RGNZ/MGPB

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 622.3
DOI: 10.17794/rgn.2024.4.7

Preliminary communication

Pressure build-up test analyses of a hydraulically fractured well with reduced half-length

Sonja Koščak Kolin[1]; Andrea Valjak[2]; Vladislav Brkić[3]; Sonja Buti Njie[4]

[1] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, ORCID 0000-0003-0056-4466*

[2] *Oil & Gas Engineering Ltd., SR Njemačke 10, 10 000 Zagreb, Croatia*

[3] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia, ORCID 0000-0003-2075-1832*

[4] *INA - Industrija nafte, d.d., Avenija Većeslava Holjevca 10, 10 020 Zagreb, Croatia*

Abstract

When the oil production of the hydraulically fractured well A-1 began to decline, a refracturing of the well was planned, as a reduction in the fracture size was assumed after a long production period. Several possibilities of the pressure build-up test analyses were performed to determine the best evaluation of the reduced fracture half-length. Although the objectives of these tests are to determine the reservoir properties, such as rock permeability and skin factor, as well as fracture conductivity, the Saphir programme is also used to model the fracture half-length. This is the most important parameter required for the design of the new fracturing process and for the creation of a new production model. For this purpose, the methods of the pressure build-up test analysis are first described theoretically. Based on different analyses of the same pressure build-up test, the one that best matches the analytical model of a fractured well with the measured pressure curve and the derivative curve is selected. It is found that the most accurate result for fracture half-length is obtained from the fractured well model with multiphase flow.

Keywords:
pressure build-up test; fracture half-length; refracturing process

1. Introduction

Throughout the life cycle of a well, from the exploration phase to decommissioning, well testing is used to collect a variety of data to describe the condition and behaviour of the well and the reservoir. Properly performed and analysed tests can provide information on the permeability of the formation, i.e. the reservoir rock, the size and extent of reservoir damage or stimulation, reservoir pressure, reservoir boundaries and heterogeneity. Well tests are also used to determine the ability of the reservoir rock to produce reservoir fluids. The tests can take less than two days to evaluate a single well, but up to several months to determine the size of the reservoir (**von Flatern, 2012**).

The pressure build-up test is the most common method for analysing wells under transient flow conditions. The test is carried out in such a way that the well produces fluids at a constant flow rate for a certain period of time and is then shut in. The pressure in the reservoir increases and is measured as a function of time, usually at the bottom of the well. The pressure build-up test of the fractured oil well A-1 was analysed using the Saphir computer programme for pressure analysis in oil and gas production engineering, which is part of the KAPPA Workstation software package (University Licence #9643). The programme uses the Bourdet derivative as the main diagnostic tool and attempts to overlap the measured and modelled data. Once a satisfactory overlap has been achieved, a reliable interpretation of the results is possible, providing much useful information about the reservoir and the wellbore (**Houze et al., 2022**).

In order to obtain more precise results, nine different cases of pressure analyses of the fractured well A-1 were carried out (**Valjak, 2021**). In comparison with laboratory data and using the possibility of an optimal matching of measured and modelled data, the method for determining the results with the smallest deviations was discussed. An attempt was also made to determine the possible influence of different values of the input parameters (**Zeng and Zhao, 2007**), which could have an impact on the deviations of the final results in determining the properties of the reservoir and the fracture.

The methods of pressure build-up test analysis in the wells being considered for refracturing are still being developed in order to as reliably as possible determine the

Corresponding author: Sonja Koščak Kolin
e-mail address: sonja.koscak-kolin@rgn.unizg.hr

size of the existing fracture half-length, i.e. the value to which it has decreased (**Ostojić et al., 2012**).

2. Methods for the pressure analysis of the well tests

In fractured wells, where the fracture has reduced after a long production period following stimulation, there are deviations in the determination of rock permeability since the standard method of infinite acting radial flow (IARF) is not always applicable. Although fluid flow models in conventional and unconventional oil and gas reservoirs are crucial for calculating the production parameters of individual wells, their application is also essential for analysing pressure build-up tests. When analysing the pressure build-up test, the models are used to determine reservoir properties, primarily reservoir rock permeability and skin factor, and are based on measured production parameters and known reservoir and well properties (**Spivey and Lee, 2013**; **Hategan and Hawkes, 2007**; **Bourdarot, 1998**).

In order to reliably apply the method for the pressure build-up test in a reservoir with low permeability, one must first be familiar with the methodology for analysing production tests in conventional reservoirs (**Koščak Kolin, 2018**). The initial method for analysing the pressure drop of a production test in a conventional reservoir is based on solving the diffusion equation for the radial flow in the infinite reservoir model by the logarithmic approximation of the exponential integral (**van Everdingen and Hurst, 1949**), which enables a semi-logarithmic presentation of the dynamic pressure as a function of time. If dimensionless variables are also defined, such as dimensionless pressure and dimensionless time, the method of type curves can be used in this analysis. In addition, the pressure derivative is used as a more accurate method. To summarise, by applying the superposition principle in the Horner method, the analysis of the production test is adapted to the pressure build-up test (**Horner, 1951**).

Modern software for analysing pressure build-up tests, such as the Saphir programme, also uses the type curve and pressure derivative methods, but in a different way (www.kappaeng.com). The programme first converts the described dimensionless solutions of the diffusion equation, i.e. the type curves, into real variables and applies the principle of superposition. On this basis, an analytical model is generated in Saphir, which is compared with the measured data and then the actual model is determined using the regression method. In the next step, matched points are defined, such as the matched pressure used to determine the permeability of the reservoir rock as well as other parameters (**Mohaghegh, 2017**). Regardless of whether it is a vertical or a hydraulically fractured well, knowledge of the reservoir properties is necessary for a determination of the production characteristics of the well, i.e. for the production modelling phase of the well, as well as for the successful business management of the entire reservoir system (**Poston et al., 2019**; **Jansen, 2017**; **Soliman et al., 2003**). The methods for pressure analysis and determining reservoir properties in vertical wells are analogously applied in determining the properties of a fractured well, so their theoretical basis for both cases is briefly presented below.

2.1. Pressure analysis of wells with radial flow

The mathematical description of fluid flow through a porous medium, i.e. the diffusion equation, is a partial differential equation. The accuracy of its solutions depends on the fulfilment of the necessary assumptions that the homogeneous and isotropic porous rock is of uniform thickness, that the properties of the fluid and the rock are independent of the pressure, that the pressure gradients are small, that Darcy's law is applicable, and that the gravitational forces are negligible. However, in order to obtain a solution to a particular problem, boundary and initial conditions are required that are characteristic of particular reservoir conditions (**Matthews and Russell, 1967**). When analysing well tests in the transient flow, a well with constant flow and an infinite reservoir is assumed. The fulfilment of such boundary conditions is necessary for the pressure transient analysis (PTA). In the later phase of well operation or during a longer test of a well in a permeable reservoir, the influence of neighbouring wells becomes noticeable when analysing the pressure curve, and the boundary between reservoir and aquifer can change the behaviour of the curve, i.e. the response of the reservoir pressure in it, and thus cause a deviation from the model (**Earlougher, 1977**).

The solutions of the diffusion equation used in the pressure analysis methods assume a flow to a centrally located well with constant production. There are three basic models with constant flow at the inner boundary of the reservoir, of which the infinite reservoir model is used in analysing well tests, as it describes the transient flow. The other models are the confined reservoir with closed outer boundary with no flow at the outer boundary and the confined reservoir model with constant pressure at the outer boundary.

The solution of the diffusion equation of the infinite reservoir model is:

$$p_{wf}(t) = p_i - \frac{qB\mu}{2\pi kh}\left[\frac{1}{2}\left(\ln\frac{kt}{\phi\mu c r_w^2} + 0.80907\right) + s\right] \quad (1)$$

where:

p_{wf} – flowing bottom hole pressure (Pa),
p_i – initial reservoir pressure (Pa),
q – flow rate (m^3/s),
B – volume factor of oil (m^3/m^3),
μ – viscosity (Pa·s),
k – permeability of the reservoir rock (m^2),
h – reservoir thickness (m),
t – time (s),

$ø$ – porosity (%),
c_t – total compressibility (Pa^{-1}),
r_w – well radius (m),
s – skin factor (–).

Graphical presentations of solutions of the diffusion equation are commonly expressed in terms of dimensionless variables, i.e. dimensionless pressure, p_D, dimensionless time, t_D, and dimensionless radius, r_D.

The solution of the dimensionless diffusion equation of the infinite reservoir model is:

$$p_D(t_D, r_D) = \frac{1}{2}\left(\ln\frac{t_D}{r_D^2} + 0.80907\right) \tag{2}$$

Equation 2 for the case $r = r_w$ and $r_D = 1$ is reduced to:

$$p_D(t_D) = \frac{1}{2}\left(\ln\ln t_D + 0.80907\right) \tag{3}$$

The solution represented by **Equation 3** is applied in the methods for analysis of production tests and for analysing pressure build-up tests in vertical wells. The graphical representation of this equation was the starting point for the development of the diagnostic log-log diagram (**Gringarten, 2008**; **Gringarten, 2012**), which led to the final Bourdet diagram for pressure analysis (see **Figure 1**), on which the Saphir programme is also based.

If the condition $t_D \leq 0.25r_{eD}^2$ can be applied, the reservoir behaves like an infinite one and **Equation 3** can be used. Methods for pressure analysis are semi-log method of pressure as a function of time, type curve method and pressure derivative method.

From the solution of **Equation 1,** it follows that the diagram of the dynamic pressure, p_{wf}, in a semi-logarithmic scale, i.e. in the function of *log t*, results in a line whose slope is, *m*. With the known slope of the line, *m*, it is possible to calculate the permeability of the reservoir, *k*:

$$k = 1.151\frac{qB\mu}{2\pi hm} \tag{4}$$

Both the production test and the pressure build-up test assume a constant flow rate. However, unlike the production test, where this is difficult to achieve, the flow rate in the pressure build-up test is constant and equal to zero (**Spivey and Lee, 2013**; **Gringarten, 2012**). By applying the superposition principle, the analysis of the production test can be adapted to the pressure build-up test. At $t = 0$, the well starts producing at a constant flow rate, *q*. After some time of production, t_p, the well closes for testing. Then there are two constant flows: one flow *q*, which starts at $t=0$ and continues until t_p, and the other flow *-q*, which starts at t_p. Then the modified Horner time is used instead of the real time (**Horner, 1951**):

$$\Delta t_e = \frac{t_p\Delta t}{t_p + \Delta t} \tag{5}$$

where, Δt, is the duration of the build-up test. If Δt is small compared to t_p, then the equivalent time can be identified with the time of the pressure build-up measurement ($\Delta te \approx \Delta t$).

Type curves, as the following method for pressure analysis, represent the graphical solution of the diffusion equation. According to the dimensionless form of the diffusion equation for an infinite reservoir with constant flow at the inner boundary of the reservoir, the approximation that takes into account the skin factor, *s*, with respect to the solution in **Equation 3**, is:

$$p_D(t_D, r_D) = \frac{1}{2}\left(\ln\frac{t_D}{r_D^2} + 0.80907\right) \tag{6}$$

The development of the method of type curves led to a new form in which the dimensionless pressure from the previous equation is given as a function of the dimensionless group t_D/C_D and each curve is characterised by the value of the parameter C_De^{2s}, where C_D is the dimensionless constant of the fluid storage in the well (see **Figure 1**). The overlap is performed in such a way as to select matching points with which it is possible to calculate the properties of the reservoir and the well. The wellbore storage effect or subsequent inflow is a phenomenon that causes variable flow after the production test begins, i.e. it allows flow even after the well has been shut in for the pressure build-up test (**Čikeš, 2015**).

The wellbore storage constant, C (m^3/Pa), is defined as:

$$C = \frac{A_{wb}}{\rho g} \tag{7}$$

where:

A_{wb} – cross-sectional area of the borehole (m^2),
g – gravitational acceleration (m/s^2),
ρ – fluid density (kg/m^3).

The dimensionless storage constant, C_D, is:

$$C_D = \frac{C}{2\pi h\phi c_t r_w^2} \tag{8}$$

The final pressure derivative method is the log-log presentation of the slope from the semi-logarithmic diagram of the dimensionless pressure as a function of dimensionless time, if the time scale in the semi-logarithmic diagram is given by the natural logarithm. **Figure 1** shows the final so-called Bourdet's diagnostic log-log diagram, in which pressure derivatives, p'_D, were introduced as a function of t_D/C_D in addition to the type curves. At the early times, the curves have a unit slope, which indicates the duration of fluid storage in the well. Later, when an IARF is reached, the curves become horizontal at the value $p'_D\,(t_D/C_D) = 0.5$. The principle of the method is that measured data is matched with type curves, from which match points are selected, which are then used to calculate the required reservoir parameters. The measured data is entered into a log-log diagram of the pressure difference, Δp, as a function of time *t*. The selected overlap points with the type curves are $(p_D)_M$ and $(\Delta p)_M$.

 pp. 89-101, DOI: 10.17794/rgn.2024.4.7

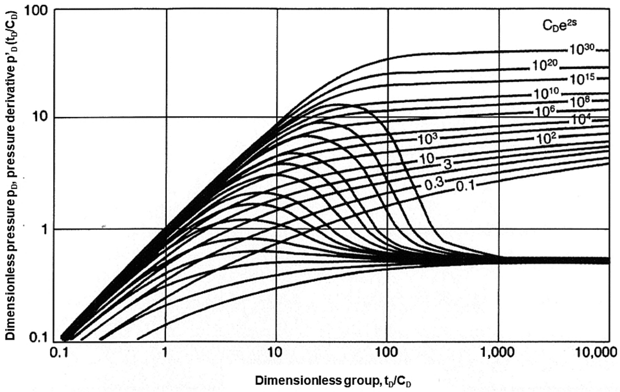

Figure 1: Type curves for an infinite reservoir with storage effect, C_D, and skin effect, s (**Economides and Nolte, 2000; Bourdet et al., 1989**)

An adapted form of the log-log diagram is also used in the Saphir programme, with which all analyses of the pressure build-up test of the fractured well A-1 were performed. The results with the smallest deviations were selected, which is explained in the discussion of the results. However, the analogy of applying the methods for analysing pressure build-up tests for vertical wells to the fractured well is briefly explained in the next paragraph.

2.2. Pressure analysis of wells with hydraulic fracture

The transient pressure behaviour in a fractured well can be described by analysing the solution of differential equations with certain initial and boundary conditions under the assumption of an ideal reservoir shape (**Spivey and Lee, 2013**; **Cinco-Ley et al., 1976**). This means that the reservoir is isotropic, homogeneous, infinite, bounded at the top and bottom by impermeable layers. It has a uniform thickness, h, permeability, k, and porosity, ϕ, independent of pressure. In addition, the reservoir contains a fluid with compressibility, c, and viscosity, μ, and both values are constant. It is also assumed that the fluid is produced through a vertical, fractured well, which is intersected by a fully penetrating fracture with half-length x_f, width w, permeability k_f, porosity ϕ_f and total compressibility c_{ft}. Their values are also assumed to be constant, and the fluid only enters the well through the fracture. Gravitational influences are negligible and the flow is laminar.

Then the inflow to the vertical well, which is located at the origin of the fracture, can be described by the diffusion equation for two-dimensional linear flow (flow through the fracture) and by the diffusion equation for one-dimensional linear flow (flow in the reservoir). The two partial differential equations are linked by initial and boundary conditions, and two solutions are developed according to their definition, of which the model of a fractured well with constant flow at the inner boundary is used in the analysis of the pressure build-up test. In this model, for a fractured well in an infinite reservoir producing at constant flow, the initial and boundary conditions are defined such that the initial pressure in the fracture is equal to the reservoir pressure, that the influx into the wellbore is through the fracture of total area, *2wh*, according to Darcy's law, and that there is no influx into the fracture through the top of the fracture. The two diffusion equations are solved semi-analytically for the pressure in the fracture, p_{fD}, i.e. for the pressure in the well, p_{wD}, which is equal to the pressure in the fracture at $x_D = 0$, while the dimensionless pressure in the oil well is defined as follows:

$$p_{wD} = \frac{2\pi kh(p_i - p_{wf})}{qB\mu} \tag{9}$$

Numerical solutions are given in the form of type curves, while approximate analytical solutions have been developed for individual time periods, i.e. flow forms. All solutions result in a functional dependence of the dimensionless pressure drop on the dimensionless production time and the dimensionless conductivity of the fracture. The first form of flow is linear flow in the fracture, where most of the fluid flowing into the well is due to the expansion of the fluid in the fracture and the flow is linear. The fracture can be considered infinite, as the flow has not yet developed over the entire length of the fracture. The linear form of flow through the fracture is usually of short duration, and in cases where a storage effect occurs, this can distort or mask the linear flow so that it is more difficult to recognise in the measured data. The next form of flow that can occur is bilinear flow, because two linear flows, one through the fracture and the other in the reservoir, occur simultaneously. Bilinear flow ends when the effect of the fracture tip is felt in the wellbore. Thereafter, linear flow takes place in the reservoir, and there may be a transition period between the period of bilinear flow and linear flow in the reservoir (**Chaudhry, 2003**). The onset of linear flow in the reservoir depends on the fulfilment of the condition $C_{fD} \geq 100$. For smaller values of dimensionless conductivity ($C_{fD} > 15$), pseudo-linear flow occurs, followed by pseudo-radial flow independent of the value of C_{fD}, which develops at late times before edge effects are observed. During the infinite acting pseudo-radial flow, the flow in the fracture has stabilised and the transient state of the flow can be equated to that in an unfractured well with a larger, i.e. effective, radius of the well, r'_w (**Economides and Nolte, 2000**), which is defined as follows:

$$r'_w = r_w e^{-s} \tag{10}$$

The establishment of the pseudo-radial flow marks the end of the transformation from a rectangular form of extraction to an elliptical and then to an almost radial form. The drainage surface of a fractured well is never completely circular, but it is close enough to be considered circular for practical purposes. Analogous to the described shapes of the fluid flow in a vertical well used to calculate the production parameters, the solutions of the diffusion equation are also used to analyse the pressure build-up test to determine the reservoir and well properties.

The objectives of analysing the transition period of pressure build-up after fracturing are to evaluate the success of fracturing and to estimate the value of half-length of the fracture, the conductivity of the fracture and the permeability of the formation (**Spivey and Lee 2013**; **Slimani and Tiab, 2008**; **Lee et al., 2003**). The use of type curves in analysing the transition phase of pressure build-up of fractured wells represents a major advance in the field and an advantage over specialised methods for different flow modes, as it is possible to interpret data corresponding to different flow phases simultaneously.

Analogous to the methodology described for the vertical well model, the Saphir programme uses similar procedures for the fractured well model. The programme first converts the described dimensionless solutions of the diffusion equation of the fractured well system and applies the principle of superposition. An analytical model is then created for the fractured well, which is then compared with the measured data and the current model is adjusted by regression. In the further process, matched points are set, such as the matched pressures, which are used to determine the properties of the reservoir and the fracture (**Mohaghegh, 2017**).

3. Basic geological and technical data of a reservoir and a fractured well A-1

Input parameters of the reservoir and well A-1 as well as data from the pressure build-up test (**Šeb, 2017**), are generated in digital form, and a tabular representation was used for data input (**Yasin, 2012**).

Well A-1 is located in an oil field in northwest Croatia. It is a hilly area crisscrossed by trenches and gullies at an altitude of 170 to 280 metres. The main hydrocarbon carriers are sandstones. The well is located in the western part of the field and is the only well used to produce hydrocarbons from the reservoir. The reservoir is fully saturated with oil and the granulometric composition of the rock is sandstone (about 70%) and coarse siltstone (about 30%).

The well is located 235.35 metres above sea level and the bottom of the well is at 1804 metres. **Table 1** shows the production intervals of the reservoir, which indicate an effective thickness of the production layer of 12 metres. The porosity in the reservoir is 19% and the water saturation is 45%.

Table 1: Reservoir layers at measured well depth

Well A-1	1590.0 – 1584.0 m (6.0 m)
	1583.0 – 1581.0 m (2.0 m)
	1580.5 – 1578.5 m (2.0 m)
	1577.0 – 1575.0 m (2,0 m)

The exploration and drilling phases of the well began in 1969 and fluid production from the well commenced in 1974. Following the initial production phase, hydraulic fracturing was carried out in the open reservoir intervals in 1993. In 2014, a well test was performed in which the production parameters were measured for two days and the pressure build-up under static conditions was measured for six days.

The production data on the operation of the well before the well test are: oil production 6.1 m^3/day, water production 0.73 m^3/day, GOR 183 m^3/m^3 and water cut 12.57%.

During the last period of hydrocarbon production, there has been no significant drop in pressure in the reservoir, which was confirmed by a pressure build-up test in March, 2014. According to the decrease of oil production, plans were made to carry out hydraulic fracturing again in order to intensify the production of hydrocarbons. The following pressure analyses investigated the possibilities of determining the most accurate state of the fracture, i.e. the value to which it has reduced, as well as the approximate value of its conductivity.

4. Results of pressure build-up test analyses

The pressure response during a well shut-in period provides information about the reservoir within the investigation radius for radial flow or for the investigation area for more complex reservoir geometries, such as a fracture. The Saphir programme, which is part of the Kappa Workstation software package (University Licence #9643), is the standard PTA programme used in all performed pressure analyses (**Houze et al., 2022**). The main diagnostic method is the log-log diagram, where the pressure and Bourdet derivative, together with the setting of the analytical model described below, allow the properties of the reservoir, i.e. the fracture half-length to be determined (see **Figures 3**, **4** and **5**).

4.1. Input data and history plot

At the beginning of the analysis, known input data is entered into the program. The thickness of the production layer is 12 m, the compressibility of the rock 5.34×10^{-10} Pa^{-1}, the porosity 19% and the top of the bed is at 1575 m. These values are the same for each analysis.

The fluid properties are then entered. For poorly compressible fluids, several PVT properties must be entered, assuming that the oil volume factor, viscosity and total compressibility of the system are constant. In cases where the analysis assumes a single-phase fluid (oil), the volume factor is 1.2 m^3/m^3, the viscosity is 0.005 Pa×s (0.5 cp) and the water saturation is 45%, while the total compressibility of the system is calculated after entering the water saturation.

When entering other parameters to create the analytical model, it is assumed that the reservoir is isotropic

Copyright held(s) by author(s), publishing rights belongs to publisher, pp. 89-101, DOI: 10.17794/rgn.2024.4.7

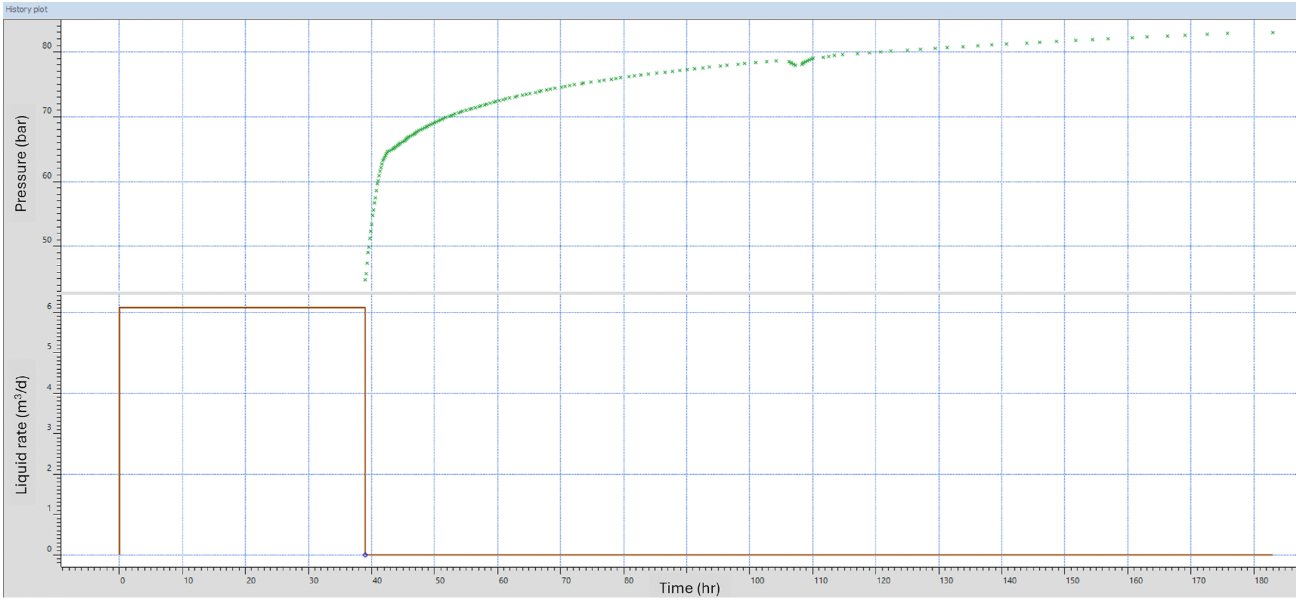

Figure 2: History plot of the pressure build-up test in well A-1

and the possibility of non-linearity with the specified parameters is excluded. In the final modelling step, specific values are selected for Wellbore storage, Well model, Reservoir model and Boundary model.

A constant value for Wellbore storage was selected, which is indicated by the direction of the unit slope in the diagnostic log-log diagram and can be shifted vertically and horizontally depending on the different conditions in the well. The unit slope indicated by the dashed line in the log-log diagram means that the effect of fluid storage persists during the early measurement of the pressure build-up in the well, which is confirmed in all analyses.

In addition to this line, when analysing the pressure in a vertical well, the slope of the second dashed line parallel to the x-axis in the diagnostic model can be used to determine the start of pressure stabilisation in the reservoir, i.e. when an IARF is reached. When interpreting the test, the condition must be met that the last points of the pressure measurement, i.e. its derivatives, coincide with this line of slope 0. If the measurement has not lasted long enough, i.e. if this stabilisation has not been achieved, or if the modelling cannot achieve an overlap of the derivatives with this line, then the interpretation results should be taken into account with the deviation factor.

The next tool in well modelling is the selection of a Well model. If the analysis is based on a vertical, unfractured well, the finite radius option is selected. In the case of the well A-1, the finite conductivity fracture model was selected (**Sun and Schechter, 2015**), which has two additional directional slopes in the log-log diagram that can be used to determine the conductivity of the fracture, F_C, and the fracture half-length, x_f. If a bilinear flow is identified in the well, then part of the data of the pressure build-up test and its derivative in the log-log diagram coincide with the lines of the slope of a 1/4, and in the case of a linear form of the flow, the slope of the lines are 1/2.

The Reservoir model is then defined. The option with double porosity was selected because it provides better analytical modelling results in all nine analyses than the assumption of a completely homogeneous reservoir (**Houze et al., 2022**), while the infinite option was chosen for the Boundary model, which is the final tool for setting up the analytical model of the well. The flow and pressure data from the pressure build-up test, which lasted 144 hours, are then entered. Prior to shut-in, the well produced for 39 hours at a constant flow rate of 6.12 m^3/day. The test lasted a full 6 days because the aim was to achieve pressure stabilisation so that the interpretation results about the amount at which the fracture closed would be as reliable as possible, regardless of the fact that the pressure response curve might feel the bourder after a relatively long test duration.

Figure 2 shows a History plot, i.e. a graph plotting the time of constant production before well closure and the duration of the build-up test with the measured increase in pressure in the reservoir (**Valjak, 2021**).

4.2. Case analyses

When modelling measured data with standard curves, the measured data is overlapped with standard curves for the build-up test analysis, whereby the maximum accuracy of the overlap in the Saphir programme is achieved by the non-linear regression method, i.e. by the 'Generate' and 'Improve' commands. The programme attempts to partially or fully overlap the type curve, i.e. the modelled curve, with the pressure response curve and to overlap the pressure derivative curve with the modelled derivative curve. Taking into account the accuracy of the

Table 2: Parameters in case analyses

Analysis	PVT model	Well model	Well radius
1	single-phase fluid	vertical well	0.03016 m
2			0.06985 m
3			0.12225 m
4		fractured well	0.03016 m
5			0.06985 m
6			0.12225 m
7	multiphase fluid	vertical well	0.06985 m
8		fractured well	0.06985 m
9	single-phase fluid	fractured well	0.06985 m

matching, it is possible to discard the selected model or keep it and further improve its modelling. In order to determine the most accurate results, a total of nine different analyses are performed (see **Table 2**), the results and modelling of which are explained along using log-log diagrams (see **Figures 3**, **4** and **5**).

In the analyses performed for the same pressure build-up test, the different models are selected to determine their influence on the results (**Valjak, 2021**). **Table 2** provides an overview of the main input parameters in each analysis. In addition to the standard analyses for vertical and fractured wells, a specialized analysis of bilinear and linear flow in a fractured well is performed as the final analysis.

4.2.1. Results of analyses 1, 2 and 3

The influence of the radius in the vertical well model was checked in the first three analyses. In analysis 1 it is 0.03016 m (tubing), in analysis 2 it is 0.06985 m (production column) and in analysis 3 it is 0.12225 m (borehole). Although the diameter of the production column is used as the reference value for the pressure measurement, the results presented in **Table 3** indicate that changing these three radius values has no influence on the results. When determining the PVT properties of the fluid in these three cases, a single-phase fluid is selected. All other parameters are the same in all three analyses. **Figure 3** shows a log-log diagram showing the overlap of the model (red and black solid lines) with the curves of the measured pressure (green data) and its derivative (red data) in analysis 2, which is not significantly different from the overlap obtained by analyses 1 and 3. Although this is a fractured well, the usual procedure is to initially set up the model as if the well were vertical, which should result in a negative skin effect, in this case it does and is approximately -3. This confirms the accuracy and connection of all the input parameters of the program, because in the case of a positive skin, the analysis should be discarded for further modelling due to the very low reliability in determining the results. In addition, in contrast to the overlapping model for an ideal vertical well, the pressure derivative curve shows that its trend does not correspond to the behaviour of the pressure derivative of a vertical well, as it is a fractured well, i.e. it is not possible to approximate it completely with the black line of the set model.

In accordance with the methods described in the second chapter, the Saphir programme, in addition to applying the PTA analysis to the log-log diagram in the form of type curves and their derivation, also offers the possibility of checking the results obtained with the first

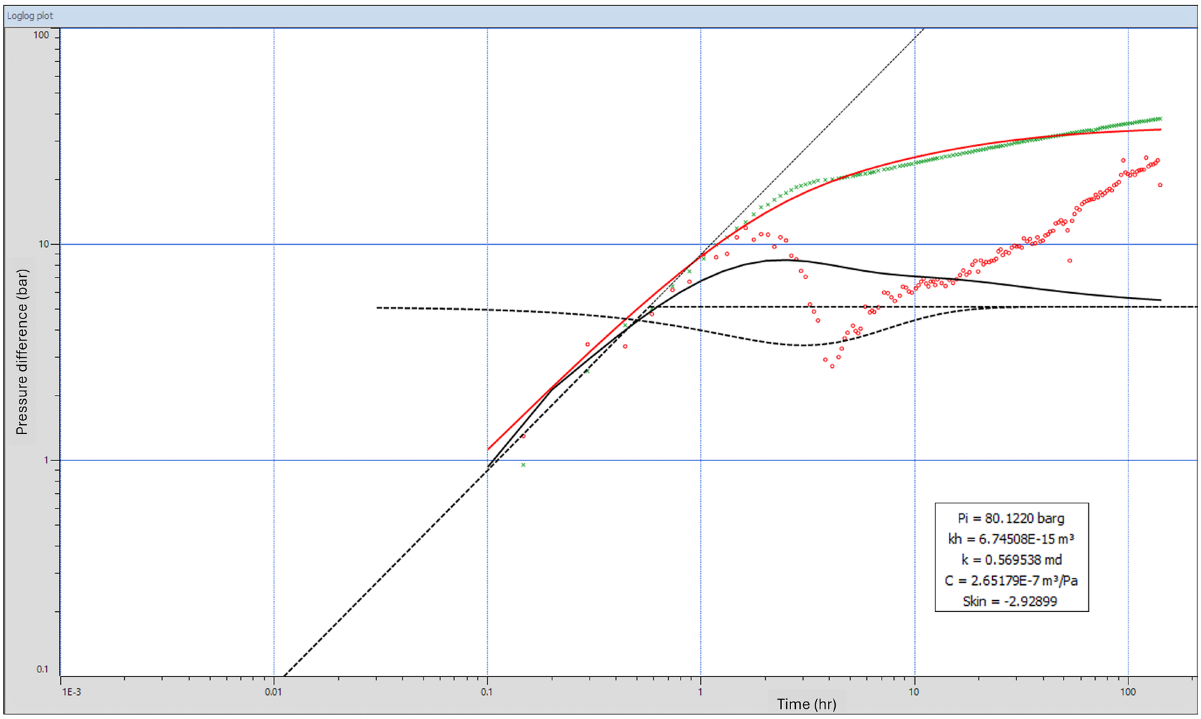

Figure 3: Pressure build-up test analysis for case 2

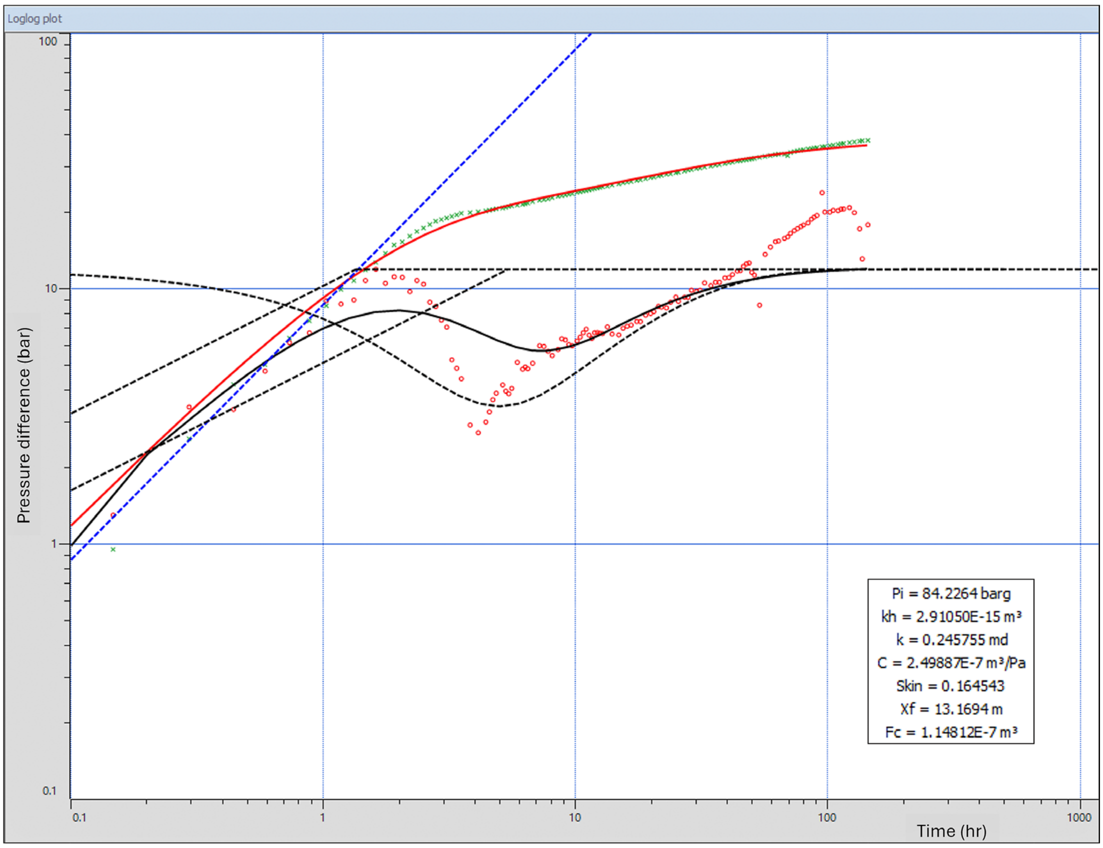

Figure 4: Pressure build-up test analysis for case 5

method, i.e. with the aid of a semi-logarithmic diagram (see **Equation 4**). According to the slope of the line in the semi-log plot method (*m = 11.4*), the calculated permeability of the pressure build-up test analysis for case 2 is 0.59 mD, while the log-log plot results in 0.57 mD (see **Figure 3**). As the other compared results of both methods are the same for each analysis, only the log-log diagrams are shown for mutual comparison of all case analyses.

However, the recommendation for future similar research studies is to double-check the results for each of the case analyses and to check in each case whether the results are approximately the same, because if this is not the case, a reinterpretation of the analysed case must be made. This means that it is not sufficient to analyse the pressure build-up test using only the log-log method in order to obtain reliable results. It is recognised that in practise there may be cases where the semi-logarithmic plot does not give the same results as the log-log plot. Therefore, one of the most important recommendations for future similar researches is to use both methods for each case analysis. If the results match, the discussion of the different analyses can then be based only on the log-log plot.

4.2.2. Results of analyses 4, 5 and 6

Analogous to the first three analyses, the influence of the radius is investigated in cases 4, 5 and 6, but for the model of a fractured well, whereby a well with a fracture of finite conductivity is selected. Since the results also proved to be independent of the radius, the reference radius of the production column of 0.06985 m is used in all subsequent analyses. In addition, a single-phase fluid is assumed in these three cases and all other input values are the same as in the previous analyses. **Figure 4** shows the log-log diagram and the results of analysis 5. The main results of the fractured well analysis are the values for the fracture half-length, x_f, and the conductivity of the fracture, F_C (see **Table 3**).

4.2.3. Results of analyses 7 and 8

In analyses 7 and 8, the 'multiphase' option is selected when entering the input data, the first referring to an assumed vertical well and the second to a fractured well (**Koščak Kolin et al., 2018**). According to the conclusions from the previous analyses, in these two cases the radius of the production column (0.06985 m) is left with the unchanged depth of the manometer with respect to the reservoir depth, but in the modelling, the single-phase fluid is replaced by a multiphase one, since the fluid contains a relatively high GOR. With this option, the program calculates the oil volume factor and viscosity based on known PVT correlations. By selecting this option, it is necessary to additionally enter or simulate data on reservoir pressure, reservoir temperature (95.7°C) and the production gas factor, GOR (183 m^3/m^3). In addition, the relative density of oil (0.821) and

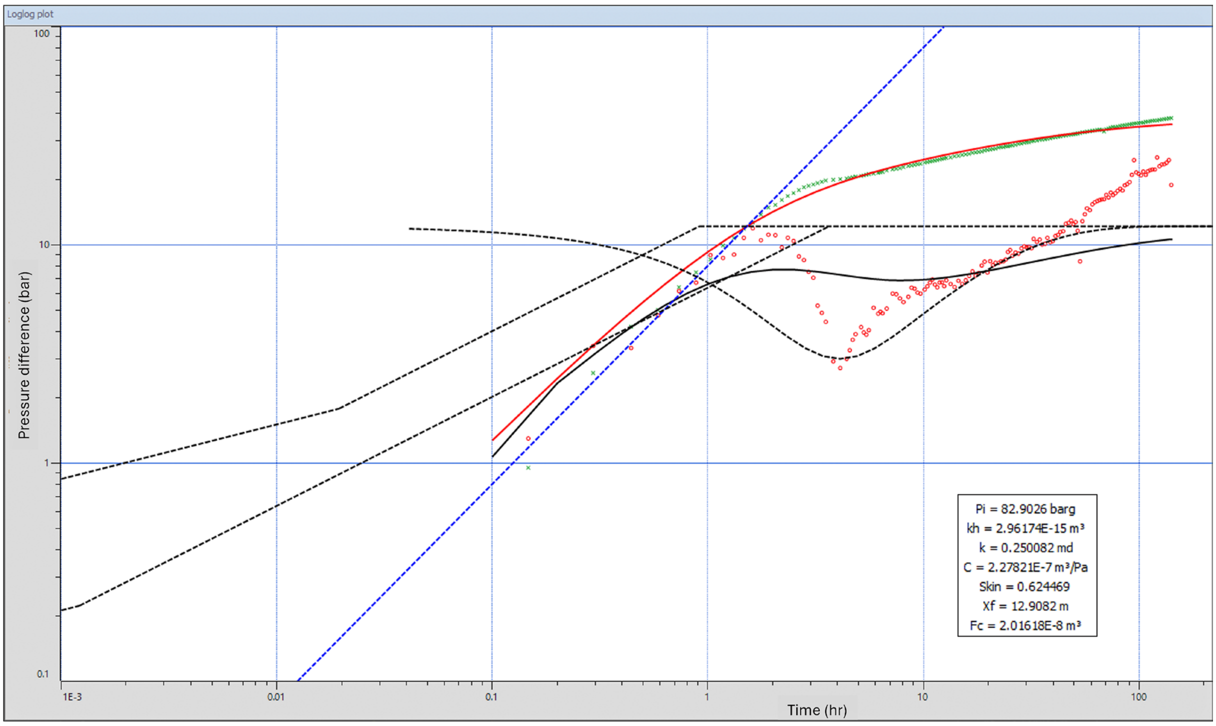

Figure 5: Pressure build-up test analysis for case 8

the relative density of gas (0.6691) are entered for the properties of oil and gas.

In analysis 8, the model of a fractured well with finite conductivity was chosen, and **Figure 5** shows the log-log diagram with the results. The aim is to determine whether the selection of the 'multiphase' option has an impact on the results or whether they differ from the single-phase models in analysis 2 for a vertical well and in analysis 5 for a fractured well. Analysis 8 was found to give the most accurate results, which differed slightly from the others. However, the key point here is that it is a model for a fractured well with multiphase fluid, which, unlike all the other cases, comes closest to the real conditions in the reservoir.

When modelling the measured data in **Figure 5**, first note the dashed blue line and its overlap with the data from the first part of the pressure curve measurement and its derivation during fluid storage. Then two black dashed parallel lines are important, from which the half-length of the fracture and its conductivity are determined. In the extreme part of the measured data, they connect adequately with the dashed line, parallel to the x-axis, which means that an IARF has been achieved, i.e. that the condition for interpreting the exact analysis results has been met. For the reasons mentioned above, this analysis and its results are selected as relevant in comparison to the others.

Deviations of the black solid line of the model from the derivative curve are to be expected in almost all cases, as it is a fractured well in which the original half-length of the fracture has closed after many years of production, and modelling in such cases usually cannot achieve better results, i.e. the curves cannot overlap, as in the case where the measurement was made immediately after the fracturing process.

4.2.4. Results of analysis 9

In contrast to the previous standard analyses, a specialized analysis of the bilinear and linear flow is carried out in this case. A new log-log diagram is created in which it is possible to place different specialized lines. For the linear flow, a slope line of 1/2 has been chosen, which is used to determine the value of the half-length, x_f, and for the bilinear flow, a slope line of 1/4 has been chosen, which indicates the value of the fracture conductivity, F_C. These pairs of parallel lines can be freely shifted in the diagram and increased or decreased in length, whereby the best overlap with both the pressure curve and the derivative curve is sought. Since none of these overlaps can be accepted because too little of the data may be contained in both the linear and bilinear forms of the flow, none of the results are an exact solution. Analysis 9 is nevertheless described as one of the general possible cases of test interpretation in a fractured well in which the results for these two forms of flow could be achieved.

The main results of all selected cases are highlighted in **Table 3** and discussed in accordance with the associated diagnostic log-log diagrams.

5. Discussion

The paper analyses the pressure build-up test of a fractured oil well, for which 9 possible interpretations are

Table 3: Results of analyses of pressure build-up test cases

Analysis	p_i, bar	k, mD	s, –	x_f, m	F_c, m²m
1	80.2221	0.563564	-3.78741	-	-
2	80.122	0.569538	-2.92899	-	-
3	80.1562	0.564552	-2.3914	-	-
4	84.1532	-	0.13975	12.9443	$1.1184 \cdot 10^{-7}$
5	84.2264	-	0.164543	13.1694	$1.1481 \cdot 10^{-7}$
6	84.0397	-	0.171733	13.0918	$1.1184 \cdot 10^{-7}$
7	80.2255	0.566543	-1.53566	-	-
8	82.9026	-	0.624469	12.9082	$2.0162 \cdot 10^{-8}$
9	-	-	-	33.8767	$1.2927 \cdot 10^{-14}$

made, with the aim of selecting the analysis that provides the most accurate results. As already mentioned, this is a well that has to be refractured after long period of production. In addition to determining the approximate permeability of the surrounding rock, the main aim is to establish how much the existing fracture half-length has decreased. The Saphir program is used to carry out a total of four analyses for the assumption of a vertical well, four for a fractured well and one specialized analysis of a fractured well. The aim is to determine the properties of the reservoir and the well and to determine how the change in individual input data affects the results of the analyses. **Šeb (2017)** states that the well test analysis resulted in a rock permeability value of 0.0007 μm² (0.7 mD) and a fracture half-length of approximately 10 m, but the full details of the pressure build-up test analysis on which these software values are based have not been published. Therefore, the reported estimates of these results have been taken as a reference and a kind of guide for the detailed analysis of the cases to confirm the accuracy of these values. In addition, the fact that the well file contained information about a laboratory measurement of the permeability of the core in the period after the well was constructed, when the value was approximately 0.002 μm² (2 mD), is important. As can be seen in **Table 3**, a permeability of 0.0005 μm² (0.5 mD) is obtained for each analysis in several modelling steps, which is a very good result considering that this is a fractured well with a significant alteration in the near-well zone. A complicating factor in the entire procedure was the lack of knowledge of the static fluid level in the borehole. It is recommended to do this before and after each measurement of the pressure build-up test, as the static fluid level in relation to the depth of the manometer could influence the determination of the reservoir pressure.

For all of the analysed log-log plots of pressure and the associated derivative as a function of time, several results can be seen (**Valjak, 2021**). Those most relevant to the discussion are highlighted in **Table 3**. In the analysis starting from a vertical well model, the primary objective was to obtain a negative skin, since it is a test of a fractured well, but from this model the permeability of the reservoir can also be approximated. When analysing wells with a fracture model, the primary objective is to determine the half-length of the fracture and its conductivity.

The initial reservoir pressure in the analyses of vertical wells 1, 2, 3 and 7 is approximately 80.2 bar, while in the wells with a finite conductivity fracture it is approximately 84.1 bar. Only in analysis 8 it is slightly lower (82.9 bar), as this model provides the closest values of the other parameters as well as the closest overlapping curves and is therefore chosen as the most appropriate. The permeability is found to be approximately 0.00056 μm2 (0.56 mD) for all vertical well analyses. Although the program also discarded smaller permeability values (up to 0.2 mD) when creating the model, the overlapping curves could not be considered satisfactory enough in these cases. A negative skin factor in these analyses indicates that it is a stimulated well, which can correspond to either a fractured vertical well or a horizontal well (**Koščak Kolin et al., 2013**). Considering the fact that in this case it is a hydraulically fractured well, further analyses are carried out for the fractured well model.

When analysing wells with a vertical fracture, in the first three analyses, i.e. 4, 5 and 6, approximately the same value is obtained for the half-length of the fracture of 13 m, as well as its conductivity of about 1.1×10^{-7} m² m. In analysis 8, the fracture half-length is also almost 13 m, but the conductivity of the fracture is slightly lower at 2.0×10^{-8} m² m. The 'multiphase' option in analyses 8 gives the most accurate results, as a model for a fractured well with multiphase fluid comes closest to the real conditions in the reservoir.

In the last, 9th analysis, an attempt is made to determine the value of the fracture half-length and the conductivity of the fracture using specialized analyses by finding bilinear and linear flow regimes. However, in the log-log diagram it is not possible to find a suitable overlap of the lines with pressure and derivative, so that the values $x_f = 33.9\ m$ and $F_C = 1.3\times10^{-14}\ m^2\ m$, cannot be accepted as correct.

6. Conclusion

The pressure build-up test of fractured oil well A-1 is analysed with the Saphir program. As the main diagnos-

 pp. 89-101, DOI: 10.17794/rgn.2024.4.7

tic tool, the program uses the log-log diagram of pressure and pressure derivation, which is also described theoretically, and the analysis attempts to overlap the measured data and the model. The analyses are performed for the assumed vertical well, where the aim is to determine the value of the permeability and skin factor, and then also for the fractured well, where the aim is to determine the half-length of the fracture and its conductivity. All analyses of the vertical well show a negative skin factor, which proves that it is a stimulated or fractured well. It is therefore possible to analyse the well with a vertical fracture and determine its parameters. In addition to determining the specified values, the influence of certain input parameters on the final results is also examined and it is found that changing the radius had no significant influence. However, selecting the 'multiphase' option in two analyses led to different results than when selecting a single-phase fluid, as it is a fluid with a relatively high GOR, and exactly one of these analyses is taken as the most accurate. In addition, specialized analyses of bilinear and linear flow are performed. However, the results of the analyses are not considered in this case, as it is not possible to include enough data when overlapping the curves, which is why the obtained results are not credible.

The most accurate results are obtained in analysis 8, where the half-length of the fracture is 12.9 m, the conductivity of the fracture is 2.0162×10^{-8} m^2 m and the initial reservoir pressure is 82.7 bar. Although the results do not differ significantly compared to other, i.e. single-phase analyses, a well model with a vertical fracture and a multiphase fluid comes closest to the real conditions in the reservoir. For all vertical well analyses, the permeability in the reservoir is 0.00056 μm2 (0.56 mD), and it is assumed that this modelled value is closest to the real one.

The advantage of this study is a new insight into confirming the accuracy of the results obtained by selecting 9 different analyses for the same pressure build-up test, which is an important guide for future similar investigations carried out on wells with a long production life after the fracturing process. In addition, the results of all 9 analytical modelling were performed very accurately and in accordance with their discussed comparison, the results can be considered very reliable.

The Saphir program enables a relatively simple analysis of the pressure build-up test using built-in functions. However, using the example of permeability and fracture half-length, it can be observed that simply following the commands in the control bar can lead to incorrect results. Without manually adjusting the values when creating the analytical model, a significantly lower permeability and a doubling of the fracture half-length were determined, which indicates the complexity of this case. Therefore, it is necessary to approach the analysis of the pressure build-up test thoroughly, taking into account previous measurements and known data about the well and the reservoir. Accordingly, it can be concluded that in the analyses presented in this paper, a good overlap of the model and the pressure curves and derivatives is achieved for the selected input parameters and that the results of the pressure build-up test are reliably determined.

This new approach of thorough analyses enables a new application in similar research with the aim of determining the most accurate results of the pressure build-up test, so that the future refracturing procedure can be based on data leading to a more successful refracturing design. Determination of fracture half-length is crucial for an optimal refracturing process. Therefore, the analytical modelling performed in all cases is a practical mean of determining the most accurate result possible. The advantage of this study is that it enables production and reservoir engineers at an operational level to more effectively apply advanced analytical techniques to actual field data as a starting point for future developments.

The plan for further research is to apply this approach to wells with a production decline due to a reduction in fracture half-length, which are candidates for refracturing to see which parameters in each analysis have the greatest impact on the results, i.e. to determine whether in the other wells the best modelling was achieved by choosing the multiphase option or the discussion of the results would indicate that the optimal choice is achieved by another analysed case.

7. References

Bourdarot, G. (1998): Well Testing: Interpretation Methods. Center for Petroleum Engineering and Project Development, Paris, 337 p.

Bourdet, D., Ayoub, J. A., Pirard, Y. M. (1989): Use of Pressure Derivative in Well-Test Interpretation. SPE Journal of Formation Evaluation, 4 (2), 293-302. https://doi.org/10.2118/12777-PA

Chaudhry, A. (2003): Oil well testing handbook. Elsevier. 525 p.

Cinco-Ley, H., Samaniego V. F., Dominguez, A. N. (1976): Transient pressure behavior for a well with a finite-conductivity vertical fracture. Society of Petroleum Engineers Journal, 18 (4), 253-264. http://dx.doi.org/10.2118/6014-PA

Čikeš, M. (2015): Proizvodno inženjerstvo nafte i plina (*Oil and Gas Production Engineering*). Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, Zagreb, 524 str.

Earlougher, R. C. (1977): Advances in well test analysis. Henry L. Doherty Memorial Fund of AIME, New York, 264 p.

Economides, M. J., Nolte, G. N. (2000): Reservoir Stimulation. John Wiley & Sons, 3rd edition, 20 Chapters.

Gringarten, A. C. (2008): From Sraight Lines to Deconvolution: The Evolution of the State of the Art in Well Test Analysis. SPE Reservoir Evaluation & Engineering, 11 (1), 41-62. https://doi.org/10.2118/102079-PA

Gringarten, A. C. (2012): Well Test Analysis in Practice. The Way Ahead, Society of Petroleum Engineers, 8 (2), 10-15.

Hategan, F., Hawkes, R. V. (2007): The Importance of Initial Reservoir Pressure for Tight Gas Completions and Long-

Term Production Forecasting. Journal of Canadian Petroleum Technology, 46 (10), 10-14. http://dx.doi.org/10.2118/2006-171

Horner, D. R. (1951): Pressure Build-Up in Wells. Third World Petroleum Congress, Sec. II., Hag., 503-523.

Houze, O. et al (2022): Dynamic Data Analysis v5.50, KAPPA, 778 p.

Jansen, J. D. (2017): Nodal Analysis of Oil and Gas Production Systems. Society of Petroleum Engineers, 368 p.

Koščak Kolin, S., Čikeš, M. and Babić, V. (2013): Analiza testa porasta tlaka horizontalne bušotine (*Pressure Build-up Test Analysis of the Horizontal Well*). Rudarsko-geološko-naftni zbornik, 26 (1), 11-28. (*in Croatian – English abstract)*

Koščak Kolin, S., Kurevija, T., Grebenar, D. (2018): Pressure Build-up Test Analysis of the Reservoir System with the Multiphase Flow. Rudarsko-geološko-naftni zbornik, 33 (3), 75-84. https://doi.org/10.17794/rgn.2018.3.8

Koščak Kolin, S. (2018): Pouzdanost određivanja propusnosti slabo propusnih plinskih ležišta optimiranjem trajanja testa porasta tlaka (*Reliability of the Permeability Determination of the Low Permeability Reservoirs by Optimizing the Pressure Build-up Test Duration*), Doktorska disertacija, Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, Zagreb, 244 str. (*in Croatian – English abstract)*

Lee J., Rollins J. B., Spivey J. P. (2003): Pressure Transient Testing. Society of Petroleum Engineers Textbook Series, Vol. 9, Richardson, 376 p.

Matthews, C. S., Russel, D. G. (1967): Pressure Buildup and Flow Tests in Wells. Monograph Volume 1, Henry L. Doherty Series, Society of Petroleum Engineers of AIME, New York, 167 p.

Mohaghegh, S. D. (2017): Data-Driven Reservoir Modeling. Society of Petroleum Engineers, 166 p.

Ostojic, J., Rezaee, R., Bahrami, H. (2012): Production Performance of Hydraulic Fractures in Tight Gas Sands, a Numerical Simulation Approach. Journal of Petroelum Science and Engineering, 88-89, 75-81. http://dx.doi.org/10.1016/j.petrol.2011.11.002

Poston, S. W., Laprea-Bigott, M., Poe Jr., B. D. (2019): Analysis of Oil and Gas Production Performance. Society of Petroleum Engineers, 175 p.

Slimani, K., Tiab, D. (2008): Pressure Transient Analysis of Partially Penetrating Wells in a Naturally Fractured Reservoir. Journal of Canadian Petroleum Technology, 47 (5), 63-69. http://dx.doi.org/10.2118/08-05-63

Soliman, M. Y., Ansah, J., Burris, J., Stephenson, S., Proett, M. (2003): Well Test Analysis in the New Economy. *Journal of Canadian Petroleum Technology*, 42 (7), 35-43. http://dx.doi.org/10.2118/03-07-03

Spivey, J. P., Lee, J. W. (2013): Applied Well Test Interpretation. Society of Petroleum Engineers, 386 p.

Stewart, G. (2011): Well test design and analysis. Penwell corporation. 1544 p.

Sun, J., Schechter, D. (2015): Investigating the Effect of Improved Fracture Conductivity on Production Performance of Hydraulically Fractured Wells: Field-Case Studies and Numerical Simulations. Journal of Petroleum Technology, 54 (6), 442-449. http://dx.doi.org/10.2118/169866-PA

Šeb, F. (2017): Proračun pridobivanja ugljikovodika iz bušotine Bilogora-3 nakon hidrauličkog frakturiranja ležišta (*Calculation of hydrocarbon recovery from the Bilogora-3 well after hydraulic fracturing of the reservoir*). Diplomski rad, Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, Zagreb, 45 str. (*in Croatian – English abstract)*

Valjak, A. (2021): Analiza testa porasta tlaka hidraulički frakturirane bušotine primjenom programa Saphir (*Pressure build-up test of the hydraulically fractured well in programme Saphir*). Diplomski rad, Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, Zagreb,78 str. (*in Croatian – English abstract)*

van Everdingen, A. F., Hurst, W. (1949): The Application of the Laplace Transformation to Flow Problems in Reservoirs. Transactions of the Society of Petroleum Engineers, Richardson, 186, 305-324.

Von Flatern, R. (2012): Well testing fundamentals. Oilfield Review, 24, 54-55.

Yasin, I. B. E. (2012): Pressure Transient Analysis Using Generated Well Test Data from Simulation of Selected Wells in Norne Field. Master Thesis. Norwegian University of Science and Technology, Trondheim, 94 p.

Zeng, F., Zhao, G. (2007): Well Testing Analysis for Variable Permeability Reservoirs, Journal of Canadian Petroleum Technology, 46 (2), 15-21. https://doi.org/10.2118/07-02-01

Internet sources:

URL: https://www.kappaeng.com/software/saphir/overview (accessed 29th February 2024)

SAŽETAK

Analize testa porasta tlaka frakturirane bušotine sa smanjenom poluduljinom frakture

Kada je proizvodnja nafte u hidraulički frakturiranoj bušotini A-1 počela opadati, planirano je ponovno frakturiranje bušotine, jer se pretpostavljalo smanjenje poluduljine pukotine nakon dužega razdoblja proizvodnje. Provedeno je nekoliko analiza testa porasta tlaka kako bi se odredila najbolja procjena smanjene poluduljine frakture. Iako su ciljevi ovih ispitivanja određivanje svojstava ležišta, kao što su propusnost stijene i skin faktor te vodljivost pukotine, program Saphir korišten je i za modeliranje poluduljine pukotine. To je najvažniji parametar potreban za projektiranje novoga postupka frakturiranja, kao i za stvaranje novoga proizvodnog modela bušotine. U tu svrhu najprije su teorijski opisane metode analize testa porasta tlaka. Na temelju različitih analiza istoga testa odabrana je ona u kojoj je postignuto najbolje preklapanje analitičkoga modela frakturirane bušotine s mjerenom krivuljom tlaka i s krivuljom njezine derivacije. Utvrđeno je da se najtočniji rezultat za poluduljinu pukotine dobiva modelom frakturirane bušotine s višefaznim protokom.

Ključne riječi:
test porasta tlaka, poluduljina frakture, refrakturiranje

Author's contribution

Sonja Koščak Kolin (1) (Assistant Professor, PhD) Conceptualization, methodology, formal analysis, interpretations and presentation of the results, writing- original draft preparation, supervision, writing – review & editing provided. **Andrea Valjak (2)** (mag. ing. petrol., Petroleum engineer) Data curation, methodology, formal analysis, investigation, interpretations and presentation of the results. **Vladislav Brkić (3)** (Associate Professor, PhD) Data validation, interpretations and presentation of the results, writing – review & editing provided. **Sonja Buti Njie (4)** (mag. ing. petrol., Oil and gas production expert) Data validation, writing – review & editing provided.