UNIVERSITY OF MISKOLC

FACULTY OF EARTH SCIENCE AND ENGINEERING

MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES

Flow Behavior Investigation of Perforated Hydrocarbon Wells

Thesis Booklet of Doctoral (PhD) Dissertation

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1. Aim and Scope of Work

The oil price crisis between 2014 and 2016 caused a more than 70% drop in the price of the crude oil. The production optimization of hydrocarbon producing wells became the first priority in this new economic environment. Productivity of a hydrocarbon well can substantially be improved by the proper planning and completion of perforating. Unfortunately, the roots of applied computational methods are used calculating the effect of perforation design on the productivity- originated back to a more than thirty-year old semi analytical method. Furthermore, many questions regarding the effects of the perforation design are yet to be answered.

During my research work I have investigated the flow behavior around perforated wells completed in consolidated petroleum reservoirs. My main goal was understanding how the individual perforation parameters affect the hydrocarbon inflow. I have found that it is rather necessary to introduce a new analytical method, as the previously formed techniques applied in the present days neglect important effects. My newly developed model provides a more accurate way to determine the pressure drop caused by the actual perforation design. The obtained results show strong correlation with field experiences.

In my recent work I introduce the perforation parameters, showing their attributes and professional information about those. Furthermore, I present methods available to characterize productivity of producing wells and the skin factor, which represents the deviation from unaltered inflow.

In the past several methods were published to calculate the flow rate of perforated wells. During my research activity I examined the most important and most widely applied theories. My results highlighted that the accuracy of these methods is rather questionable as these neglect important features.

In the following steps I identified the flow zones around perforation channels and the previously neglected flow influencing factors. I determined the relationship between the flow rate and pressure drop in the identified zones and the effects of influencing factors.

I examined my newly developed method in details regarding to the effect of the individual perforation parameters on inflow in case of both oil and gas flow. I investigated the effect of the invaded zone in case of different perforation lengths and the effect of production intensification in such cases.

The results show exceptionally good correlation with field experiences. My conclusions provide a good guideline for perforation planning and this method can also be applied for examining other, different production optimizations.

2. The Significance of Results

It has already been mentioned that the obtained results show a very good correlation with field experiences. It has been one of the main goals of several service companies to reach the longest open perforation channels possible for a long time achieving best productivity, converging to relevant field experiences. The application of the optimal phase angles of 45°and 60° is also a common practice. Furthermore, it was also observed a long time ago that the productivity of gas wells is more sensitive to the perforation design.

The method I introduced in my work has several advantages - being easily programable and requiring less resource comparing to other simulation methods. With this, the design of optimal perforations – both in a technical and an economic manner – becomes possible in the planning phase:

- The optimal productivity can be modeled and determined,
- it is possible to evaluate a cost sensitivity analysis on the design,
- selection of the technology and the provider service company can easily be done,
- the cost-efficiency study of the different designs can be visualized.

The method can be applied effectively in case of production intensification procedures because:

- it is suitable to investigate the reasons for insufficient productivity,
- it can be applied to evaluate the efficiency of different intensification procedures, making the economic evaluation possible.

Based on the presented statements the model can be utilized during any steps of the intensification project, from the candidate selection to the success evaluation.

In summary, reaching the desired productivity by the most cost-efficient way is crucial in the present world economic environment. . The developed method provides the necessary means to fulfill that desire both for the newly drilled wells and for the wells which are already in production.

3. Applied Assumptions

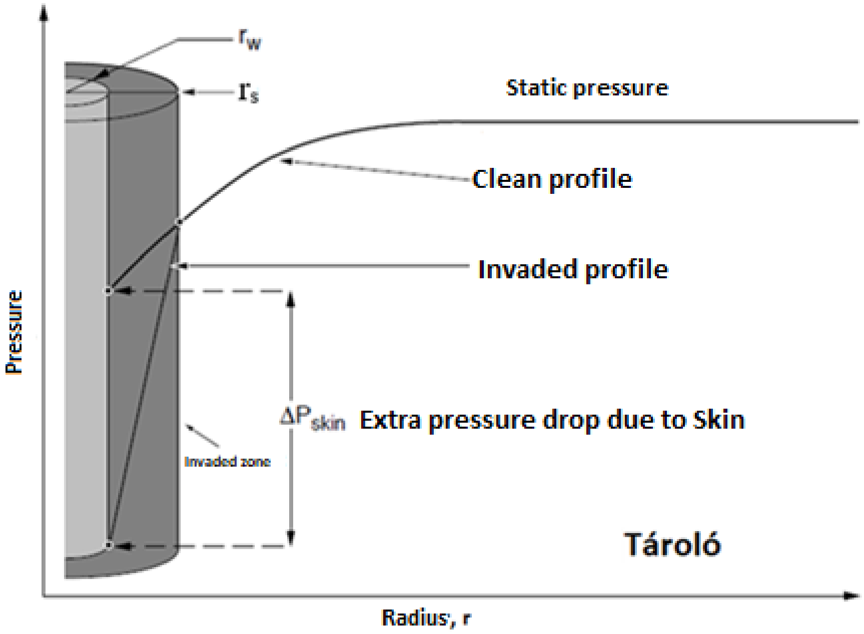

Figure 1.: Effect of skin (invaded zone) (Ballistics, 2014)

The factors influencing productivity can be characterized by the extra pressure drop caused, according to the figure above (Figure 1.). This pressure drop changes alongside the flow path, thus the flow path should be split according to the influencing factors:

1. Pressure drop in the vicinity of the well (flow perpendicular to the axis of the well).
2. Pressure drop in the vicinity of the perforation channels (flow perpendicular to the axis of perforation channels).
3. Pressure drop in the crushed zone.
4. Pressure drop in the perforation channels.

As it has been indicated by most of the skin theories the different effects are interdependent, so they cannot be examined independently. For example, the length of the first flowing phase depends on the location where the flow changes direction from perpendicular to the axis of the well to perpendicular to the axis of the perforation channels, which is not independent from the pressure loss around and inside the perforations. For this reason, it is reasonable to solve the problems by taking into consideration the different factors “backwards”.

3.1 Pressure Drop in the Perforation Channels

The pressure loss inside the perforation channels was completely neglected by previous authors. It was assumed that the rate inside the channels is only a small portion of the complete flow rate and the conductivity of those channels is magnitudes bigger than the conductivity of the reservoir rock. As a result, the pressure loss can be neglected inside the perforation channels.

However, as the pressure loss in the channels can affect the pressure loss in the other zones, this neglection is not so obvious. Assuming interdependence the pressure drop inside the perforation can affect the length of the different flow sections. For this reason, this phenomenon must be investigated in details.

3.2 Pressure Drop in the Crushed Zone

The crushed zone is formed around the perforation channels and has a decreased permeability comparing to the rock's permeability around the channels. The effect of this zone can be characterized similarly to the effect of the invaded zone around a well with open hole completion. Thus, the pressure loss in this region can be calculated according to Hawkin's method (Hawkins Jr., 1956). The problem regarding this zone arises from the nature of the permeability change. Pucknell and Behrmann (Pucknell & Behrmann, 1991) observed that besides the permeability reduction - the porosity of the region remains the same as prior the perforation process. They explained this observation with the fragmentation of the particles, which is caused by the impact of the perforator gun. The fragmentation decreased the size of the pores.

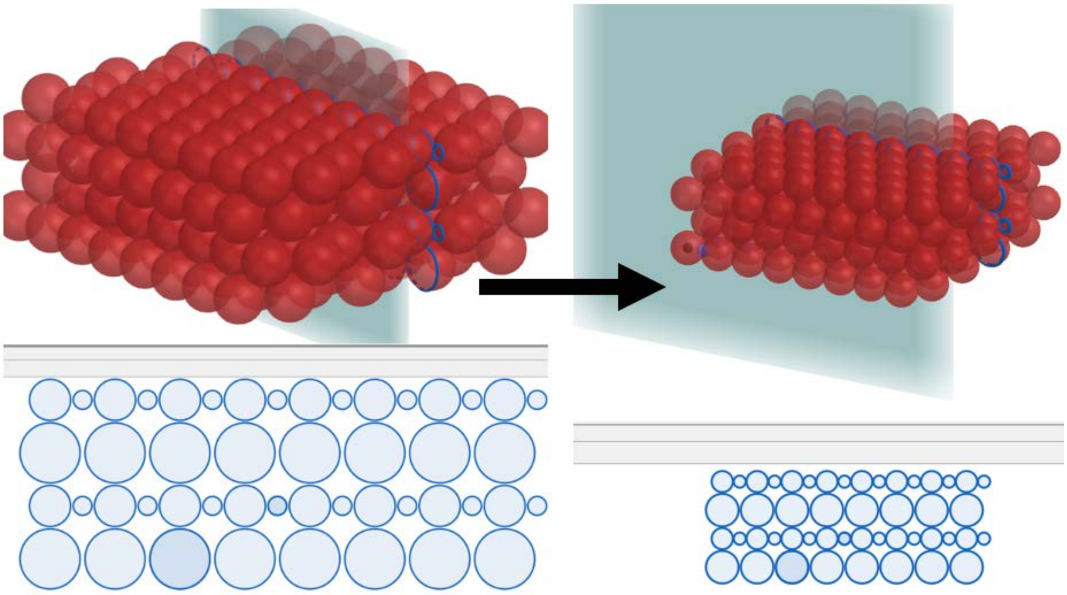

Figure 2.: Effect of particle fragmentation

As it is shown in the figure above (Figure 2.), reduction of the particles will not change the fraction of the void space in the whole volume just the size of the pore throats. If this statement is proven to be valid it would mean that its effect cannot be altered with an acid treatment.

3.3 Pressure Drop Around the Perforation Channels

When considering the pressure loss around the perforation channels both their shape and their effect on each other needs to be taken into account. The shape of the perforation channels is not cylindrical, but rather conical (Snider, et al., 1997). The neighboring channels can interfere with each other through their drainage spaces just like producer wells drilled close to each other.

Effect of the shape:

The flow equations are expressed in cylindrical coordinate system to describe the inflow of wells. A basic assumption of these models is that the drainage conduit has the shape of a cylinder. To apply these methods in case of the perforation channels - geometrical transformations are needed. For this the radius of the cylinder, which would result the same pressure loss as the cone (with the same lengths), is to be found. The radius of such a cylinder is called the equivalent radius. (Figure 3.).

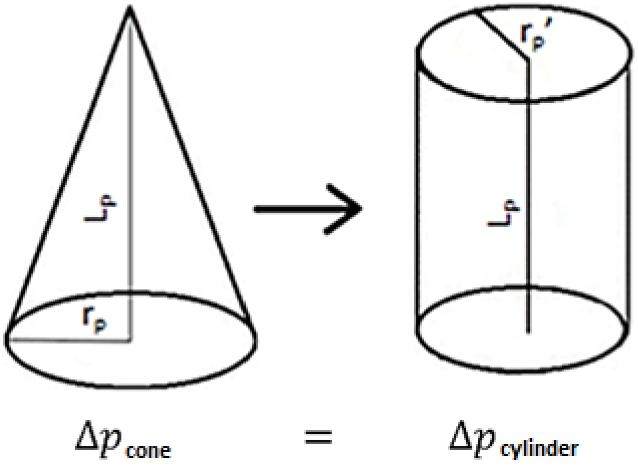

Figure 3.: Equivalent radius

Restricting effects:

The radius of the drainage area is a crucial parameter of the inflow performance relationship. As the pressure drop around the perforation channels can be described by the inflow performance relationship of the channels, the determination of the radius of their drainage area is important. The importance of this element is emphasized by the results observed during the investigation of McLeod’s model. He assumed that the radius of the drainage area is the radius of the crushed zone, so he overestimated the non-darcy parameter of the flow equation.

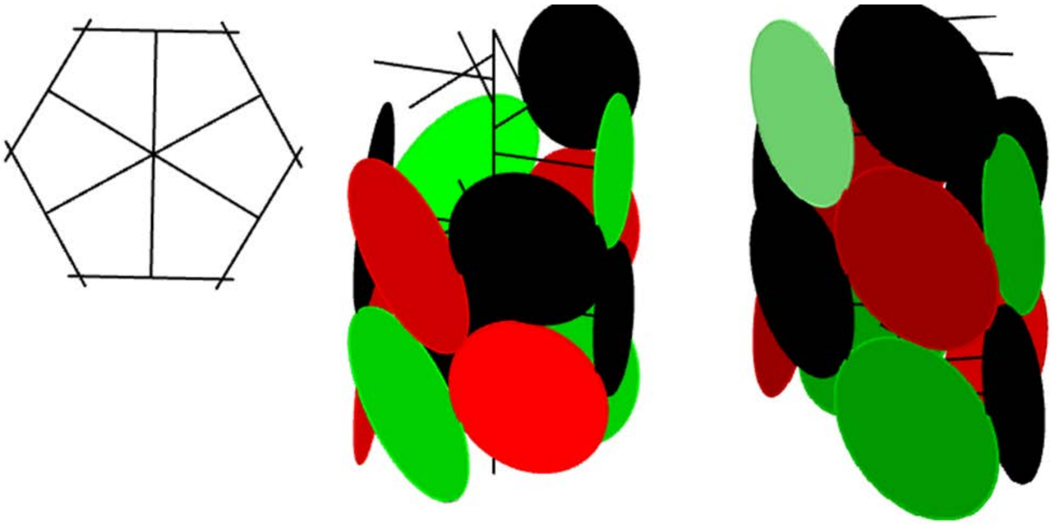

Figure 4.: Restricting effect of neighboring channels (θ =60°)

The drainage area of a channel is restricted by its neighboring channels. The plane segment of the drainage areas perpendicular to the axis of the channel is shown on the figure above (Figure 4.). It can be seen that the shape of the drainage area on the plane segment is an ellipse, which is bounded by the drainage areas of the adjacent perforations. Similar effect can be observed at producer wells close to each other. To determine the actual shape the equidistant point between two perforations must be found.

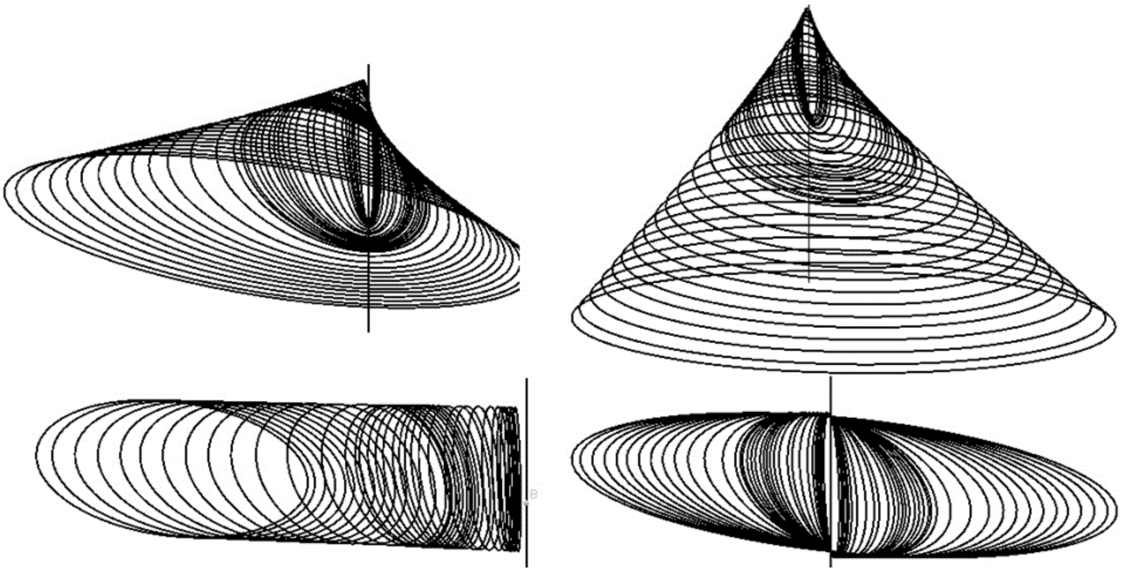

Figure 5.: Drainage area of a perforation channel (θ =60°)

The figure above (Figure 5.) represents the shape of the drainage area around a perforation channel.

3.4 Pressure Drop to the Vicinity of the Well

The pressure drop can easily be determined by using the distance of direction change as the radius of the well in the inflow performance relationship equation when the flow is perpendicular to the axis of the well. So, it can be assumed as a flow towards of a well with an extended radius.

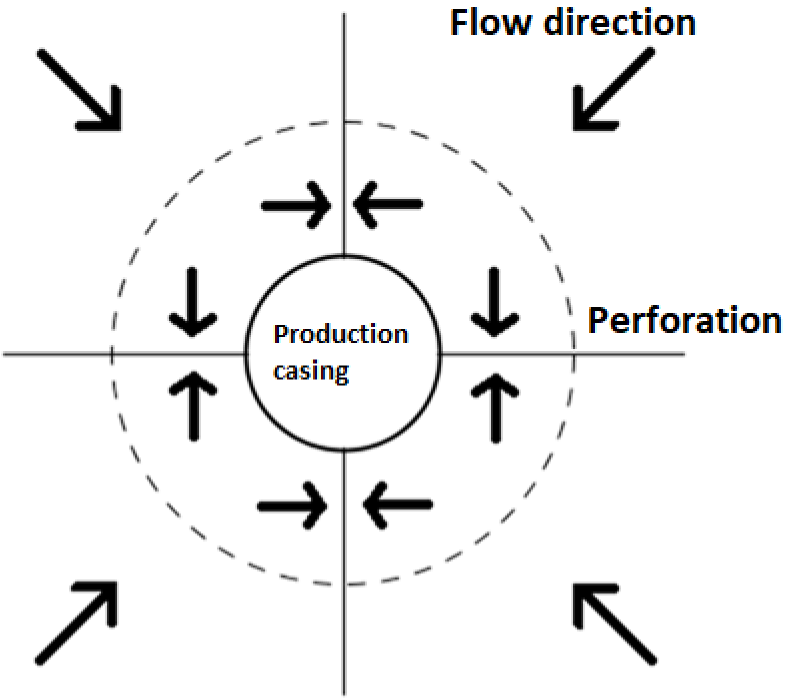

Figure 6.: Change in flow direction around the well

The source of difficulty in the calculation is the distance of directional change. It is obvious that the flow does not change direction at a discrete point in space but continuously along the perforations. For the sake of computability this continuous direction change must be translated to a discrete-point-change which has the same effect.

3.5 Effect of Invaded Zone

The effect of the invaded zone calls for further considerations. Two possible cases can be distinguished.

<u>The perforations do not reach the unaltered zone:</u>

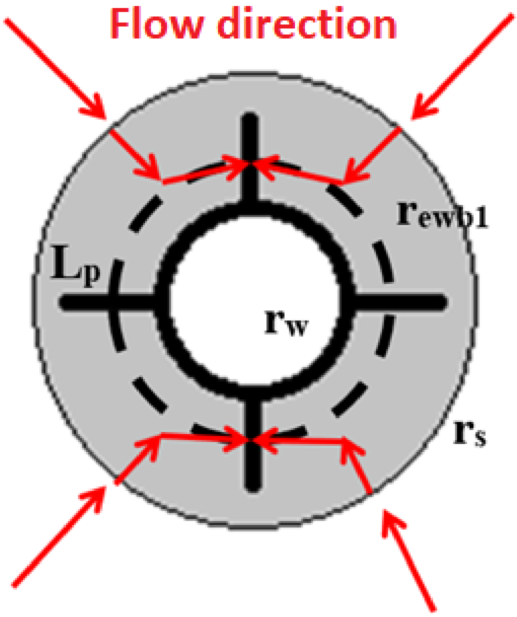

Figure 7.: Flow to the well (perforations do not reach the unaltered zone)

In this case the pressure loss can be characterized as follows:

1. Pressure drop in the invaded zone (flow is perpendicular to the axis of the well).
2. Pressure drop in the point of direction change in the invaded zone (flow is perpendicular to the axis of the well).
3. Pressure drop around the perforation channels in the invaded zone (flow is perpendicular to the axis of the perforations)
4. Pressure drop in the crushed zone.
5. Pressure drop inside the perforation channels.

<u>The perforations reach the unaltered zone:</u>

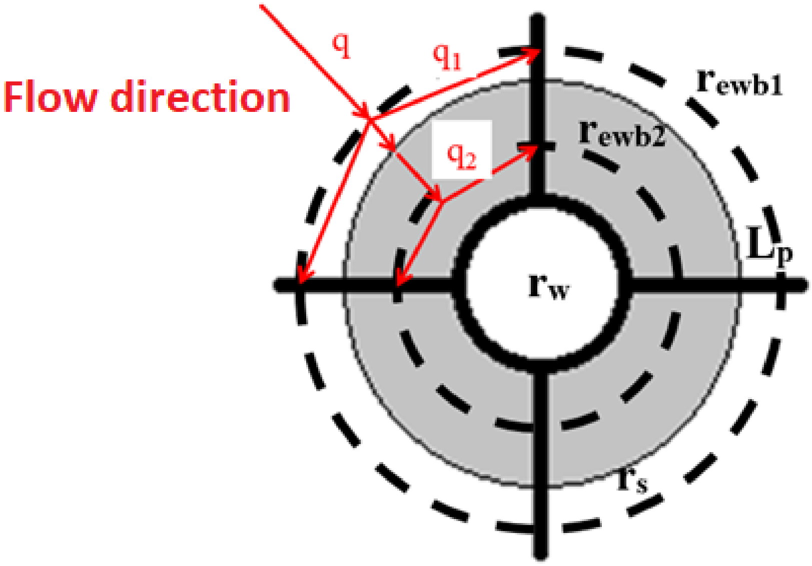

Figure 8.: Flow to the well (perforations reach the unaltered zone)

In this case the characterization of the pressure loss is more complex as the flow must be split in accordance to the direction change:

1. Pressure drop in the vicinity of the well (flow is perpendicular to the axis of the well) [q].
2. Pressure drop after the first change in flow direction ($\Delta p_{q_1} = \Delta p_{q_2}$):
    a. Δp_{q_1}:
        i. Pressure drop around the perforations in the unaltered zone (flow is perpendicular to the axis of the perforation) [q_1]
        ii. Pressure drop in the crushed zone (unaltered zone) [q_1].
        iii. Pressure drop inside the perforation channels [q_1].
    b. Δp_{q_2}:
        i. Pressure drop in the point of the second change in flow direction in the invaded zone (flow is perpendicular to the axis of the well) [q_2].
        ii. Pressure drop around the perforation channels in the invaded zone (flow is perpendicular to the axis of the perforation) [q_2].
        iii. Pressure drop in the crushed zone (invaded zone) [q_2].
        iv. Pressure drop inside the perforation channels [q_2].

The split in the flow must fulfill $q = q_1 + q_2$ and $\Delta p_{q_1} = \Delta p_{q_2}$ conditions simultaneously.

4. Theses

1. **The former, non-analytical methods are not suitable to determine the pressure loss accurately.**

A great number of methods can be found in the professional literature to determine the pressure loss caused by the perforation design. Yldiz investigated the accuracy of these methods by comparing the skin factor obtained with the given techniques and with measured values (Yldiz, 2016). Vast majority of the methods proved to be inaccurate in his work. In case of McLeod's method this was caused by the non-darcy term of the flow equation. The remaining methods do not take the flow rate dependent non-darcy term into consideration, thus the results of Yldiz can be accepted for them.

My investigation showed that the method of McLeod does not take the effect of phase angle into consideration, so it is not sufficient for examining the effect of all the perforation parameters. My results pointed out that the method of Karakas and Tariq do not take the flow rate dependent term of the flow equation into consideration, thus underestimating the effect of the perforation design on the productivity of gas wells.

In the light of all of this, it can be stated that the former methods are not suitable for the accurate design of the perforation.

2. **The shape of the perforation channels is conical not cylindrical, so correction must be applied on them in the calculations.**

Snider et al. (Snider, et al., 1997) presented the shape of many perforation channels created by different perforator guns. Their work indicates that the shape of the perforation channels generally conical. As the methods which are suitable to calculate the pressure loss are derived in polar coordinate system, they are valid for cylindrical drainage conduits. The difference in the shape must cause deviations as both the length of the flow path and the direction are different in case of the cone shaped perforations. In order to take this difference into consideration the radius of a cylinder, which is indifferent to a perforation regarding the pressure loss, must be applied in the equations instead of the radius of the perforation channel. The validation of the obtained transformation method was carried out by the application of computational fluid dynamics simulations.

3. **The perforation channels restrict the drainage area of each other.**

It is a well-known fact that the producing wells which are close to each other restrict their drainage areas. The same phenomenon should apply for the perforation channels, as they are relatively close to each other. The formed drainage volumes are affected by the phase angle and the shot density. The computational fluid dynamics simulations, which were carried out during the work, proved the concept, and showed similar shapes as the derived method.

4. **The pressure drop inside the perforation channels can be neglected.**

As the inside properties of the perforation channels are not known exactly, the accurate determination of the pressure loss through them is not possible. By assuming that the wall of the channels is rough, and the roughness is caused by sand particles, the range of the pressure loss can be determined. With this determined range the conductivity of the channels and the rock can be compared. It is also important to note that all the assumption in the work were made in a way to overestimate the pressure loss in the perforation channels. For the realistic range of oil and gas flow the following can be concluded:

- the pressure drop is a hundred folds bigger in the reservoir rock than in the perforations - in case of gas flow,
- this difference is thousand folds in case of oil flow.

As a result, the flow resistance inside of the perforations can be neglected.

5. **Parallel flow is created in the different zones.**

The effect of the invaded zone is crucial from the viewpoint of optimization. Depending on whether the perforation channels extend beyond the invaded zone or not, the calculation method changes. If the channels do not extend beyond the invaded zone, decreased permeability needs to be used in the calculations. Otherwise, inflow can be observed to the channels both in the invaded and in the clean zones. The phenomenon is analogous to the division of electric current flowing through parallel connected resistors. This is also confirmed by CFD simulations.

6. **The length of the perforations must be prioritized over the radius during the design.**

The size of the perforator guns used to create the perforation channels is limited by the size of the production casing. For this reason, the volume of the applied explosives – and thus the volume of the created channels – are limited.

In my work I have investigated how the different perforation parameters affect the productivity of oil and gas wells. The obtained results indicate that the effect of the radius is negligible comparing to the effect of the length.

7. **The optimal phasing to reach the best productivity are 60° and 45°.**

Phasing affects size and shape of drainage area and the distance where the flow direction changes. The sensitivity analyses run with the newly developed method show that decreasing the phase angle to 60°improves the productivity. Further decreasing the phase angle to 45° will result in negligible improvement or, in some cases, reduction. Productivity is altered by many factors and each setup has different optimal phasing, which is somewhere between 60° and 45°orientation.

8. **There is a perforation length where the effect of invaded zone becomes negligible.**

The investigation of the effect of invaded zone pointed out the importance of reaching the clean zone during perforating. My results showed that after a given perforation length the difference between the productivity of a well with/without an invaded zone disappears. With the increasing length the portion of fluid entering into the perforation from the unaltered zone grows. Thus, after a given length almost all fluid enters into the perforation at the clean zone.

5. List of related publications

Kovács, M. & Pásztor, Á., 2019. Effect on the non-Darcy flow. Zagreb, 6th Annual Student Energy Congress ASEC .

Pásztor, Á., 2015. A Perforáció Kialakításának Hatása A Szénhidrogén Termelő Kutak Produktivitására. Miskolc, Diáktudomány: A Miskolci Egyetem Tudományos Diákköri Munkáiból VIII. pp. 27-32, pp. 27-32.

Pásztor, Á., 2016. The Invaded Zone’s Effect on The Inflow of Perforated Wells, Szolnok: Low and volatile oil price environment – Technical responses in the Pannonian Basin Conference.

Pasztor, A. & Kamenar, M., 2019. A novel modular method for intensification planning. INTERNATIONAL MULTIDISCIPLINARY SCIENTIFIC GEOCONFERENCE, 19(1.2), pp. 605-614.

Pásztor, A. & Kosztin, B., 2015. A Novel Method for Optimal Perforation Design. Budapest, SPE European Formation Damage Conference and Exhibition.

Pasztor, A. & Lengyel, T., 2019. Method to calculate apparent permeability of hydraulic fractures. International Multidisclipinary Scientific Geoconference 19, 19(1.2), pp. 985-992.

Pasztor, A. & Schultz, V., 2015. Analytical IPR equation for perforated wells, Visegrád, Hungary: SPE International Hungarian Section.

Pasztor, A. & Schultz, V., 2016. Analytical determination of the perforation design’s effect on the productivity. MOL GROUP Professional Journal, Issue 1, pp. 108-117.

Pásztor, Á. & Schultz, V. M., 2017. A Perforációk Gyűjtőterének Hatása a Kutak Hozamegyenletérs. Miskolc: Műszaki Földtudományi Közlemények 86 : 2 pp. 114-130..

Pasztor, A. V., 2018. Effect of Microfractures on Filtration. International Multidisclipinary Scientific Geoconference, 18(1.4), pp. 413-420.

Pasztor, A. V., 2018. Pressure drop through perforation channels. International Multidisclipinary Scientific Geoconference , 18(1.4), pp. 697-704.

Pasztor, Á. V. & Remeczki, F., 2018. Method to analyze the effect of fractures in tight reservoirs. Zagreb, Annual Student Energy Congress.

Pásztor, Á. V. & Tóth, A., 2017. Effect of Perforation Parameters on the Productivity of Geothermal Wells. Miskolc, MultiScience - XXXI. microCAD International Multidisciplinary Scientific Conference.

Pásztor, Á. V. & Tóth, A. N., 2017. A Simple Method for Optimizing the Perforation Design of Geothermal Wells. International Multidisclipinary Scientific Geoconference, 17(42), pp. 11-18.

Turzó, Z. & Pásztor, Á., 2017. Perforálási hatékonyság értékelése CFD számítás alkalmazásával, Siófok: XXXI. Nemzetközi Olaj - és Gázipari Konferencia, Kiállítás.

Veleczki, P. & Pásztor, Á., 2019. In search of proper way to measure beta factor. Zagreb, 6th Annual Student Energy Congress ASEC .

6. References

Hawkins Jr., M. F., 1956. A Note on the Skin Effect. Journal of Petroleum.

Pucknell, J. K. & Behrmann, L. A., 1991. An Investigation of the Damaged Zone Created by Perforating.: Society of Petroleum Engineers doi:10.2118/228811-MS.

Snider, P. M., Benzel, W. M., Barker, J. M. & Leidel, D. J., 1997. Perforation Damage Studies in Unconsolidated Sands: Changes in Formation Particle Sizes and the Distribution as a Function of Shaped Charge Design.

Yldiz, T., 2016. Assessment of Total Skin Factor in Perforated Wells. SPE Reservoir Evaluation & Engineering, 9(01), pp. 62-76.