a = \frac{2.30 \times 10^{-14} \times \beta B_o^2 \rho \left(\frac{1}{r_p} - \frac{1}{r_c} \right)}{L_p^2}, \quad (2.2.)$$

$$b = \frac{\mu_o B_o \left[\ln \frac{r_c}{r_p} \right]}{7.08 \times 10^{-3} \times L_p k_p}. \quad (2.3.)$$

For gas wells:

$$p_{wfs}^2 - p_{wf}^2 = a \left(\frac{q}{n_s \times h_p} \right)^2 + b \left(\frac{q}{n_s \times h_p} \right), \quad (2.4.)$$

$$a = \frac{3.16 \times 10^{-12} \times \beta \gamma_g T z \left(\frac{1}{r_p} - \frac{1}{r_c} \right)}{L_p^2}, \quad (2.5.)$$

$$b = \frac{1.424 \times 10^3 \mu_g T z \left[\ln \frac{r_c}{r_p} \right]}{L_p k_p}. \quad (2.6.)$$

These equations can be combined together with the Jones IPR equation as follows:

For oil wells:

$$p_r - p_{wf} = A q^2 + B q, \quad (2.7.)$$

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho (1 + \lambda)}{h_p^2 k^{1.201} r_w}, \quad (2.8.)$$

$$B = 141.24 \times \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + \Delta s + s_{perf} \right]}{k h}. \quad (2.9.)$$

For gas wells:

$$p_r^2 - p_{wf}^2 = Aq^2 + Bq, \quad (2.10.)$$

$$A = 7.3628 \times 10^{-2} \frac{\gamma_g T z (1+\lambda)}{h_p^2 k^{1.201} r_w}, \quad (2.11.)$$

$$B = 141.24 \times \frac{\mu_g T z \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + \Delta s + s_{perf} \right]}{kh}, \quad (2.12.)$$

$$s_{perf} = \frac{\ln \left(\frac{r_c}{r_p} \right)}{n_s L_p \alpha \varepsilon}, \quad (2.13.)$$

$$\lambda = \frac{\frac{r_w}{r_p} - \frac{r_w}{r_c}}{L_p^2 n_s^2 \alpha^{1.201}}. \quad (2.14.)$$

The derivation of the equations is given in Appendix A.

2.2 Method by Karakas and Tariq

Karakas and Tariq presented a semi-analytical solution for the skin calculation in perforated completions. They have quantified the wellbore and vertical-flow effects by accurate finite-element simulations. They have showed that the skin effect which is caused by perforations (s_p) is a combination of four different effects as follows: horizontal skin (s_H), vertical skin (s_V), wellbore skin (s_{wb}), and crushed zone-effects (s_c):

$$s_p = s_H + s_V + s_{wb} + s_c \quad (2.15.)$$

$$s_H = \ln \left(\frac{r_w}{r_{we}} \right) \quad (2.16.)$$

$$s_{wb}(\theta) = c_1(\theta) e^{c_2(\theta) r_{wD}} \quad (2.17.)$$

$$s_V = 10^a h_D^{b-1} r_{pD}^b \quad (2.18.)$$

$$s_c = \frac{\delta_p}{L_p} \left(\frac{k}{k_p} - 1 \right) \ln \left(\frac{r_c}{r_p} \right) \quad (2.19.)$$

The applied variables and constants (r_{we} , r_{pD} , h_D , c_1 , c_2 , a , b) are explained in details in Appendix B.

2.3 Complex method

The previously presented methods investigate the effect of perforation design on the inflow from different aspects. They are the most widely accepted methods to calculate the pressure drop through the perforations. However, both of them fail in certain cases. The equation proposed by McLeod does not include the phase angle; Karakas' and Tariq's solution does not include the turbulent effect of the perforations.

I propose a new method, which takes all of the effects into account, which are due to perforations:

For oil wells:

$$p_r - p_{wf} = Aq^2 + Bq, \quad (2.20.)$$

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho (1+\lambda)}{h_p^2 k^{1.201} r_w}, \quad (2.21.)$$

$$B = 141.24 \times \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + \Delta s + s_{pt} \right]}{kh}. \quad (2.22.)$$

For gas wells:

$$p_r^2 - p_{wf}^2 = Aq^2 + Bq, \quad (2.23.)$$

$$A = 7.3628 \times 10^{-2} \frac{\gamma_g T z (1+\lambda)}{h_p^2 k^{1.201} r_w}, \quad (2.24.)$$

$$B = 141.24 \times \frac{\mu_g T z \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + \Delta s + s_{pt} \right]}{kh}, \quad (2.25.)$$

where s_{pt} is the total skin by perforations and Δs is the skin by other effects.

$$s_{pt} = s_{perf} + s_V + s_H + s_{wb} \quad (2.26)$$

Some of the variables need further discussion or modification for a better accuracy.

2.3.1 Crushed-zone permeability

Klotz et al pointed out that the permeability of the crushed-zone is less than the wellbore permeability, which has been reduced by drilling fluid and cement filtrates. For example, if the permeability in the vicinity of the wellbore is 40% of the reservoir permeability, the permeability of the compacted zone may be 10% of the former one, or 4% of the latter one.^[4]

2.3.2 Modification of the perforation tunnel – and crushed zone radius

In the presented equations the shape of perforations are assumed to be cylindrical, but in most cases the perforations are conical. Therefore, I correct the radius of the penetration and the crushed zone. The full detailed explanation of the modifications is given in Appendix C.

Correction of the perforation radius r_p :

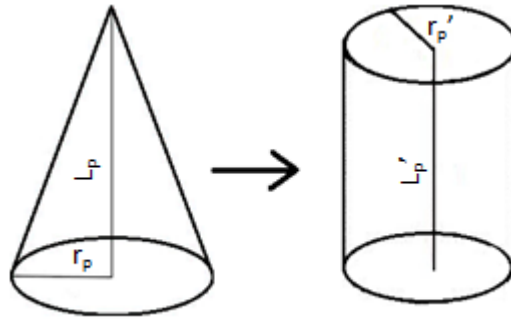


Figure 2.2: Correction of the perforation radius r_p

The surface area of the cone using the uncorrected radius and the surface area of the cylinder applying the corrected radius must be equal. The modified perforation tunnel radius r'_p is given by:

$$r'_p = \frac{r_p \sqrt{r_p^2 + L_p^2}}{2L_p}. \quad (2.27.)$$

I assume that the length of the conical zone L_p is much larger than the uncorrected radius (r_p) and therefore simplify Eq 2.27. to:

$$r'_p \cong \frac{r_p}{2} \quad (2.26.)$$

Modification of the crushed zone radius r_c :

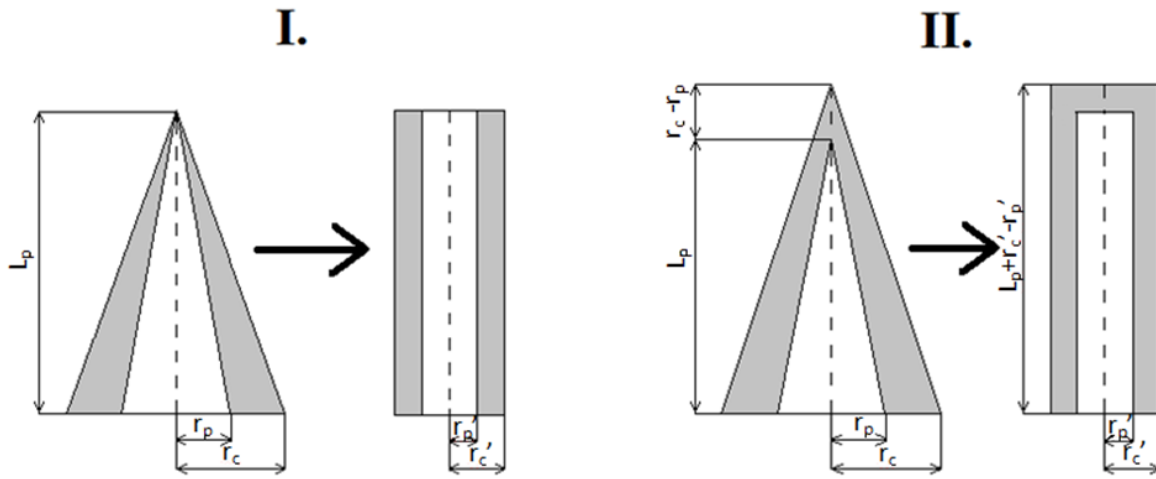


Figure 2.3: Modification of crushed-zone radius

The crushed zone radius is corrected in such a way that the volume of the crushed zone is kept constant (shaded regions in Figure 2.3). I consider two cases: (1) when the crushed zone length and the perforation tunnel length are equal, and (2) when the crushed zone length is longer by $r_c - r_p$. In both cases I get:

$$r'_c = \sqrt{\frac{r_c^2 - r_p^2}{3}} + r_p'^2. \quad (2.27.)$$

Investigations showed that the thickness of the crushed zone is between 0.5-0.75 inch.^[2, Hiba! A hivatkozási forrás nem található., Hiba! A hivatkozási forrás nem található.]

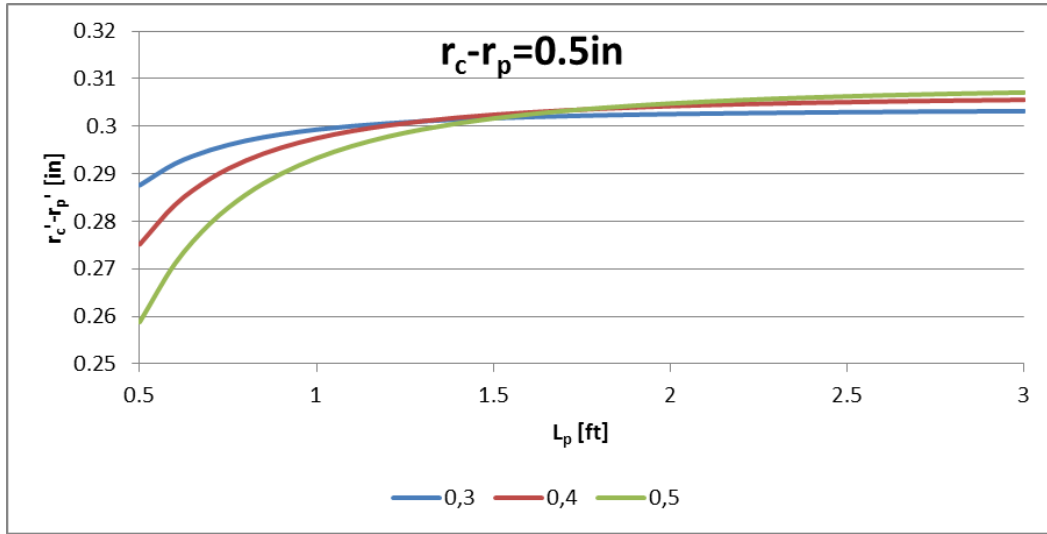


Figure 2.4: Changes of $r_c' - r_p'$ as a function of L_p for different r_p values ($r_c - r_p = 0.5$ in)

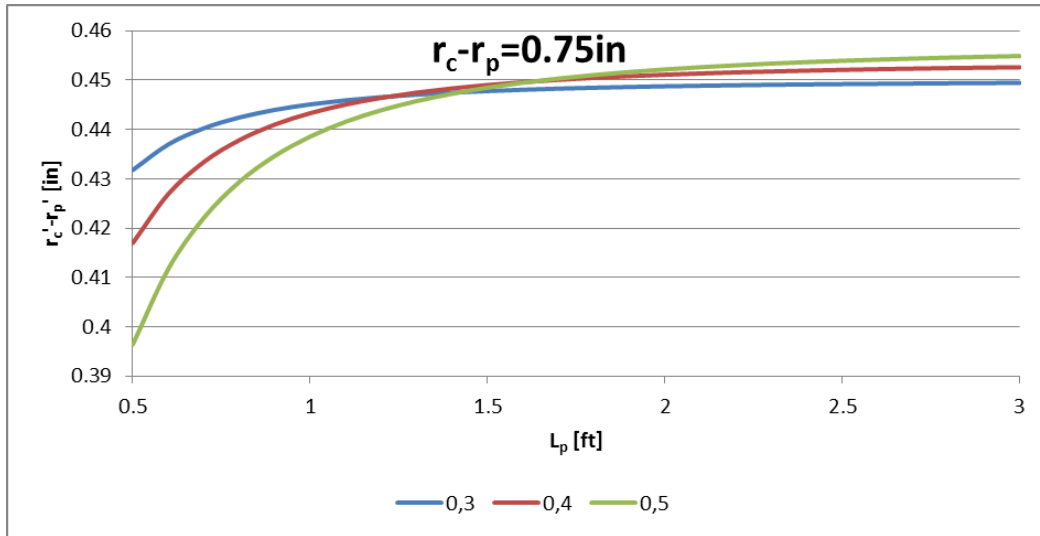


Figure 2.5: Changes of $r_c' - r_p'$ as a function of L_p for different r_p values ($r_c - r_p = 0.75$ in)

Karakas and Tariq pointed out that the perforation tunnel radius must be modified with considering the anisotropic effect.^[3] Muskat argued that the solution of the isotropic formation can also be used for the anisotropic formations, providing that the dimensionless height and perforation radius are modified accordingly. In anisotropic formations, the dimensionless spacing is modified by the square root of the anisotropy ratio. In addition, the flow into perforations in the vertical plane is elliptical in anisotropic formations. Therefore the effective perforation radius in an anisotropic formation is^[6, 7]:

$$r_{pe} = \left(\frac{r_p}{2}\right) \left(1 + \sqrt{\frac{k_V}{k_H}}\right). \quad (2.28.)$$

Including all of the corrections yields the following equations for the perforation and crushed zone radius:

$$r_{pe}' = \left(\frac{r_{p'}}{2}\right) \left(1 + \sqrt{\frac{k_V}{k_H}}\right), \quad (2.29.)$$

$$r_{ce}' = r_{pe}' + r_c' - r_p'. \quad (2.30.)$$

3 Effects of the perforation parameters on the productivity

To validate the proposed new method I have applied it on theoretical oil and gas wells. In the first case it was assumed that the wells were completed with open hole. In the second case I assumed perforations. In both cases, the inflow performance curves were plotted with two different permeability values. Data of the theoretical oil and gas wells can be found in Appendix D

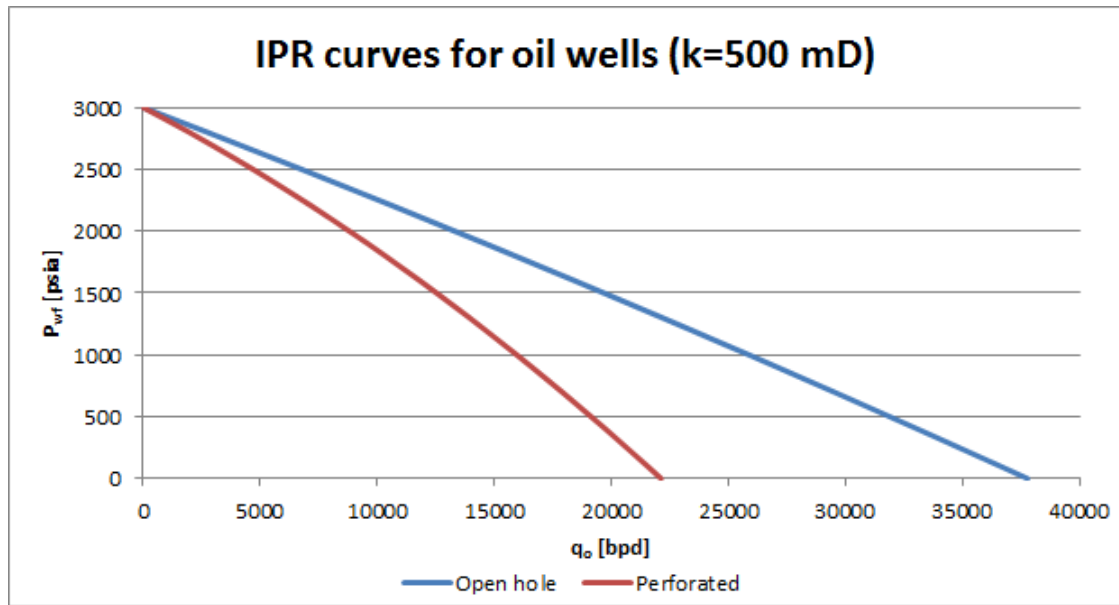


Figure 3.1: IPR curves for oil wells k=500 mD

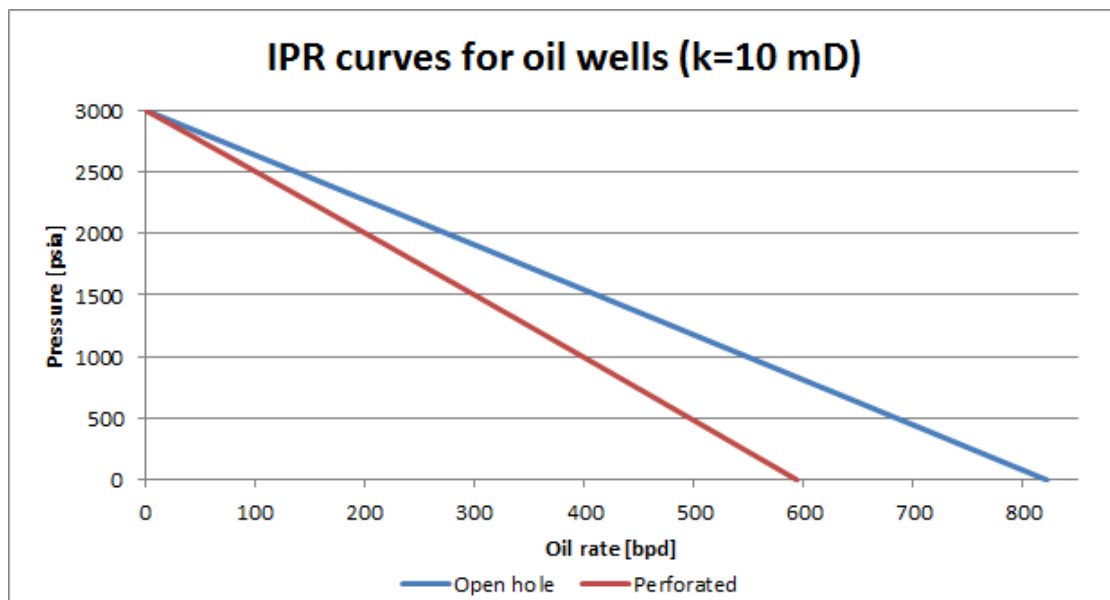


Figure 3.2: IPR curves for oil wells $k=10$ mD

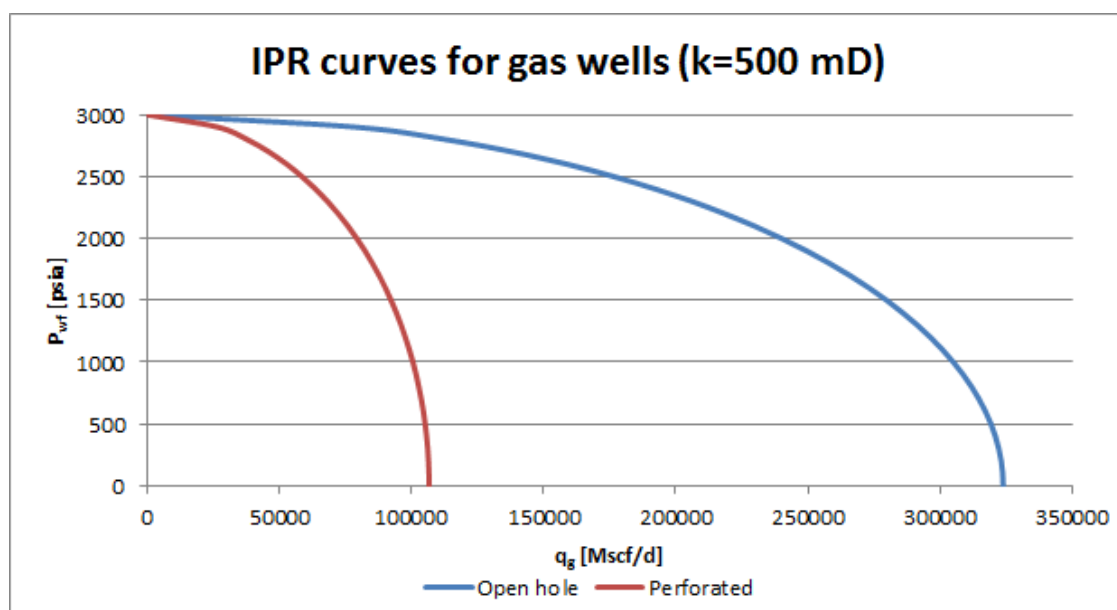


Figure 3.3: IPR curves for gas wells $k=500$ mD

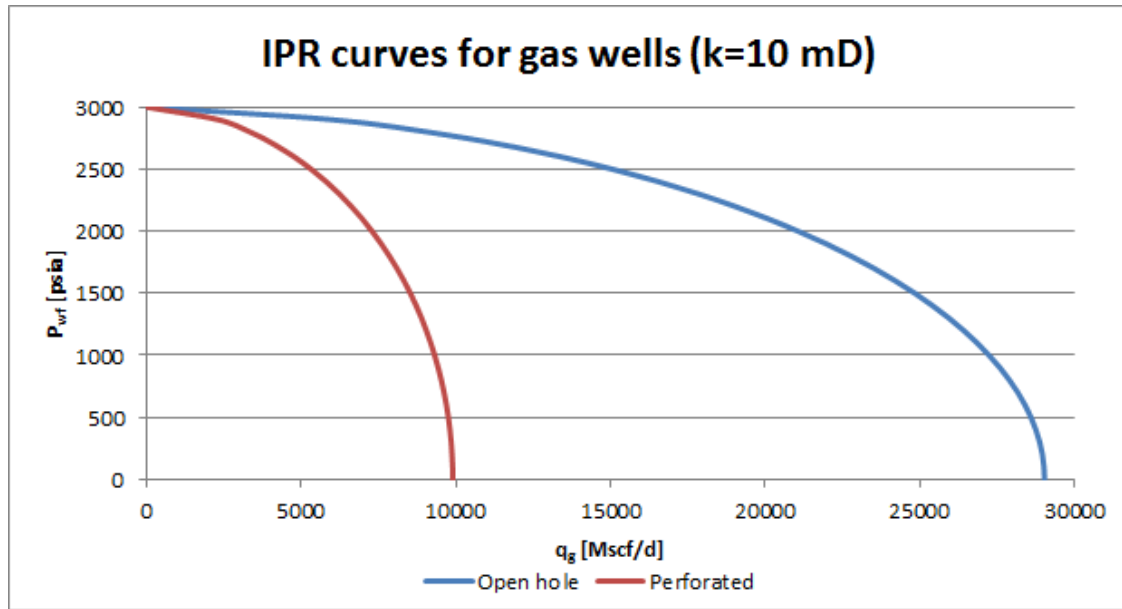


Figure 3.4: IPR curves for gas wells $k=10$ mD

The figures show that productivity drops significantly in case of perforated wells, especially in gas wells. Sensitivity tests were performed in order to take the effect of perforation parameters into account.

3.1 Sensitivity tests

In Section 1 it was shown that the absolute open flow potential of a well can be calculated by applying parameters “a” and “b”. The productivity of two wells can be compared by their AOFPs. This can be used for investigating the effects of perforation parameters on the productivity.

First, the well’s AOFP is calculated in case of open hole completion (assuming that the skin is zero) and second perforated completion using different perforation parameters. In the next step, the ratio of the open hole and the perforated completion is plotted in function of the variable parameter. 20 values for each parameter were used in the investigation. Table 3.1. shows the first and last values:

Variable	Starting value	End value
Shot density [spf]	2	8
α	0.1	0.6
Perforation length [ft]	0.15	2.85
Perforation tunnel radius [in]	0.09	0.36

Table 3.1: Variable parameters of the perforations

The results of the tests (graphs and tables) are presented in Appendix E for oil wells and in Appendix F for gas wells.

Note that the results represent the percentage of the open hole completed well's absolute open flow potential. Its primary importance is summarized as follows:

- The AOFP percentage can be more than 100% if the perforated well has a better productivity than the open hole completed well. Figure E.3 represents this case, which indicates that the performance of wells with sufficiently long perforation channels is better than the one of wells with open hole completion.
- Low permeability yields better results than high permeability. This finding can be explained by the open hole completed well having lower AOFP.

The ratio of the crushed zone permeability and the permeability of the surrounding rock, was specified by previous authors ^[9], and its value is between 0.1 and 0.4. 0.4 is for underbalanced perforated wells. Greater values can only be achieved by stimulation, which is indicated with a dashed red line in the plots.

To demonstrate the extent of the different perforation parameters' effects on the productivity, the following tables represent the calculated AOFP % using both starting and end parameter values in case of $\Theta=90^\circ$

Oil wells k= 500 mD			
Variable	AOFP %		
	At starting value	At end value	Increment
Shot density	31.5	77.9	46.4
α	39.5	72.9	33.4
Perforation length	13.9	100.4	86.5
Perforation tunnel radius	48.5	74.3	25.8
Oil wells k= 10 mD			
Variable	AOFP %		
	At starting value	At end value	Increment
Shot density	49.3	90.2	40.9
α	59.9	83.5	23.6
Perforation length	28.4	110.4	82.0
Perforation tunnel radius	69.2	85.7	16.5

Table 3.2: Extent of the perforation parameters' effects on the productivity (oil wells)

Gas wells k= 500 mD			
Variable	AOFP %		
	At starting value	At end value	Increment
Shot density	13.9	48.7	34.9
α	17.8	46.7	28.9
Perforation length	5.3	70.6	65.3
Perforation tunnel radius	23.0	46.9	23.8
Gas wells k= 10 mD			
Variable	AOFP %		
	At starting value	At end value	Increment
Shot density	14.5	50.2	35.7
α	18.6	48.1	29.5
Perforation length	5.5	72.2	66.7
Perforation tunnel radius	24.0	48.3	24.2

Table 3.3: Extent of the perforation parameters' effects on the productivity (gas wells)

It can be seen that the most important parameter of the perforation is the length of perforation channels.

3.2 Productivity with proper perforation design

To investigate the cumulative effect of perforation parameters on the productivity, investigations were performed using a good quality perforation design with the following parameters:

- Perforation length : 2 ft
- Shot density: 6 spf
- α parameter: 0.4
- ε parameter: 1
- Phase angle: 90°
- Perforation tunnel radius: 0.3 in
- Crushed zone radius: 0.8 in

The following table represents the calculated AOFP % of the wells:

AOFP %		
	Oil well	Gas well
k=500 mD	104.4	80.5
k=10 mD	111.1	81.9

Table 3.4: Productivity of optimally perforated wells

In order to compare theoretically perforated wells (with the perforation design of theoretical wells) and optimally perforated wells I plot the following figures:

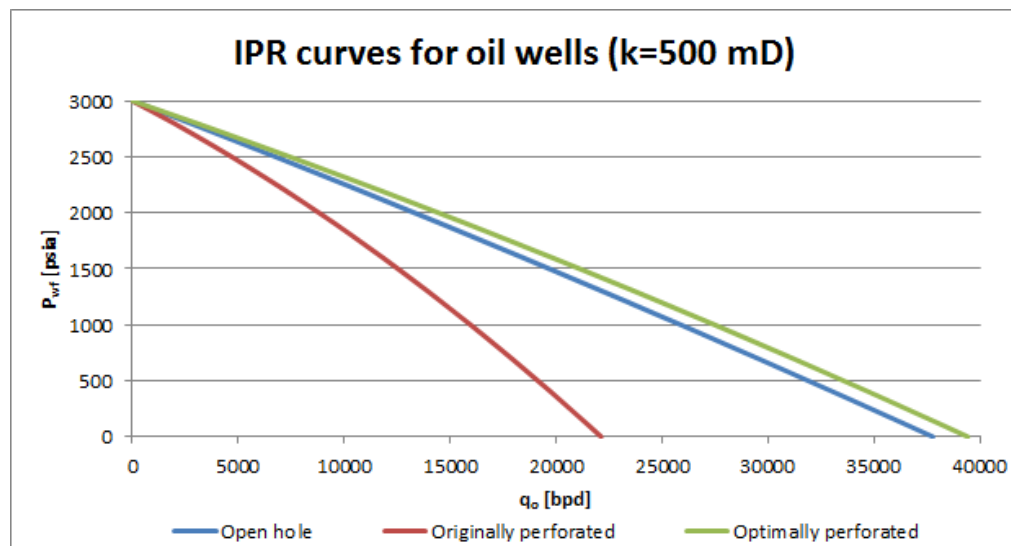


Figure 3.5: Joint effect demonstrating IPR curves (oil k=500 mD)

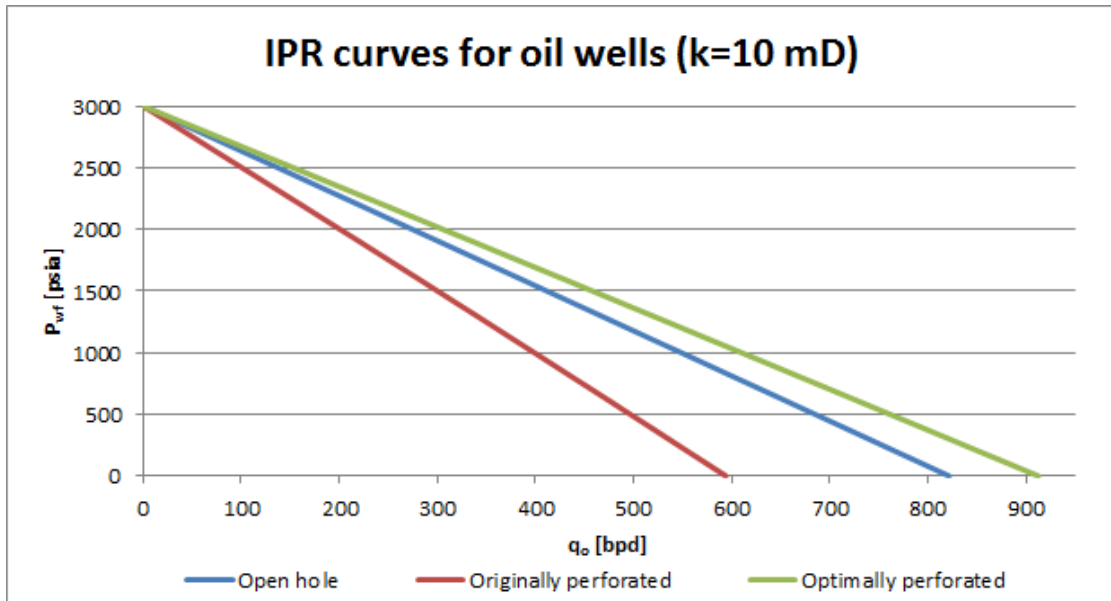


Figure 3.6: Joint effect demonstrating IPR curves (oil $k=10$ mD)

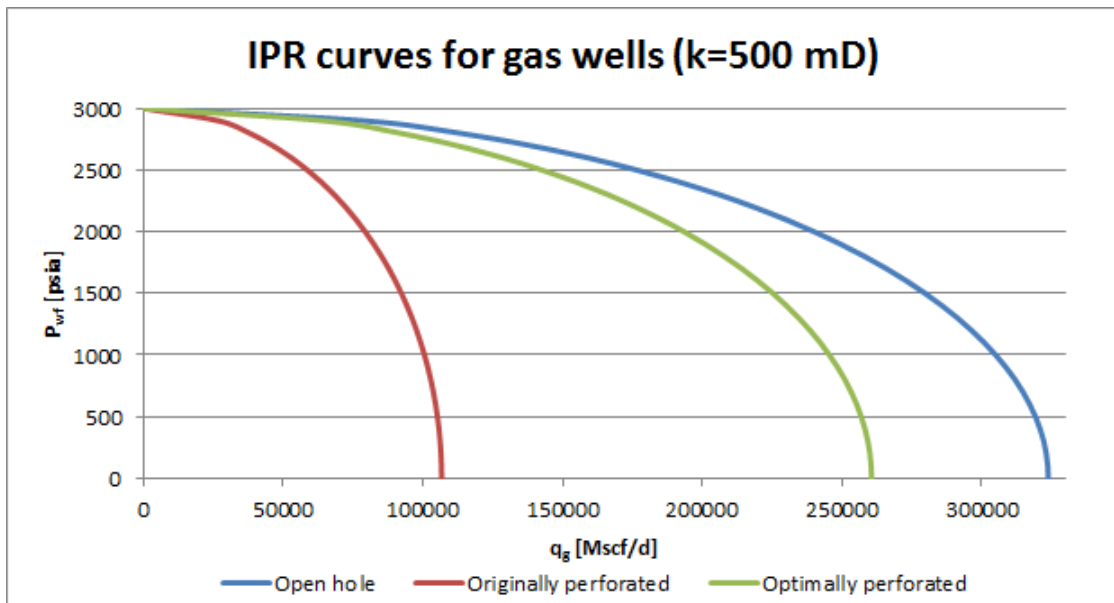


Figure 3.7: Joint effect demonstrating IPR curves (gas $k=500$ mD)

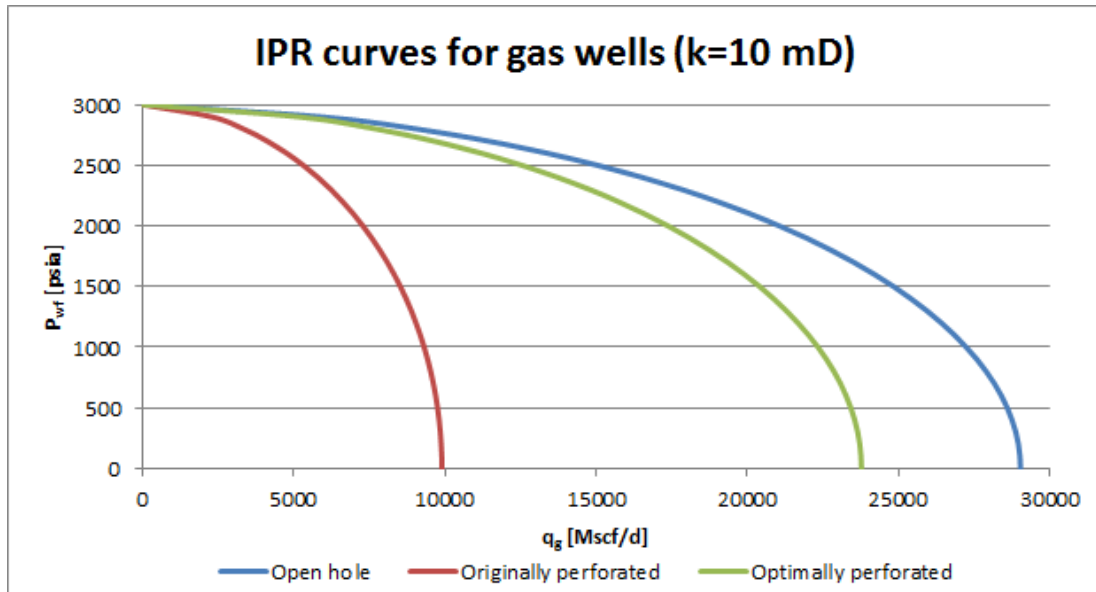


Figure 3.8: Joint effect demonstrating IPR curves (gas $k=10$ mD)

The importance of good perforation design is clearly indicated by the tables and figures.

4 Conclusion

The examination of the effects of perforation parameters on the productivity of hydrocarbon wells results in the following conclusions:

- Best productivity can be achieved with the application of 90° phase angle.
- In case of gas wells, the effect of phase angle on productivity is negligible.
- The perforation length has the greatest effect on the productivity; furthermore the radius of the perforation tunnel has the smallest one. The consequence of the mechanics of the perforation process is that they are not independent; therefore long perforations are more preferred than wide ones.
- I have showed in Chapter 3 that good perforation design is essential for increasing reservoir quality.
- In case of oil wells, better productivity can be achieved by proper perforation design than by open hole completion.
- It is more difficult to achieve a good productivity in gas wells by proper perforation design because the large energy loss of transient flows. Thus, it is very important to achieve a low λ value (high $L_p^2 \times n_s^2$).

Nomenclature

a	Turbulent term		γ_g	Gas specific gravity	[-]
A	Turbulent term for perforation		δ_d	Spacing between perforations	[ft]
b	Darcy flow term		ε	h_p/h	[-]
B	Darcy flow term for perforation		Θ	Phase angle	[°]
B_o	Formation volume factor of oil	[bbl/stb]	λ	Perforation's impact on turbulent term	
h	Net thickness of the formation	[ft]	μ_g	Viscosity of gas	[cP]
h_D	Dimensionless perforation spacing	[-]	μ_o	Viscosity of oil	[cP]
h_p	Perforated interval	[ft]	ρ	Fluid density	[lb/cf]
k_o	Permeability of oil	[mD]			
k_p	Permeability of crushed zone	[mD]			
L_p	Perforation tunnel length	[ft]			
n_s	Shot density	[shot/ft]			
p_r	Average reservoir pressure	[psia]			
p_{wf}	Flowing bottomhole pressure in wellbore	[psia]			
p_{wfs}	Bottomhole flowing pressure at sandface	[psia]			
q_g	Gas flow rate into the well	[Mcf/d]			
q_o	Oil flow rate into the well	[stb/d]			
r_c	Radius of crushed zone	[in]			
r_e	Radius of drainage	[ft]			
r_p	Radius of perforation tunnel	[in]			
r_{pD}	Dimensionless perforation radius	[-]			
r_w	Wellbore radius	[ft]			
r_{wD}	Dimensionless well radius	[-]			
r_{we}	Effective wellbore radius	[ft]			
s_c	Crushed-zone effects				
s_H	Horizontal skin caused by perforations				
s_p	Skin effect caused by perforations				
s_t	Total skin	[-]			
s_V	Vertical skin caused by perforations				
s_{wb}	Wellbore skin caused by perforations				
T	Temperature	[°R]			
z	Supercompressibility	[-]			
α	k_p/k	[-]			
β	Biott coefficient	[ft ⁻¹]			

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Appendix A: Incorporation of McLeod's equation into the Jones method

For oil wells:

$$p_r - p_{wf} = \left(a_1 + \frac{a_2}{(n_s \times h_p)^2} \right) q^2 + \left(b_1 + \frac{b_2}{n_s \times h_p} \right) q \quad (\text{A.I.})$$

$$p_r - p_{wf} = Aq^2 + Bq \quad (\text{A.II.})$$

$$A = a_1 + \frac{a_2}{(n_s \times h_p)^2} \quad (\text{A.III.})$$

$$B = b_1 + \frac{b_2}{n_s \times h_p} \quad (\text{A.IV.})$$

For gas wells the left part of Eq. A.I. changes to $p_r^2 - p_{wf}^2$.

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho}{h_p^2 k^{1.201}} \left[\frac{1}{r_w} + \frac{\frac{1}{r_p} - \frac{1}{r_c}}{L_p^2 n_s^2 \alpha^{1.201}} \right] \quad (\text{A.V.})$$

Let's define λ as the impact of the perforation on the turbulent term!

$$\lambda = \frac{\frac{r_w}{r_p} - \frac{r_w}{r_c}}{L_p^2 n_s^2 \alpha^{1.201}} \quad (\text{A.VI.})$$

With this the A become:

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho}{h_p^2 k^{1.201}} \left[\frac{1}{r_w} + \frac{\lambda}{r_w} \right] \quad (\text{A.VII.})$$

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho (1 + \lambda)}{h_p^2 k^{1.201} r_w} \quad (\text{A.VIII.})$$

Let's define Δs as $s_t - s_{\text{perf}}$!

$$B = \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + \Delta s \right]}{7.08 \times 10^{-3} \times k h} + \frac{\frac{\mu_o B_o \left[\ln \frac{r_e}{r_p} \right]}{7.08 \times 10^{-3} \times L_p k p}}{n_s \times h_p} \quad (\text{A.IX.})$$

$$B = \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + s_t \right]}{7.08 \times 10^{-3} \times k h} \quad (\text{A.X.})$$

Solving Eq.A.X. For s_t :

$$s_t = \frac{B \times 7.08 \times 10^{-3} \times kh}{\mu_o B_o} - \ln \left(0.472 \left(\frac{r_e}{r_w} \right) \right) \quad (\text{A.XI.})$$

Substituting Eq. A.IX. In Eq. A.XI.:

$$s_t = \Delta s + \frac{\ln \left(\frac{r_c}{r_p} \right) \frac{kh}{L_p k_p}}{n_s \times h_p} \quad (\text{A.XII.})$$

Let s_{perf} be the skin component caused by the perforation!

$$s_{\text{perf}} = s_t - \Delta s \quad (\text{A.XIII.})$$

$$s_{\text{perf}} = \frac{\ln \left(\frac{r_c}{r_p} \right)}{n_s L_p \alpha \varepsilon} \quad (\text{A.XIV.})$$

$$B = 141.24 \times \frac{\mu_o B_o \left[\ln \left(0.472 \left(\frac{r_e}{r_w} \right) \right) + \Delta s + s_{\text{perf}} \right]}{kh} \quad (\text{A.XV.})$$

For gas wells:

$$A = 7.3628 \times 10^{-2} \frac{\gamma_g T z (1 + \lambda)}{h_p^2 k^{1.201} r_w} \quad (\text{A.XVI.})$$

$$B = 141.24 \times \frac{\mu_g T z \left[\ln \left(0.472 \left(\frac{r_e}{r_w} \right) \right) + \Delta s + s_{\text{perf}} \right]}{kh} \quad (\text{A.XVII.})$$

Appendix B: Constants and variables used in the Karakas and Tariq method

$$r_{wD} = \frac{r_w}{L_p + r_w} \quad (\text{B.I.})$$

$$r_{pD} = \left(\frac{r_p}{2\delta_p} \right) \left(1 + \sqrt{\frac{k_V}{k_H}} \right) \quad (\text{B.II.})$$

$$h_D = \left(\frac{\delta_p}{L_p} \right) \sqrt{\frac{k_H}{k_V}} \quad (\text{B.III.})$$

$$r_{we}(\theta) = \begin{cases} \frac{1}{4} L_p, & \theta = 0^\circ \\ \alpha_\theta (r_w + L_p), & \text{otherwise} \end{cases} \quad (\text{B.IV.})$$

$$a = a_1 \log_{10} r_{pD} + a_2 \quad (\text{B.V.})$$

$$b = b_1 r_{pD} + b_2 \quad (\text{B.VI.})$$

Θ	α_Θ	c_1	c_2	a_1	a_2	b_1	b_2
0° (360°)	0.250	1.6×10^{-1}	2.675	-2.091	0.0453	5.1313	1.8672
180°	2.500	2.6×10^{-2}	4.532	-2.025	0.0943	3.0373	1.8115
120°	0.648	6.6×10^{-3}	5.320	-2.018	0.0634	1.6136	1.7770
90°	0.726	1.9×10^{-3}	6.155	-1.905	0.1038	1.5674	1.6935
60°	0.813	3.0×10^{-4}	7.509	-1.898	0.1023	1.3654	1.6490
45°	0.860	4.6×10^{-5}	8.791	-1.788	0.2398	1.1915	1.6392

Table B.1 Constants used in the Karakas and Tariq method

Appendix C: Modification of perforation tunnel – and crushed zone radius

Modification of r_p :

$$A_{cone} = \pi \times r_p \times \sqrt{r_p^2 + L_p^2} \quad (C.I.)$$

$$A_{cylinder} = 2r'_p L_p \pi \quad (C.II.)$$

$$A_{cone} = A_{cylinder} \quad (C.III.)$$

$$\pi \times r_p \times \sqrt{r_p^2 + L_p^2} = 2r'_p L_p \pi \quad (C.IV.)$$

$$r'_p = \frac{r_p \sqrt{r_p^2 + L_p^2}}{2L_p} \quad (C.V.)$$

As L_p is at least ten times bigger than r_p from Eq 5.:

$$r'_p \cong \frac{r_p}{2} \quad (C.VI.)$$

Modification of r_c :

First case:

$$\frac{r_c^2 \pi L_p}{3} - \frac{r_p^2 \pi L_p}{3} = r_c'^2 \pi L_p - r_p'^2 \pi L_p \quad (C.VII.)$$

$$r'_c = \sqrt{\frac{r_c^2 - r_p^2}{3}} + r_p'^2 \quad (C.VIII.)$$

Second case:

$$\frac{r_c^2 \pi}{3} (L_p + r_c - r_p) - \frac{r_p^2 \pi}{3} L_p = r_c'^2 \pi (L_p + r'_p - r'_c) - r_p'^2 \pi L_p \quad (C.IX.)$$

$$\frac{r_c^2}{3} L_p + \frac{r_c^3}{3} - \frac{r_p r_c^2}{3} - \frac{r_p^2 L_p}{3} + r_p'^2 L_p = r_c'^3 + r_c'^2 L_p - r_c'^2 r_p' \quad (C.X.)$$

$$\frac{r_c^2}{3} + \frac{r_c^3}{3L_p} - \frac{r_p r_c^2}{3L_p} - \frac{r_p^2}{3} + r_p'^2 = \frac{r_c'^3}{L_p} + r_c'^2 - \frac{r_c'^2 r_p'}{L_p} \quad (C.XI.)$$

$$\frac{r_c^3}{3L_p}, \frac{r_p r_c^2}{3L_p}, \frac{r_c'^3}{L_p}, \frac{r_c'^2 r_p'}{L_p} \cong 0 \text{ because } L_p \gg r_n^3$$

$$r'_c = \sqrt{\frac{r_c^2 - r_p^2}{3}} + r_p'^2 \quad (C.XII.)$$

Appendix D: Basic data of the wells

Gas wells				
Completion	Open hole	Perforated	Open hole	Perforated
P_r [psi]	3000.00	3000.00	3000.00	3000.00
k [mD]	10.00	10.00	500.00	500.00
r_e [ft]	1000.00	1000.00	1000.00	1000.00
k_H [mD]	10.00	10.00	500.00	500.00
k_V [mD]	1.00	1.00	50.00	50.00
T [R°]	630.00	630.00	630.00	630.00
z	0.89	0.89	0.89	0.89
μ_o [cP]	0.02	0.02	0.02	0.02
V_g	0.64	0.64	0.64	0.64
r_w [ft]	0.29	0.29	0.29	0.29
h [ft]	25.00	25.00	25.00	25.00
L_p [ft]		1.00		1.00
ns [spf]		5.00		5.00
α		0.30		0.30
ε		1.00		1.00
θ [°]		0.00		0.00
r_p [in]		0.18		0.18
r_c [in]		0.68		0.68
AOFP [cft/d]	29041.81	9904.52	323840.76	106682.62

Table D.1 : Basic data of Gas wells

Oil wells				
Completion	Open hole	Perforated	Open hole	Perforated
k [mD]	10.00	10.00	500.00	500.00
r_e [ft]	1000.00	1000.00	1000.00	1000.00
P_r [psi]	3000.00	3000.00	3000.00	3000.00
k_H [mD]	10.00	10.00	500.00	500.00
k_V [mD]	1.00	1.00	50.00	50.00
API density	45.38	45.38	45.38	45.38
μ_o [cP]	0.75	0.75	0.75	0.75
B_o	1.16	1.16	1.16	1.16
r_w [ft]	0.29	0.29	0.29	0.29
h [ft]	25.00	25.00	25.00	25.00
L_p [ft]		1.00		1.00
ns [spf]		5.00		5.00
α		0.30		0.30
ε		1.00		1.00
θ [°]		0.00		0.00
r_p [in]		0.18		0.18
r_c [in]		0.68		0.68
AOFP [bpd]	821.45	593.84	37782.81	22126.73

Table D.2: Basic data of oil wells

Appendix E: Sensitivity test results for oil wells

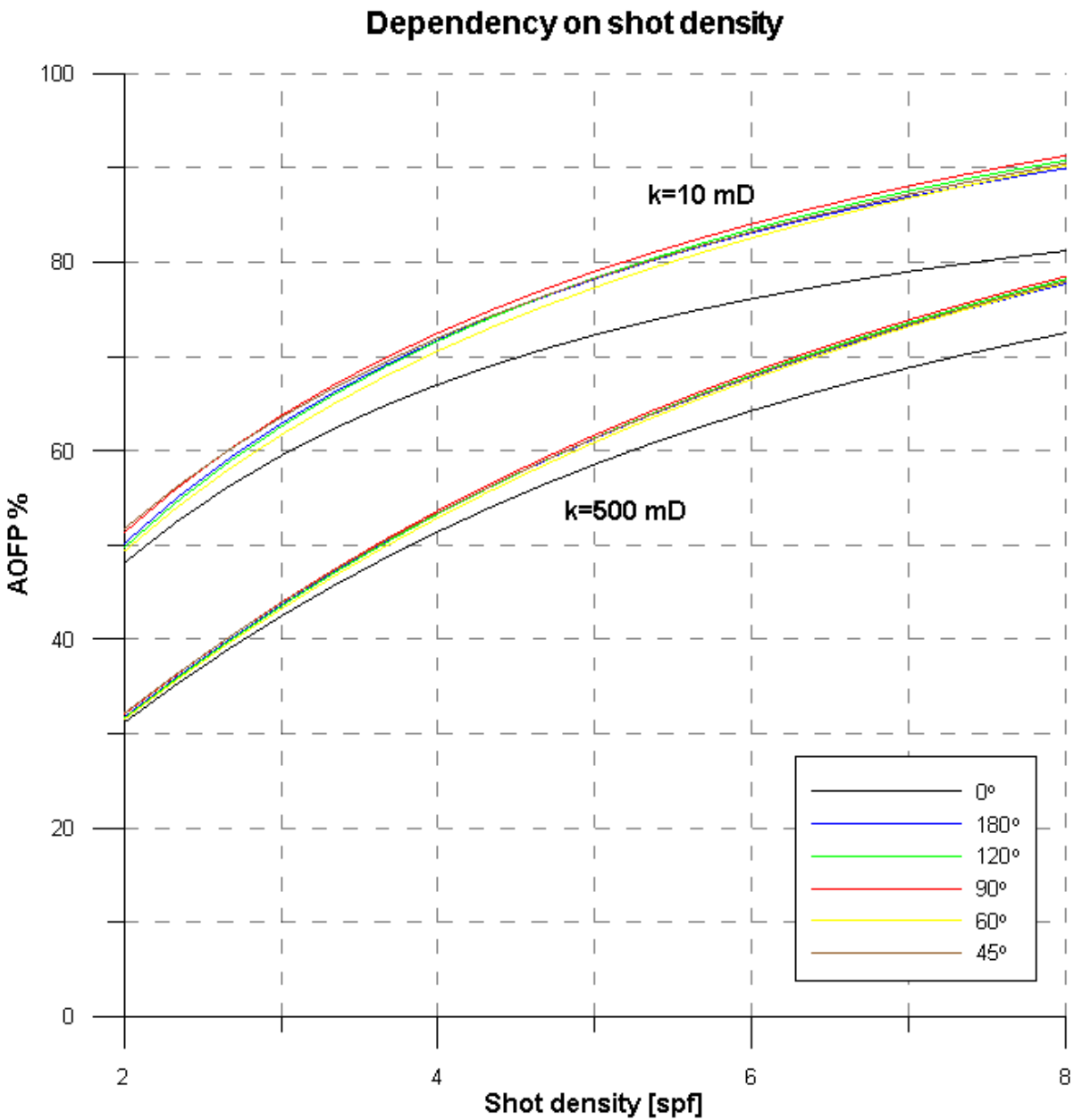


Figure E.1: Oil well's productivity dependency on shot density

Oil well's dependency on shot density												
Variable	%											
	k=500 mD						k=10 mD					
ns	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
2.00	31.16	31.73	31.61	32.03	31.50	32.13	48.10	50.15	49.73	51.31	49.31	51.70
2.33	35.21	35.95	35.83	36.25	35.65	36.30	52.45	54.94	54.55	55.98	53.93	56.16
2.67	38.96	39.90	39.79	40.19	39.55	40.19	56.21	59.15	58.79	60.08	58.02	60.08
3.00	42.44	43.61	43.51	43.89	43.21	43.84	59.47	62.86	62.56	63.72	61.67	63.55
3.33	45.67	47.07	46.99	47.36	46.64	47.25	62.31	66.16	65.92	66.96	64.95	66.65
3.67	48.66	50.32	50.25	50.60	49.87	50.44	64.81	69.10	68.93	69.87	67.90	69.44
4.00	51.42	53.35	53.31	53.64	52.89	53.44	67.02	71.74	71.64	72.50	70.58	71.96
4.33	53.99	56.19	56.17	56.50	55.73	56.24	68.98	74.12	74.09	74.87	73.03	74.26
4.67	56.36	58.84	58.86	59.17	58.40	58.88	70.73	76.27	76.32	77.04	75.26	76.36
5.00	58.56	61.32	61.38	61.68	60.91	61.35	72.29	78.22	78.35	79.02	77.31	78.28
5.33	60.60	63.65	63.75	64.04	63.28	63.67	73.70	80.00	80.21	80.84	79.20	80.05
5.67	62.49	65.83	65.97	66.25	65.50	65.86	74.97	81.63	81.92	82.51	80.94	81.69
6.00	64.25	67.87	68.05	68.33	67.59	67.91	76.12	83.12	83.49	84.06	82.56	83.21
6.33	65.88	69.78	70.01	70.28	69.56	69.85	77.16	84.49	84.94	85.49	84.07	84.63
6.67	67.40	71.57	71.85	72.13	71.42	71.67	78.12	85.76	86.29	86.82	85.47	85.95
7.00	68.81	73.26	73.58	73.86	73.18	73.39	78.99	86.93	87.53	88.06	86.78	87.18
7.33	70.12	74.84	75.21	75.49	74.84	75.02	79.79	88.01	88.70	89.21	88.01	88.34
7.67	71.34	76.32	76.75	77.03	76.40	76.55	80.52	89.02	89.78	90.29	89.16	89.43
8.00	72.48	77.72	78.20	78.49	77.88	78.00	81.20	89.95	90.79	91.31	90.24	90.45

Table E.1: Oil well's dependency on shot density

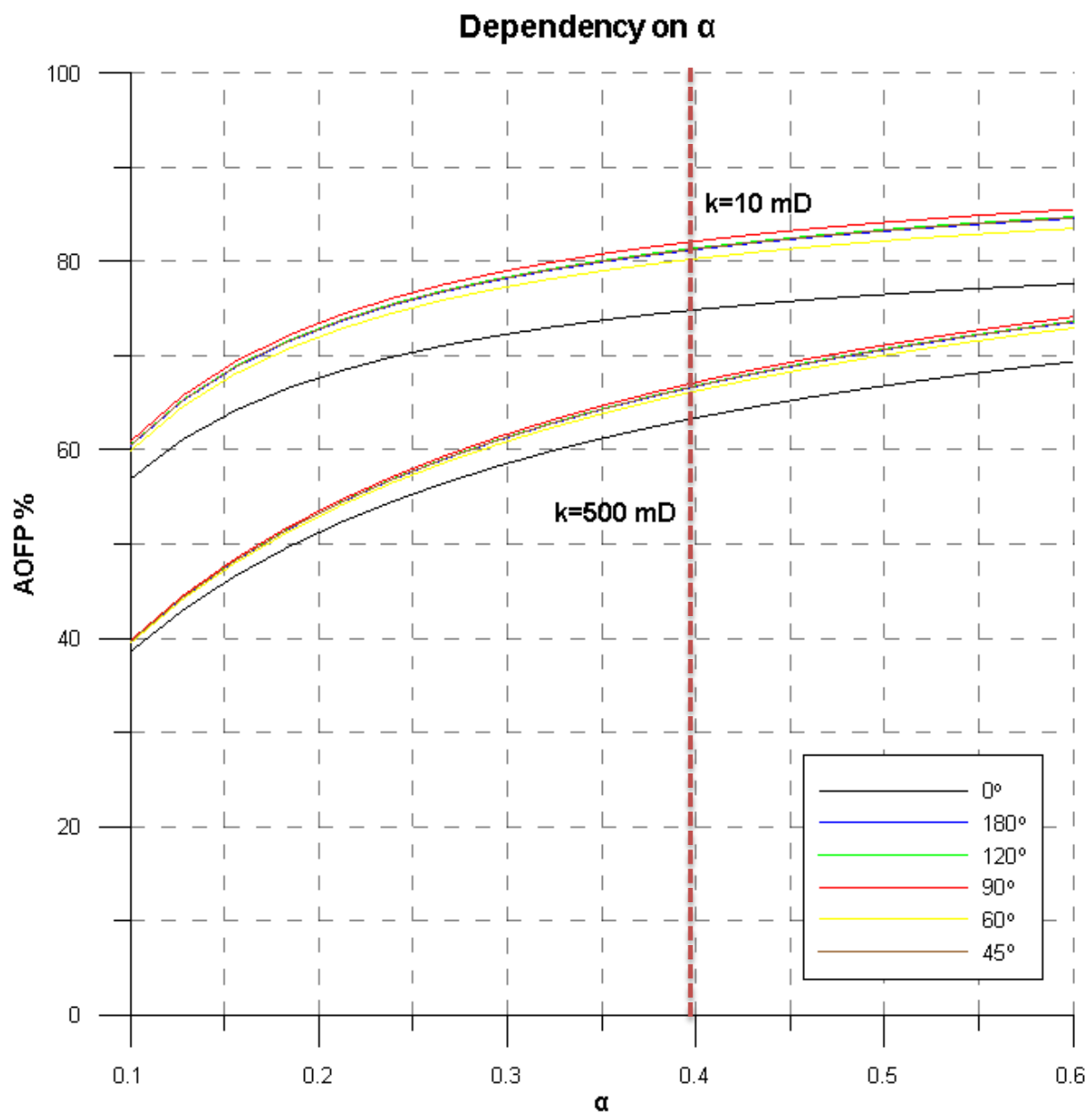


Figure E.2: Oil well's productivity dependency on α

Oil well's dependency on α												
Variable	%											
	k=500 mD						k=10 mD					
	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
0.10	38.57	39.63	39.65	39.77	39.48	39.64	56.90	60.42	60.49	60.88	59.88	60.45
0.13	42.98	44.33	44.36	44.50	44.13	44.34	61.10	65.20	65.29	65.75	64.58	65.24
0.16	46.60	48.22	48.26	48.43	47.98	48.24	64.17	68.73	68.83	69.34	68.04	68.78
0.18	49.65	51.52	51.56	51.76	51.24	51.54	66.51	71.45	71.55	72.11	70.69	71.50
0.21	52.25	54.36	54.40	54.63	54.05	54.38	68.36	73.60	73.71	74.30	72.79	73.65
0.24	54.51	56.84	56.88	57.13	56.49	56.86	69.85	75.34	75.46	76.08	74.50	75.40
0.27	56.49	59.02	59.07	59.35	58.64	59.04	71.08	76.79	76.91	77.55	75.91	76.84
0.29	58.24	60.96	61.02	61.31	60.56	60.99	72.11	78.00	78.13	78.80	77.09	78.06
0.32	59.80	62.70	62.76	63.07	62.27	62.73	72.98	79.04	79.17	79.85	78.10	79.10
0.35	61.19	64.27	64.33	64.66	63.81	64.30	73.73	79.93	80.07	80.77	78.98	79.99
0.38	62.46	65.68	65.75	66.10	65.20	65.72	74.39	80.71	80.85	81.56	79.73	80.77
0.41	63.60	66.98	67.05	67.41	66.47	67.01	74.96	81.39	81.53	82.26	80.40	81.46
0.43	64.64	68.16	68.23	68.61	67.63	68.19	75.47	82.00	82.14	82.89	80.99	82.07
0.46	65.59	69.24	69.32	69.71	68.69	69.28	75.93	82.54	82.69	83.44	81.52	82.61
0.49	66.47	70.24	70.32	70.73	69.67	70.27	76.33	83.03	83.17	83.94	81.99	83.09
0.52	67.27	71.16	71.24	71.67	70.58	71.20	76.70	83.46	83.61	84.38	82.42	83.53
0.54	68.02	72.01	72.10	72.53	71.41	72.05	77.03	83.86	84.01	84.79	82.80	83.93
0.57	68.71	72.81	72.89	73.34	72.19	72.85	77.33	84.22	84.37	85.16	83.16	84.29
0.60	69.35	73.55	73.64	74.10	72.92	73.59	77.61	84.55	84.71	85.50	83.48	84.62

Table E.2: Oil well's dependency on α

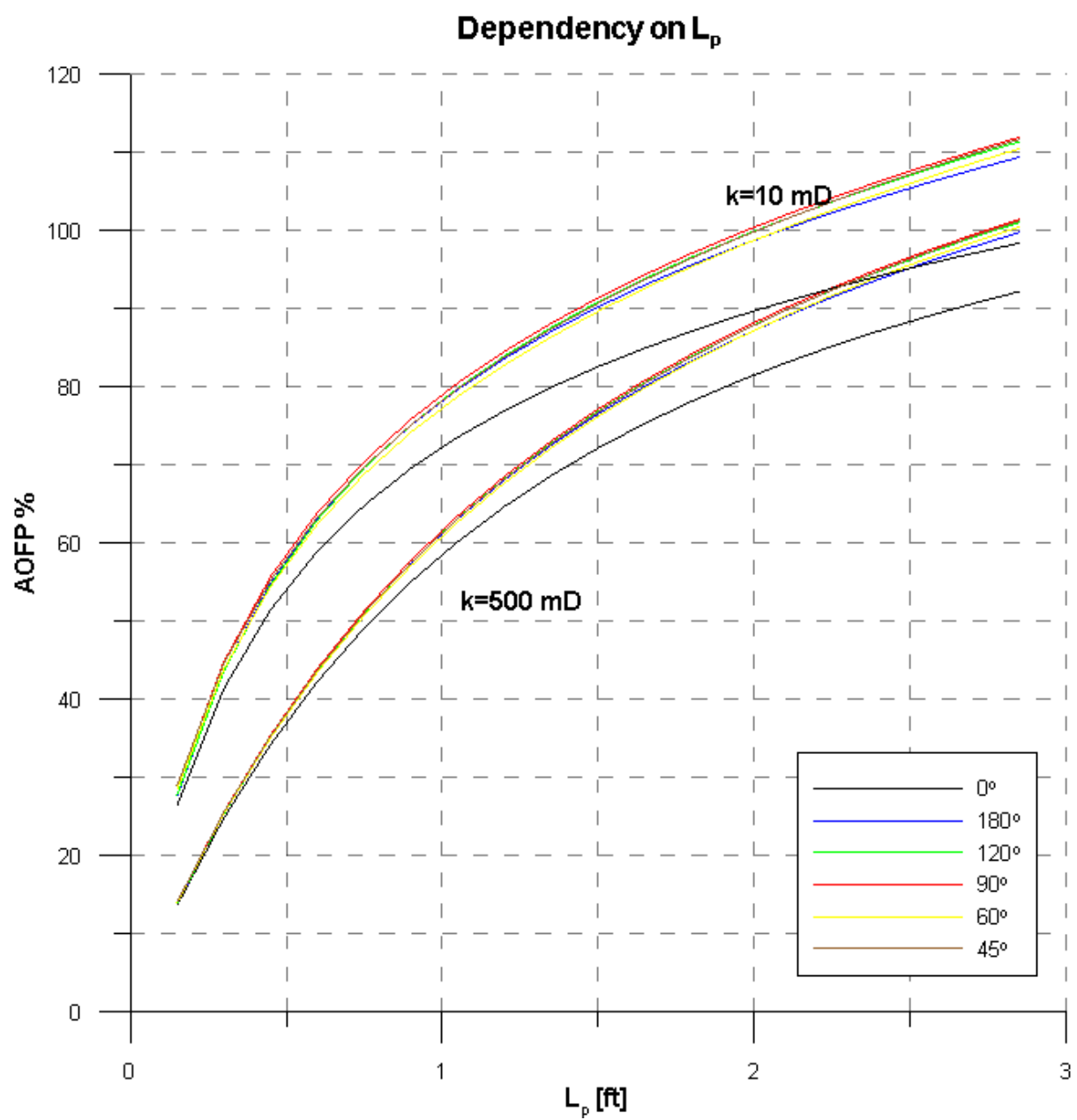


Figure E.3: Oil well's productivity dependency on perforation length

Oil well's dependency on perforation length												
Variable	%											
	k=500 mD						k=10 mD					
L_p	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
0.15	13.61	13.81	13.83	14.01	13.95	14.02	26.35	27.58	27.67	28.82	28.42	28.92
0.30	24.81	25.36	25.33	25.59	25.39	25.54	41.37	43.74	43.62	44.81	43.89	44.59
0.45	34.26	35.22	35.16	35.46	35.11	35.34	51.52	54.85	54.66	55.72	54.47	55.27
0.60	42.28	43.71	43.65	43.96	43.47	43.76	59.00	63.15	62.98	63.91	62.44	63.32
0.75	49.14	51.07	51.03	51.34	50.73	51.08	64.83	69.71	69.63	70.44	68.84	69.76
0.90	55.06	57.49	57.50	57.80	57.09	57.50	69.57	75.10	75.14	75.86	74.18	75.13
1.05	60.20	63.13	63.21	63.50	62.71	63.16	73.54	79.67	79.84	80.49	78.77	79.75
1.20	64.70	68.11	68.28	68.57	67.71	68.21	76.95	83.62	83.95	84.55	82.80	83.81
1.35	68.66	72.55	72.81	73.09	72.18	72.72	79.93	87.11	87.59	88.15	86.40	87.43
1.50	72.19	76.53	76.88	77.17	76.22	76.79	82.58	90.22	90.87	91.40	89.66	90.71
1.65	75.33	80.11	80.56	80.85	79.87	80.48	84.95	93.05	93.85	94.37	92.64	93.71
1.80	78.16	83.35	83.91	84.20	83.21	83.84	87.11	95.63	96.59	97.09	95.39	96.47
1.95	80.72	86.30	86.97	87.27	86.26	86.93	89.09	98.00	99.12	99.62	97.94	99.05
2.10	83.05	89.00	89.78	90.09	89.08	89.77	90.91	100.21	101.48	101.98	100.33	101.45
2.25	85.19	91.49	92.37	92.69	91.68	92.39	92.60	102.27	103.68	104.19	102.57	103.72
2.40	87.14	93.78	94.77	95.10	94.10	94.83	94.18	104.20	105.76	106.28	104.70	105.86
2.55	88.95	95.91	97.00	97.34	96.35	97.11	95.66	106.02	107.72	108.25	106.71	107.89
2.70	90.63	97.89	99.09	99.44	98.46	99.24	97.05	107.74	109.58	110.13	108.62	109.82
2.85	92.19	99.74	101.04	101.40	100.44	101.24	98.37	109.38	111.36	111.92	110.45	111.66

Table E.3: Oil well's dependency on perforation length

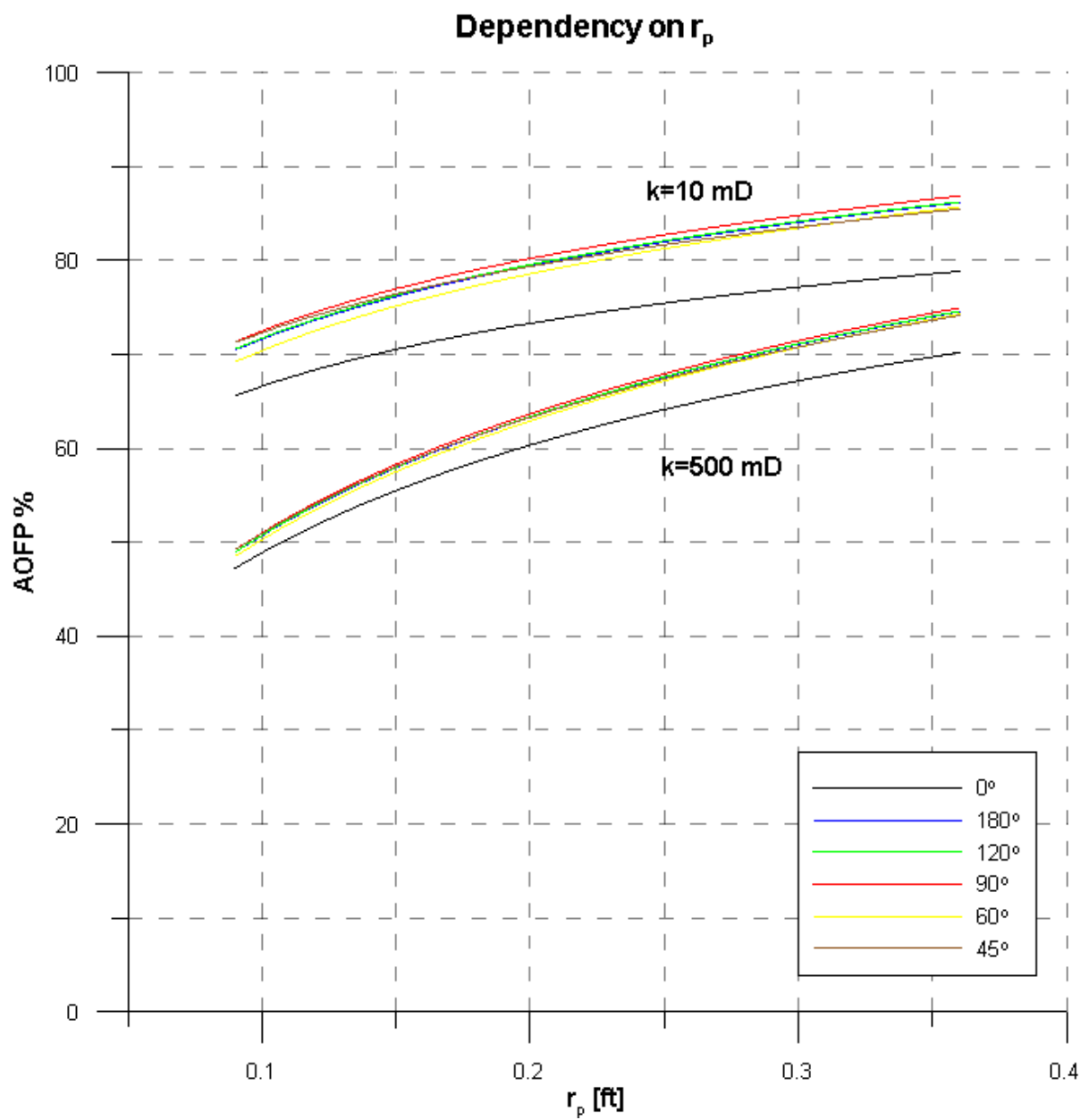


Figure E.4: Oil well's productivity dependency on perforation tunnel radius

Oil well's dependency on perforation tunnel radius												
Variable	%											
	k=500 mD						k=10 mD					
	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
r _p												
0.09	47.25	48.94	48.97	49.22	48.50	49.20	65.62	70.49	70.57	71.34	69.19	71.26
0.11	49.68	51.57	51.61	51.87	51.14	51.79	67.10	72.18	72.29	73.04	70.97	72.81
0.12	51.83	53.91	53.96	54.23	53.48	54.10	68.38	73.66	73.78	74.51	72.53	74.16
0.14	53.76	56.02	56.07	56.35	55.59	56.17	69.51	74.98	75.10	75.81	73.90	75.35
0.15	55.51	57.94	57.99	58.28	57.52	58.05	70.53	76.16	76.29	76.98	75.15	76.42
0.17	57.10	59.70	59.76	60.05	59.28	59.77	71.45	77.23	77.37	78.05	76.27	77.39
0.18	58.56	61.32	61.38	61.68	60.91	61.35	72.29	78.22	78.35	79.02	77.31	78.28
0.20	59.92	62.83	62.89	63.19	62.43	62.82	73.06	79.13	79.26	79.92	78.26	79.10
0.21	61.17	64.24	64.29	64.60	63.84	64.18	73.78	79.98	80.10	80.75	79.15	79.86
0.23	62.34	65.55	65.61	65.92	65.17	65.46	74.44	80.76	80.88	81.53	79.98	80.57
0.24	63.43	66.78	66.84	67.16	66.41	66.65	75.05	81.50	81.62	82.26	80.76	81.24
0.26	64.46	67.94	68.00	68.32	67.58	67.77	75.63	82.20	82.31	82.94	81.49	81.87
0.27	65.42	69.04	69.10	69.42	68.69	68.83	76.17	82.85	82.96	83.59	82.18	82.46
0.29	66.33	70.08	70.13	70.47	69.74	69.84	76.68	83.48	83.58	84.20	82.84	83.02
0.30	67.18	71.06	71.12	71.45	70.74	70.79	77.16	84.06	84.16	84.78	83.46	83.55
0.32	67.99	72.00	72.05	72.39	71.68	71.69	77.62	84.62	84.72	85.34	84.05	84.06
0.33	68.76	72.89	72.94	73.29	72.59	72.55	78.05	85.16	85.24	85.87	84.62	84.55
0.35	69.49	73.74	73.79	74.14	73.45	73.37	78.46	85.67	85.75	86.37	85.16	85.01
0.36	70.19	74.55	74.60	74.95	74.28	74.15	78.84	86.15	86.23	86.85	85.67	85.46

Table E.4: Oil well's dependency on perforation tunnel radius

Appendix F: Sensitivity test results for gas wells

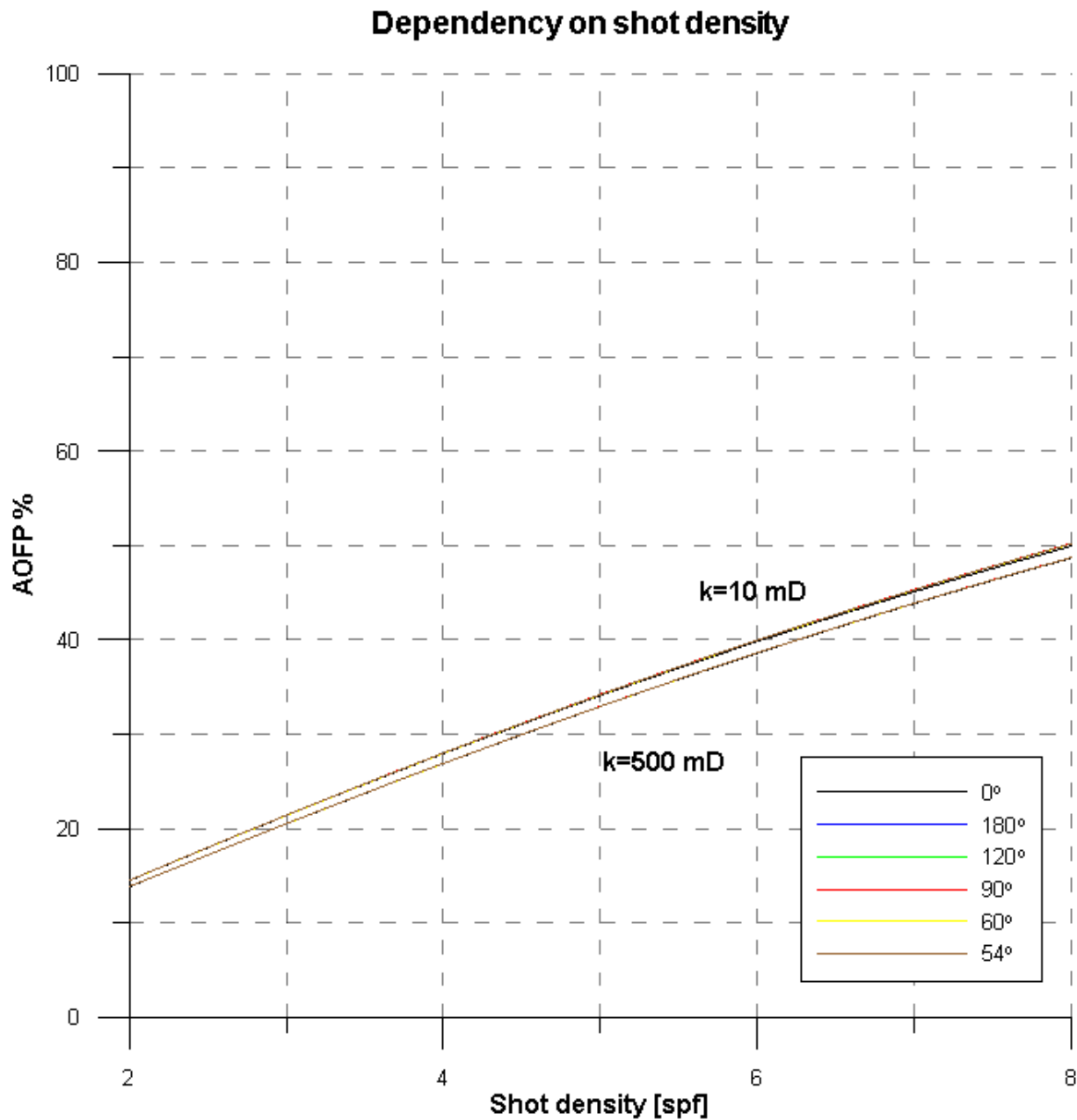


Figure F.1: Gas well’s productivity dependency on shot density

Gas well's dependency on shot density												
Variable	%											
	k=500 mD						k=10 mD					
	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
2.00	13.85	13.85	13.85	13.85	13.85	13.85	14.49	14.51	14.50	14.52	14.50	14.52
2.33	16.10	16.10	16.10	16.10	16.10	16.10	16.83	16.85	16.84	16.85	16.84	16.85
2.67	18.32	18.33	18.33	18.33	18.32	18.33	19.13	19.15	19.15	19.16	19.14	19.16
3.00	20.51	20.52	20.52	20.52	20.52	20.52	21.39	21.42	21.42	21.43	21.41	21.43
3.33	22.68	22.69	22.69	22.69	22.68	22.69	23.62	23.66	23.65	23.66	23.64	23.66
3.67	24.81	24.82	24.82	24.82	24.81	24.82	25.80	25.85	25.85	25.86	25.84	25.85
4.00	26.90	26.91	26.91	26.91	26.91	26.91	27.94	28.00	28.00	28.01	27.99	28.01
4.33	28.95	28.97	28.97	28.97	28.97	28.97	30.04	30.11	30.11	30.12	30.10	30.12
4.67	30.97	30.99	30.99	30.99	30.98	30.99	32.10	32.18	32.18	32.19	32.17	32.18
5.00	32.94	32.96	32.96	32.96	32.96	32.96	34.10	34.20	34.20	34.21	34.19	34.20
5.33	34.87	34.90	34.90	34.90	34.89	34.90	36.06	36.17	36.17	36.18	36.16	36.17
5.67	36.76	36.79	36.79	36.79	36.78	36.79	37.97	38.09	38.10	38.11	38.08	38.10
6.00	38.60	38.63	38.63	38.63	38.63	38.63	39.83	39.97	39.98	39.99	39.96	39.97
6.33	40.40	40.43	40.43	40.43	40.43	40.43	41.64	41.79	41.80	41.81	41.79	41.80
6.67	42.15	42.18	42.19	42.19	42.18	42.18	43.40	43.57	43.58	43.59	43.56	43.57
7.00	43.85	43.89	43.89	43.90	43.89	43.89	45.11	45.30	45.31	45.32	45.29	45.30
7.33	45.51	45.55	45.56	45.56	45.55	45.55	46.77	46.97	46.99	47.00	46.97	46.98
7.67	47.12	47.17	47.17	47.17	47.17	47.17	48.38	48.60	48.62	48.63	48.60	48.61
8.00	48.69	48.74	48.74	48.74	48.74	48.74	49.95	50.18	50.20	50.21	50.19	50.19

Table F.1: Gas well's dependency on shot density

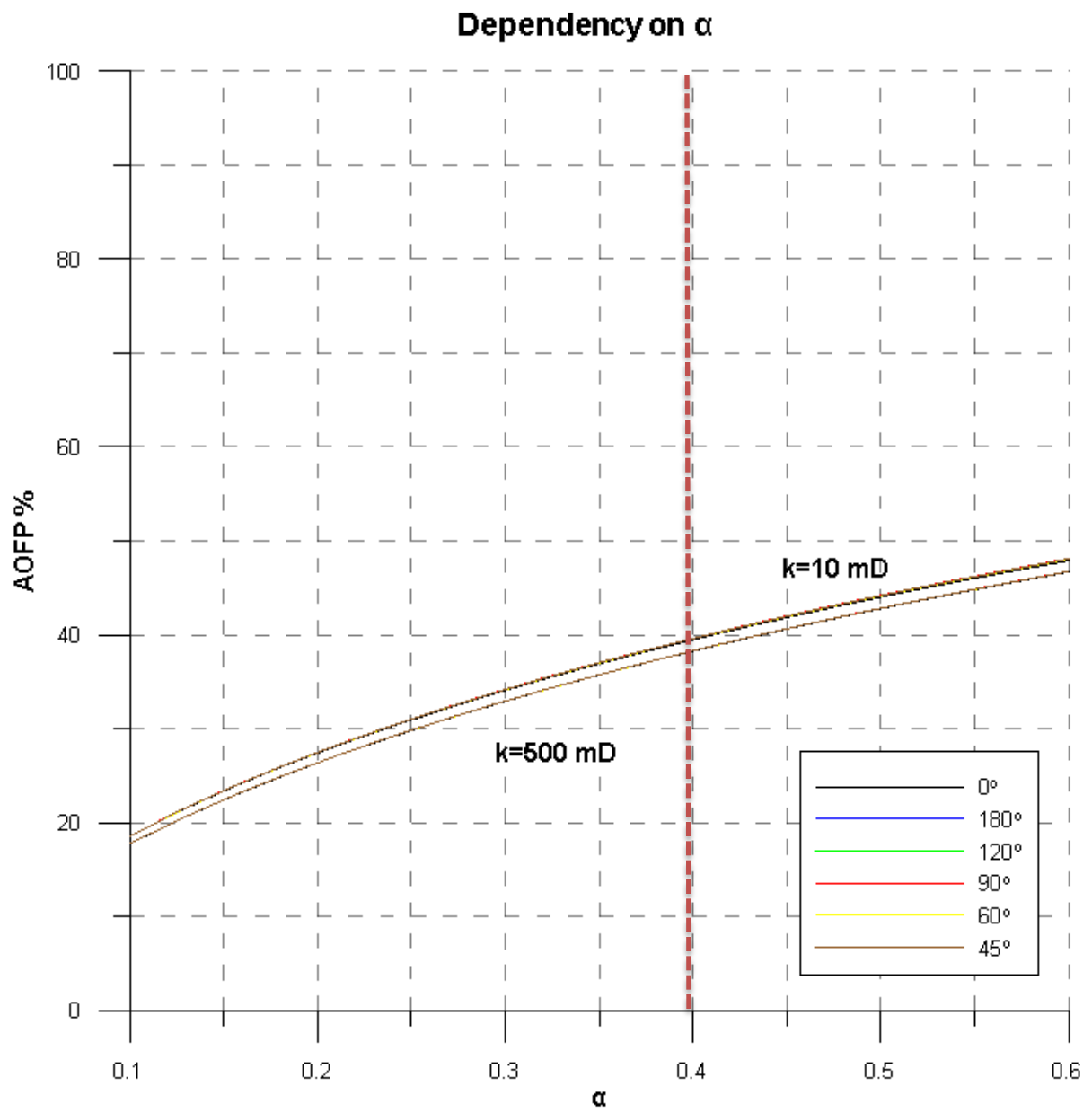


Figure F.2: Gas well's productivity dependency on α

Gas well's dependency on α												
Variable	%											
	k=500 mD						k=10 mD					
α	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
0.10	17.78	17.79	17.79	17.79	17.79	17.79	18.58	18.61	18.61	18.61	18.60	18.61
0.13	20.48	20.49	20.49	20.49	20.49	20.49	21.37	21.41	21.41	21.41	21.40	21.41
0.16	22.92	22.93	22.93	22.93	22.93	22.93	23.88	23.92	23.93	23.93	23.92	23.92
0.18	25.15	25.16	25.16	25.16	25.16	25.16	26.16	26.22	26.22	26.23	26.21	26.22
0.21	27.21	27.22	27.22	27.22	27.22	27.22	28.27	28.33	28.34	28.34	28.32	28.33
0.24	29.12	29.14	29.14	29.14	29.14	29.14	30.23	30.30	30.30	30.31	30.29	30.30
0.27	30.92	30.94	30.94	30.94	30.94	30.94	32.05	32.14	32.14	32.15	32.13	32.14
0.29	32.62	32.63	32.63	32.64	32.63	32.63	33.77	33.87	33.87	33.88	33.85	33.87
0.32	34.22	34.24	34.24	34.24	34.23	34.24	35.39	35.50	35.50	35.51	35.48	35.50
0.35	35.74	35.76	35.76	35.76	35.75	35.76	36.93	37.04	37.04	37.05	37.02	37.04
0.38	37.18	37.20	37.20	37.21	37.20	37.20	38.38	38.50	38.50	38.52	38.48	38.50
0.41	38.56	38.58	38.58	38.59	38.58	38.58	39.77	39.90	39.90	39.91	39.88	39.90
0.43	39.87	39.90	39.90	39.90	39.89	39.90	41.09	41.22	41.23	41.24	41.20	41.22
0.46	41.13	41.16	41.16	41.16	41.15	41.16	42.35	42.49	42.50	42.51	42.47	42.49
0.49	42.33	42.37	42.37	42.37	42.36	42.37	43.55	43.71	43.71	43.73	43.68	43.71
0.52	43.49	43.52	43.52	43.53	43.52	43.52	44.70	44.87	44.87	44.89	44.85	44.87
0.54	44.60	44.64	44.64	44.64	44.63	44.64	45.81	45.98	45.99	46.01	45.96	45.99
0.57	45.67	45.71	45.71	45.71	45.70	45.71	46.88	47.06	47.06	47.08	47.03	47.06
0.60	46.70	46.74	46.74	46.74	46.73	46.74	47.90	48.09	48.09	48.11	48.06	48.09

Table F.2: Gas well's dependency on α

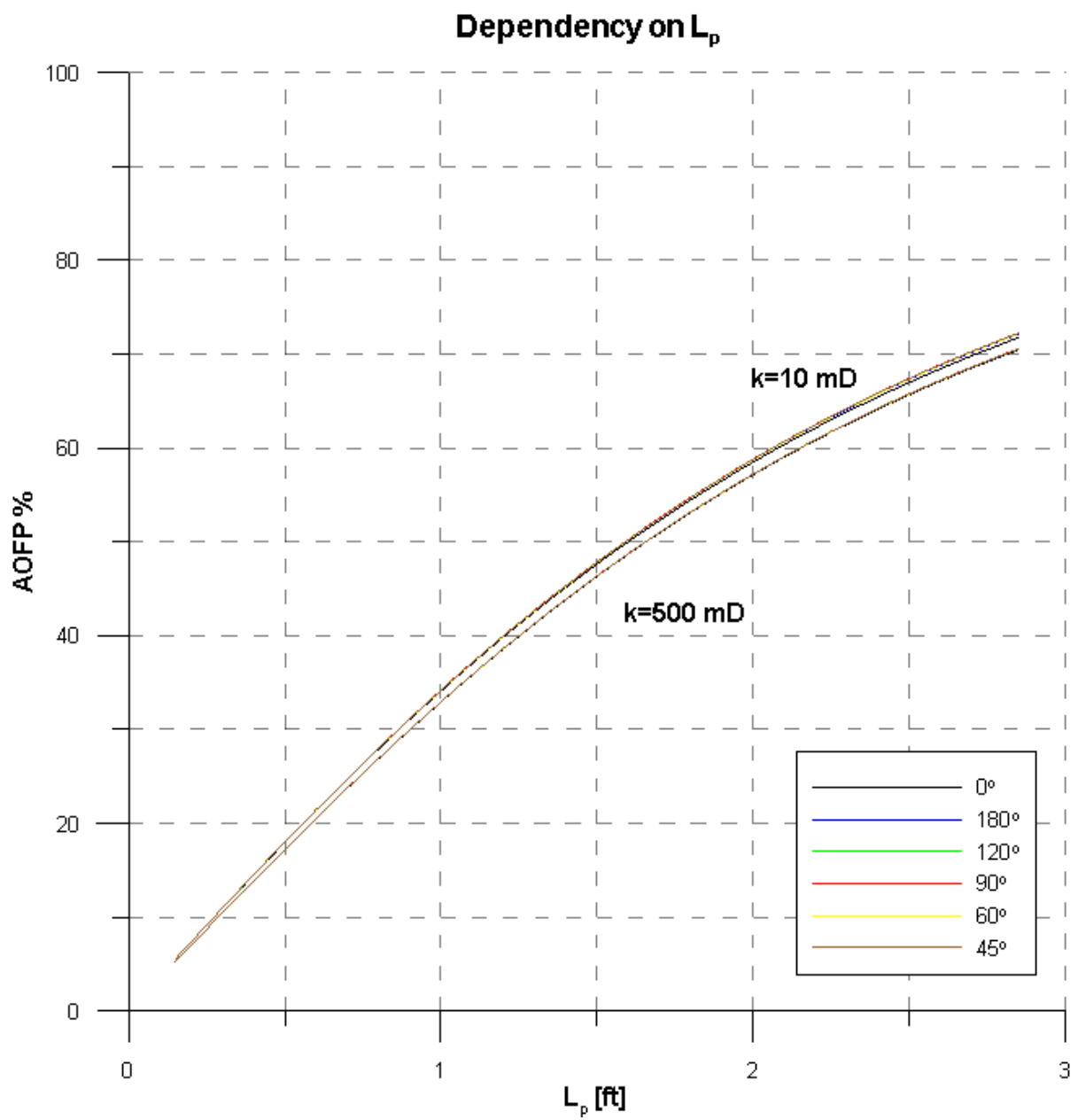


Figure F.3: Gas well's productivity dependency on perforation length

Gas well's dependency on perforation length												
Variable	%											
	k=500 mD						k=10 mD					
L_p	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
0.15	5.26	5.26	5.26	5.26	5.26	5.26	5.54	5.54	5.54	5.55	5.54	5.55
0.30	10.44	10.45	10.45	10.45	10.45	10.45	10.95	10.97	10.97	10.97	10.97	10.97
0.45	15.54	15.55	15.55	15.55	15.55	15.55	16.25	16.28	16.27	16.28	16.27	16.28
0.60	20.52	20.52	20.52	20.53	20.52	20.52	21.39	21.43	21.43	21.43	21.42	21.43
0.75	25.33	25.34	25.34	25.35	25.34	25.35	26.34	26.39	26.39	26.40	26.38	26.39
0.90	29.97	29.98	29.98	29.98	29.98	29.98	31.07	31.15	31.15	31.16	31.14	31.15
1.05	34.40	34.42	34.42	34.42	34.41	34.42	35.58	35.68	35.69	35.70	35.67	35.69
1.20	38.61	38.63	38.63	38.63	38.63	38.63	39.85	39.98	39.98	39.99	39.96	39.98
1.35	42.59	42.62	42.62	42.62	42.62	42.62	43.87	44.03	44.04	44.05	44.01	44.03
1.50	46.34	46.37	46.38	46.38	46.37	46.37	47.65	47.83	47.84	47.85	47.82	47.84
1.65	49.85	49.89	49.90	49.90	49.89	49.90	51.18	51.39	51.41	51.42	51.38	51.40
1.80	53.14	53.19	53.19	53.19	53.19	53.19	54.47	54.71	54.73	54.75	54.70	54.73
1.95	56.20	56.26	56.26	56.27	56.26	56.26	57.54	57.80	57.83	57.85	57.80	57.83
2.10	59.05	59.11	59.12	59.12	59.11	59.12	60.39	60.68	60.71	60.73	60.68	60.71
2.25	61.70	61.77	61.77	61.78	61.77	61.77	63.02	63.34	63.38	63.40	63.35	63.38
2.40	64.15	64.22	64.23	64.24	64.23	64.23	65.47	65.81	65.86	65.88	65.83	65.86
2.55	66.43	66.50	66.51	66.52	66.51	66.52	67.73	68.10	68.15	68.17	68.12	68.16
2.70	68.53	68.61	68.62	68.63	68.62	68.63	69.83	70.22	70.28	70.29	70.25	70.28
2.85	70.48	70.56	70.58	70.58	70.57	70.58	71.76	72.18	72.24	72.26	72.21	72.25

Table F.3: Gas well's dependency on perforation length

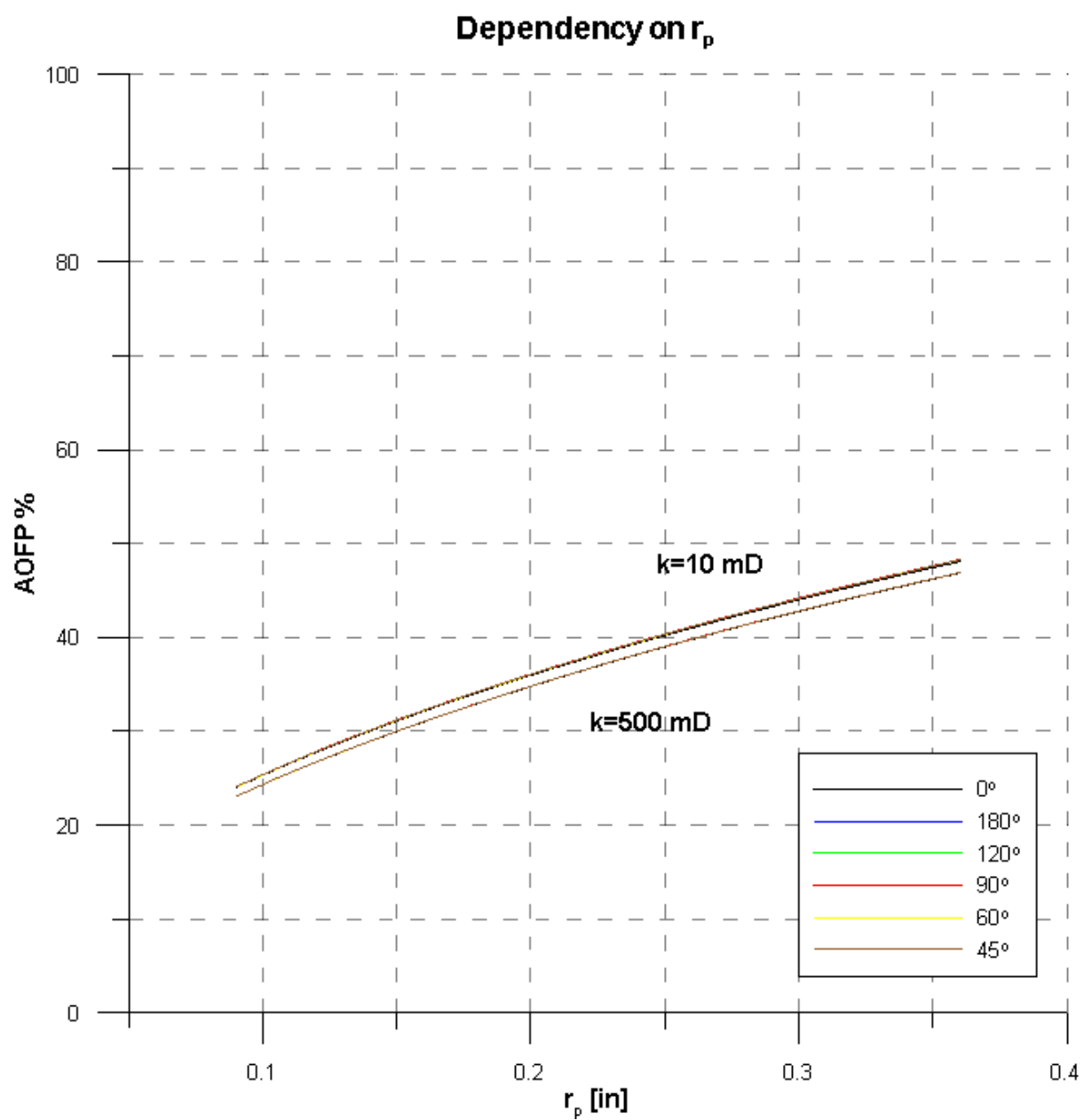


Figure F.4: Gas well's productivity dependency on perforation tunnel radius

Gas well's dependency on perforation tunnel radius												
Variable	%											
	k=500 mD						k=10 mD					
r_p	0°	180°	120°	90°	60°	45°	0°	180°	120°	90°	60°	45°
0.09	23.04	23.05	23.05	23.05	23.05	23.05	24.01	24.06	24.06	24.07	24.05	24.07
0.11	24.94	24.95	24.95	24.95	24.95	24.95	25.96	26.02	26.02	26.02	26.00	26.02
0.12	26.72	26.73	26.73	26.73	26.73	26.73	27.78	27.84	27.84	27.85	27.83	27.85
0.14	28.40	28.41	28.41	28.41	28.41	28.41	29.49	29.56	29.56	29.57	29.54	29.56
0.15	29.98	30.00	30.00	30.00	30.00	30.00	31.10	31.18	31.18	31.19	31.17	31.18
0.17	31.50	31.51	31.51	31.52	31.51	31.51	32.64	32.72	32.73	32.74	32.71	32.73
0.18	32.94	32.96	32.96	32.96	32.96	32.96	34.10	34.20	34.20	34.21	34.19	34.20
0.20	34.33	34.35	34.35	34.35	34.35	34.35	35.51	35.61	35.61	35.62	35.60	35.61
0.21	35.66	35.69	35.69	35.69	35.68	35.69	36.86	36.97	36.97	36.98	36.95	36.97
0.23	36.95	36.98	36.98	36.98	36.97	36.97	38.15	38.27	38.28	38.29	38.26	38.27
0.24	38.19	38.22	38.22	38.22	38.22	38.22	39.41	39.53	39.53	39.55	39.52	39.53
0.26	39.39	39.42	39.42	39.42	39.42	39.42	40.61	40.75	40.75	40.76	40.74	40.74
0.27	40.56	40.59	40.59	40.59	40.58	40.58	41.78	41.92	41.93	41.94	41.91	41.92
0.29	41.68	41.71	41.71	41.72	41.71	41.71	42.91	43.06	43.07	43.08	43.05	43.05
0.30	42.78	42.81	42.81	42.81	42.81	42.81	44.01	44.17	44.17	44.18	44.16	44.16
0.32	43.84	43.87	43.87	43.88	43.87	43.87	45.07	45.24	45.24	45.26	45.23	45.23
0.33	44.87	44.91	44.91	44.91	44.91	44.91	46.10	46.28	46.28	46.30	46.27	46.27
0.35	45.88	45.92	45.92	45.92	45.91	45.91	47.11	47.29	47.29	47.31	47.28	47.28
0.36	46.86	46.89	46.90	46.90	46.89	46.89	48.08	48.27	48.28	48.29	48.26	48.26

Table F.4: Gas well's dependency on perforation tunnel radius