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Possibilities of analysing the pressure build-up test in the vertical oil well with decreased production

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Abstract

The paper describes the pressure build-up test analysis of the vertical oil well using the Saphir programme. The main objective is to determine the permeability of the rock and the skin factor. In order to obtain the most reliable results, three cases are analysed depending on the PVT properties of the fluid. In the first case, the fluid is assumed to be single-phase, in the second case two-phase and in the third case multiphase. Although the Bourdet log-log diagram method did not reach the transient phase in any of three cases because there was no complete overlap of the measured data and modelled curves, the results can be accepted with sufficient accuracy according to the descriptions in the discussion. The most reliable result is obtained in the first analysis. The permeability of the rock is determined to be 0.18 mD (1.78E-16 m^2) and the corresponding skin factor is 3.7.

Keywords: Pressure build-up test analysis; rock permeability; skin effect

1. Introduction

Well testing represents an important segment of oil and gas production and reservoir engineering. Analysis of the well test data indicates the possibility that the reservoir rock can produce reservoir fluids. The interpretation of the measured data can reveal the permeability of the reservoir rock, reservoir pressure, skin effect, radius of the stimulation, hydrodynamic connection of reservoir parts or boundaries of the reservoir (**Bourdarot, 1998**). Information about the reservoir and the well is collected throughout the life of the well in order to obtain the most accurate descriptions of the changes in production conditions in the well and in the reservoir by means of pressure analyses. The most common method for well testing is pressure build-up test, as it provides the necessary data for well models that continuously monitor, describe and forecast well production. A pressure build-up test is performed by allowing the well to produce at a constant flow rate and then shutting it down for a certain period of time. During the entire process, the pressure in the well is monitored and recorded. In this way, pressure build-up curve is obtained over a certain period of time, which is then analysed using the Saphir computer programme, that is part of the KAPPA Workstation software package (University Licence #9643) (www.kappaeng.com). During the analysis, the software first transforms the dimensionless solutions of the diffusion equation according to the principle of superposition (**Houze, et al., 2022**). The resulting solutions are then used to create a model that is compared by the programme with the measured values. In this way, matching points are obtained from which certain properties of the reservoir can be determined (**Koščak Kolin, 2018**). The main purpose of such tests is mainly to determine the permeability of the reservoir rock (k) and the skin factor (s) as well as the reservoir pressure.

The pressure build-up test of vertical well X, located on reservoir Y, is analysed with the Saphir programme. Three analyses of the pressure build-up test are performed assuming a single-phase, two-phase and multiphase fluid in order to compare the results and determine the permeability of the reservoir rock (k) and the skin effect (s) as accurately as possible. After entering the input data and describing the analytical model for each case, a discussion of the results obtained is carried out.

2. Methods

The fluid flow in the reservoir is the theoretical basis for analysing the pressure increase test in the vertical well, since the corresponding solutions of the diffusion equation for radial flow are used, as in production tests, but assuming a constant flow, which is 0 because the well is closed during the test (**Čikeš, 2015**). Based on these solutions, the equations are adapted to determine certain properties such as the permeability of the reservoir rock (k) and the skin effect (s). The final form of the diffusion equation in the radial system is shown by **Equation 1**:

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{\phi \mu c_t}{k}\frac{\partial p}{\partial t} \qquad (1)$$

where are:
p – pressure (Pa),
r – radius (m),
ϕ – porosity (%),
μ – viscosity (Pa·s),
c_t – total compressibility (Pa^{-1}),
k – rock permeability (m^2),
t – time (s).

In the analysis of the pressure build-up test, the dimensionless form of the diffusion equation is used, which is expressed with dimensionless variables: dimensionless pressure (p_D), dimensionless time (t_D) and dimensionless radius (r_D). With initial and boundary conditions, the solution of the dimensionless form of the diffusion equation for transient flow is in an infinite reservoir (**Čikeš, 2015**):

$$p_D(t_D) = \frac{1}{2}(\ln t_D + 0.80907) \qquad (2)$$

Using the dimensionless variables, type curves are defined for the analysis of production tests and pressure build-up tests in the method called Bourdet log-log diagram, (**Figure 1**), that is integrated into the Saphir programme as well. The analysis of the pressure build-up test is based on the PTA theory or Pressure Transient Analysis. The reason for this is that the well must be kept closed for the measurement until the pressure in the well stabilises, and stabilisation is achieved when the infinite acting radial flow (IARF) is reached. The wellbore storage effect occurs after closing and manifests as a left asymptote, which has a slope of one during the entire storage effect. This Bourdet diagram is solved by grouping dimensionless variables, where the dimensionless pressure (p_D) is a function of the dimensionless group (t_D/C_D) and the curves are described by the value of the parameter (C_De^{2s}) (**Bourdet, 1989**). At the beginning, all curves asymptotically approach the line with the slope of value one, and after the initial phase, the solution of the diffusion equation for an infinite reservoir is applied. In the further development of the typical curves, the derivative of the pressure (p_D') is introduced. Initially, the given curves in the log-log system have a unit slope, while the curves become horizontal at the moment the IARF is reached and have a value of 0.5. If the measurement data in the log-log diagram correspond to the second asymptote at the end of the measurement, this means that pressure stabilisation has been achieved (**Gringarten, 2008**). The application of the typical curve method consists of overlapping the measured data with typical curves. After overlapping, matching points are selected and used to calculate the rock properties (**Liu et al., 2018**; **Jirjis and Abdulaziz, 2019**).

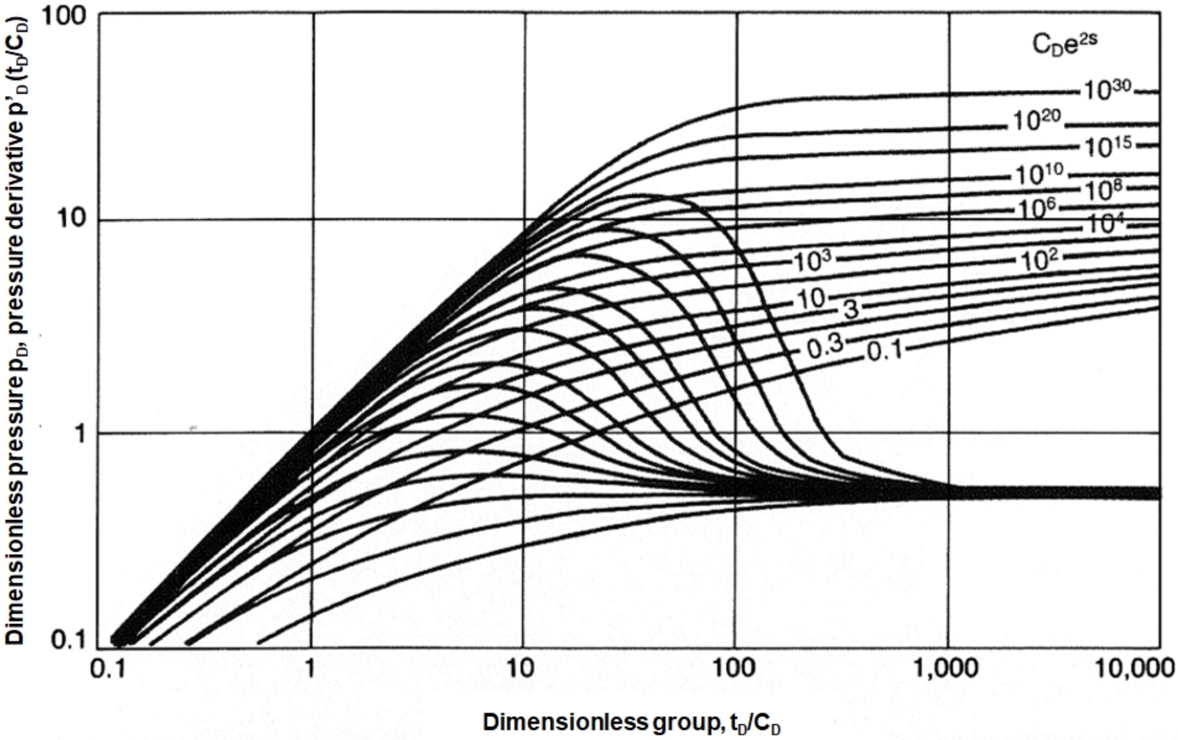


Figure 1: Bourdet diagram with type curves for an infinite reservoir (**Economides and Nolte, 2000**)

In the following, an analysis of the pressure build-up test of a vertical oil well was carried out using the Saphir programme (**Houze et al., 2022**). All reservoir and well parameters are taken from INA's technical documentation (**INA, 2014**). The actual name of the well or oil field is not given, as the name of the field is labelled Y and the well is labelled X.

3. Basic technical data of a well X

The well is located on a reservoir Y in the north-west of Croatia. The altitude in this area is between 150 and 250 metres. The reservoir is completely saturated with oil, and well X, which is located in the centre of reservoir Y, is a production well. Oil field Y has been exploited continuously since 1989, with the exception of six months in 1997, when it was temporarily shut down due to high transport costs (**INA, 2014**).

The length of well is 2283 m (TMD-True Measured Depth). The bottom of the column is at 1460 metres. The top of the cement plug is at 1460 metres and there are three open intervals in the well. The first interval is at a depth of 1425 metres to 1431 metres (TMD), the second interval is at a depth of 1433 metres to 1441 metres (TMD) and the third interval is at a depth of 1445 metres to 1488 metres (TMD). Well X is producing with the aid of down hole pump.

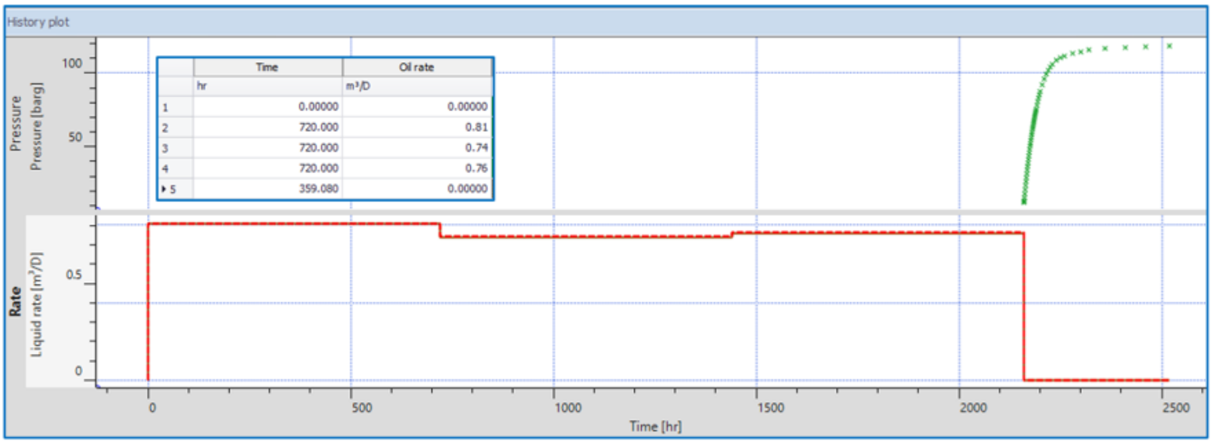
4. Main results of pressure build-up test analyses

The pressure build-up test in the vertical oil well X, which is analysed using the Saphir programme (University Licence #9643), lasted a full 360 hours (**Jukić, 2022**). The dynamic pressure at the bottom of the oil well was 31.8 bar at the time of closure and rose to 118.5 bar, after pressure stabilisation at the end of the measurement (**Figure 2**).

At the beginning of the analysis, the data required for the interpretation and calculation of the results are entered into the programme (**Houze et al., 2022; Kappa-Workstation, 2024**). These are the well radius of 0.03016 m, the thickness of the production layer, which in this case is effectively 6.9 m, the compressibility of the rock of 4.9E-10 Pa^{-1}, the porosity of 22.3% and the depth of the production layer of 1425 m. In the next step, the properties of the fluid are entered, such as the volume factor of oil 1.285 m^3/m^3, viscosity 7E-4 Pas, and total compressibility 1.26E-9Pa^{-1}.

When defining the parameters for the analytical model in the final step of entering the input data, four key conditions are selected to determine the output model in analysis of the pressure build-up test. These are Wellbore storage, which is constant in this case, the Well model, i.e. the vertical well, the Reservoir model, for which homogenity is assumed, and the Boundary model, in which the reservoir is assumed to be infinite (**Kappa-Workstation, 2024)**.

In accordance with the flow and pressure measurement data before and after closing the well for the build-up test, the entire test is shown in **Figure 2**, which is analysed with the change in PVT data. This means that the test is first analysed assuming a single-phase fluid, then for a two-phase fluid and finally for a multiphase fluid (**Valjak, 2021**). This case analyses are performed to determine the most accurate properties of the reservoir, i.e. the results for rock permeability (k) and skin factor (s), because after the long-term operation of the well since 1989, the hydrodynamic state of the reservoir has also changed significantly, which affects the results of such analyses. Therefore, the overlap of the measured data with the typical curves in the log-log diagram can hardly be fully realised, which is discussed by presenting the results of individual cases (**Azi et al., 2008**).



	Time	Oil rate
	hr	m^3/D
1	0.00000	0.00000
2	720.000	0.81
3	720.000	0.74
4	720.000	0.76
▸ 5	359.080	0.00000

Figure 2: History plot

Figure 2 shows that the well was stabilised over a long period of time before it was closed in order to obtain more accurate results during interpretation (**Jukić, 2022**). An attempt was made to maintain a constant flow, which strongly influences the accuracy of the application of theoretical solutions. The diagram shows three phases of well stabilisation, i.e. stabilisation of flow, prior to the actual shut-in, initially producing at a constant oil flow of 0.81 m^3/day for a period of 720 hours, then at a constant flow of 0.74 m^3/day for the next 720 hours and finally at a flow of 0.76 m^3/day for the next 720 hours. As mentioned earlier, this was followed by a 360-hour pressure build-up test, during which the measurement curve increased from a dynamic pressure of 31.8 bar at the time the well was closed to a static pressure of 118.5 bar at the end of the test. In **Figure 2**, these pressure measurement data are marked with green crosses. Although the build-up test for a conventional reservoir type theoretically lasted long enough in terms of permeability, the results for all three analysis cases show that pressure stabilisation could not be fully achieved even though all production requirements for well operation were met. This is shown by the insufficient overlap of the curve of the pressure derivative with the typical curves, i.e. with the modelled curves in the log-log diagram, which is discussed later. At this point, it should be noted that the test conducted was carried out in 2007, when the well reached a relatively low flow rate and was a potential candidate for future hydraulic fracturing. For this reason, it was necessary to carry out such detailed tests because the success of the stimulation procedure design to increase the productivity of the well, i.e. the success of the hydraulic fracturing procedure (**Sun and Schechter, 2015**), depends largely on the required results for rock permeability (k) and skin factor (s).

The 'History plot' in **Figure 2** refers to the first case of analysis of the pressure build-up test for a single-phase fluid, where it is assumed that the well produces only oil, the flow of which is shown with a red line before closing.

4.1. Pressure analysis for a case of a single-phase fluid

Figure 3 shows the log-log diagram for the first case of the analysis, where the fluid is assumed to be single-phase, and **Figure 4** shows the corresponding results of this analysis, where the key to the comparison with the other two cases for two-phase and multiphase fluid are the rock permeability (k) and the skin factor (s). In the diagram, the measured pressure data are marked with green crosses and their derivatives with red circles, while the solid red and black lines refer to type curves, i.e. modelled pressure values and derivatives that the programme approximates, achieving maximum accuracy when the curves overlap. The theoretical conditions must be satisfied that the beginning of the measured and derived data coincides with the first dashed direction of slope 1, which indicates the period of fluid storage in the well, which is fulfilled, and that the final derived pressure values coincide with the second dashed direction, i.e. with an asymptote of 0.5, which is not completely fulfilled. The reason for this could be the possible proximity of the fault (**Koščak Kolin, et al., 2013**), as a result of which the pressure response does not enter the stabilisation, but it can be concluded that the scattering of the data around the asymptote of 0.5 indicates a slight anomaly, the influence of which could not have been known before the measurement.

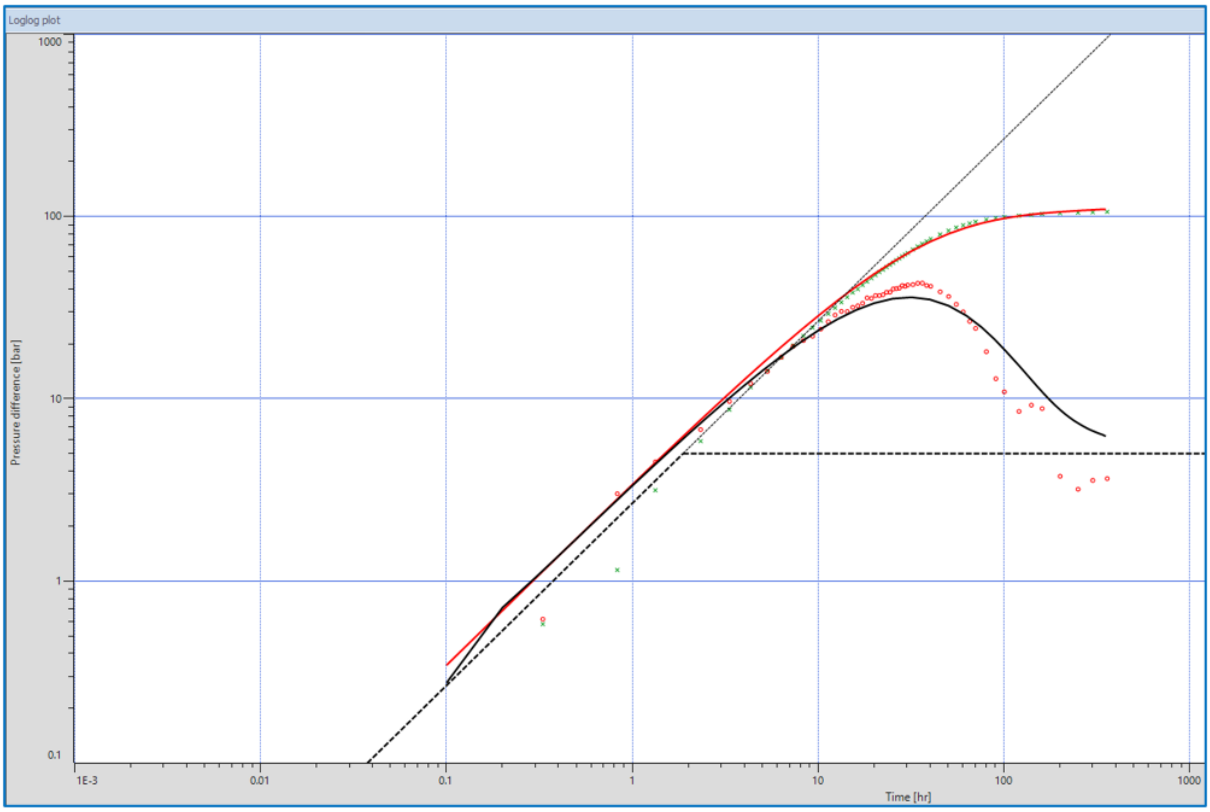
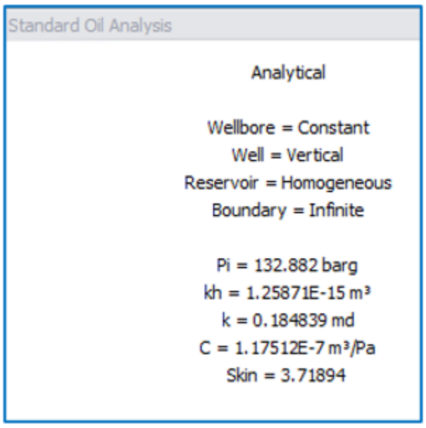


Figure 3: The first analysis for a single-phase fluid

When displaying the results in **Figure 4**, the programme lists the conditions selected when creating the analysis model. The most important results for all three analyses are presented together in **Table 1**. In addition to the results for reservoir pressure (p_i), permeability (k) and skin factor (s) already mentioned, the product of permeability and effective reservoir thickness (kh) and the storage constants (C) are also given.



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Standard Oil Analysis

Analytical

Wellbore = Constant
Well = Vertical
Reservoir = Homogeneous
Boundary = Infinite

Pi = 132.882 barg
kh = 1.25871E-15 m³
k = 0.184839 md
C = 1.17512E-7 m³/Pa
Skin = 3.71894
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Figure 4: Results of the first analysis

4.2. Pressure analysis for a case of a two-phase fluid

Figure 5 shows the log-log diagram for the second analysis, in which the data had to be supplemented with additional laboratory parameters for the two-phase fluid compared to the first analysis, which unfortunately were not all known, as additional laboratory tests have to be carried out. Since some of them are not available, they are assumed in accordance with software corellation, in order to obtain the first insight into the evaluation of the results of the second analysis. For this reason, in practise only the analysis for a single-phase fluid is usually carried out. As it can be seen, the overlap of measured and modelled data has not improved compared to the first analysis, but there were differences in the results (**Figure 6**), which are discussed according to **Table 1**.

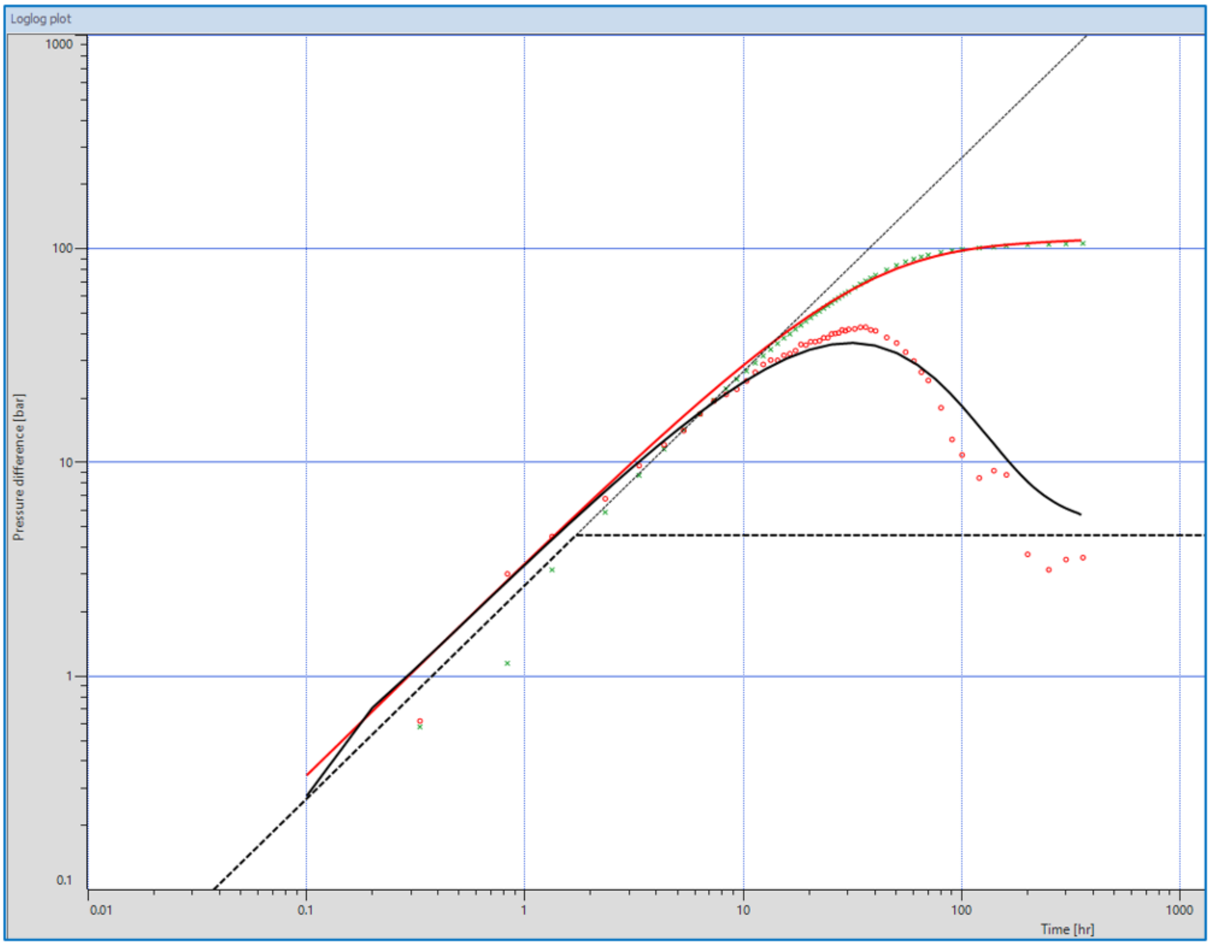
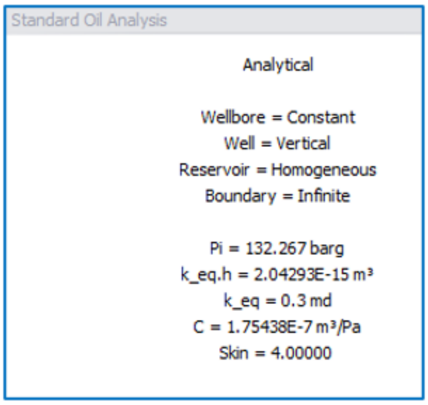


Figure 5: The second analysis for a two-phase fluid



Analytical

Wellbore = Constant
Well = Vertical
Reservoir = Homogeneous
Boundary = Infinite

Pi = 132.267 barg
k_eq.h = 2.04293E-15 m^3
k_eq = 0.3 md
C = 1.75438E-7 m^3/Pa
Skin = 4.00000

Figure 6: Results of the second analysis

4.3. Pressure analysis for a case of a multiphase fluid

Analogous to the second analysis, **Figure 7** shows the log-log diagram for the third analysis of the pressure build-up test, in which the input data for the PVT properties also had to be supplemented with additional laboratory parameters for the multiphase fluid (**Kamal and Pan, 2011; Koščak Kolin, et al., 2018; Perrine, 1956**), not all of which were available. For this reason, some of them were also corellated to provide a first insight into the evaluation of the results of the third analysis (**Figure 8**). As it can be seen again, the overlap of the measured and modelled data in the log-log diagram did not improve compared to either the first or the second analysis, i.e. it remained almost identical to the single-phase fluid. For this reason, the further option of the Saphir programme to improve the analytical model into a numerical one was not implemented, as there would again be a lack of input parameters. This is a common case in practise, considering that the relatively expensive process of their determination in the laboratory is an additional cost factor in relation to the high price of the measurements and the price of their high-quality interpretation.

However, in the case of well X, the available production parameters indicate that the water and gas content in the production was not significant and therefore the single-phase assumption is optimal and sufficient. This ultimately means that the first analysis shows a smaller deviation in the results than the others, which assumed more parameters in the definition of the model.

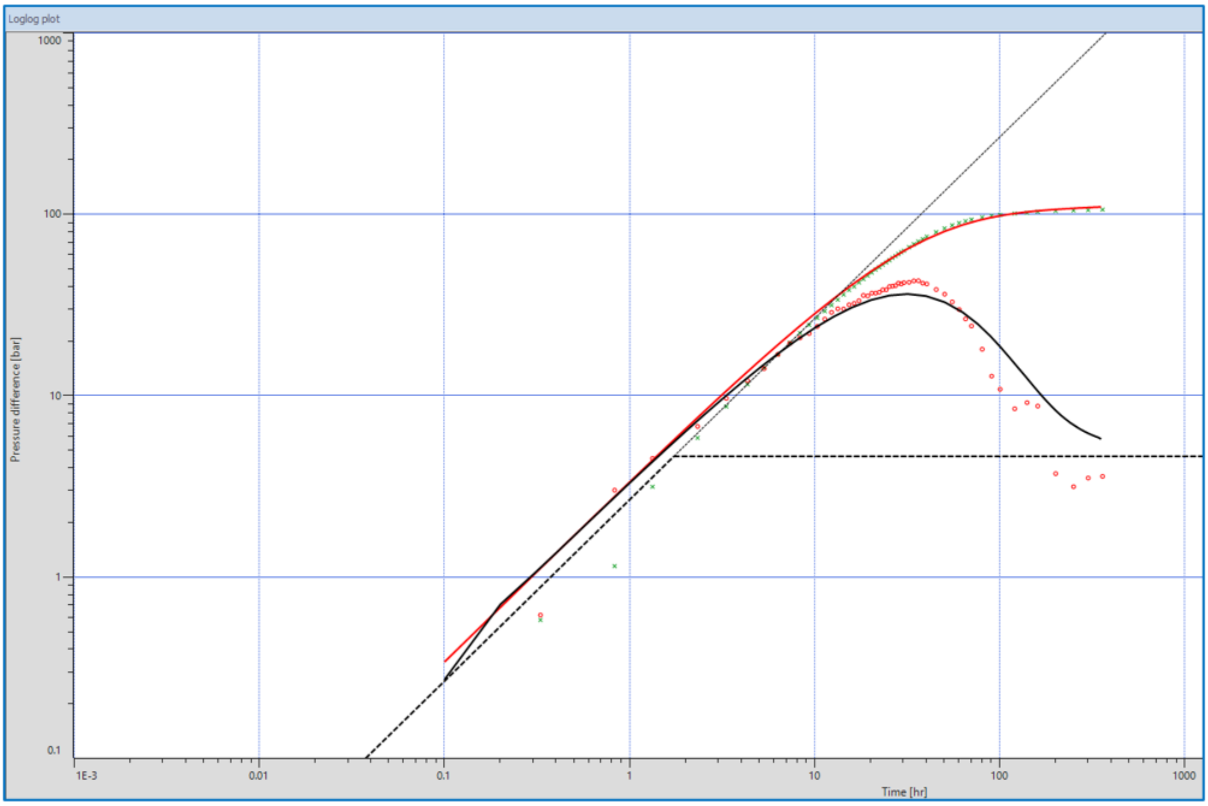
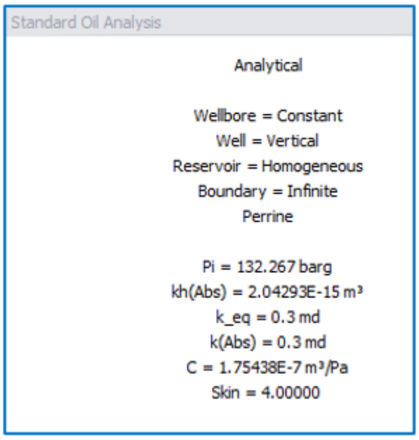


Figure 7: The third analysis for a multiphase fluid



Analytical

Wellbore = Constant
Well = Vertical
Reservoir = Homogeneous
Boundary = Infinite
Perrine

Pi = 132.267 barg
kh(Abs) = 2.04293E-15 m^3
k_eq = 0.3 md
k(Abs) = 0.3 md
C = 1.75438E-7 m^3/Pa
Skin = 4.00000

Figure 8: Results of the third analysis

5. Discussion

Table 1 shows the results of all three analyses of the pressure build-up test in the vertical oil well X, which lasted 360 hours (**Jukić, 2022**). From all the interpreted log-log diagrams in **Figures 3**, **5** and **7**, it can be concluded that the necessary pressure stabilisation at the end of the test is not completely fulfilled, as the second asymptote of 0.5 shows an incomplete overlap with the derivatives of the last measured pressures. According to the theoretical assumptions of the PTA analysis described above, achieving the IARF is a condition for the applied model to provide reliable results. Another possibility of incomplete overlap could be the proximity of the fault, which could have an influence on the pressure response where the derivatives do not match the second asymptote even after a longer measurement period. However, it should be noted that although the modelled line does not overlap with the second asymptote, it still satisfactorily describes the derived data throughout the test. The same applies to the modelled line, which describes the entire pressure curve very well, meaning that the results can still be taken with approximate accuracy.

In this regard, the investigation of the influence of fault is omitted, as the dispersion of the results in each analysis is not too large, especially in relation to the values obtained for permeability. The main conclusion is therefore that the most reliable result was obtained in the first analysis, i.e. that the permeability of the reservoir rock is 0.18 mD (1.78E-16 m^2), regardless of the fact that a value of 0.3 mD (2.96E-16m^2) is obtained in the other two analyses. Although this is not a big difference compared to the first result, in the second and third analyses a larger number of assumptions are entered for the PVT parameters based on the built corelations, which increases the deviation of their results.

Taking the above explanations into account, the result for the skin factor is also selected from the first analysis because it depends on the permeability and is 3.7. Furthermore, it can be concluded that well X is a good candidate for hydraulic fracturing as its production rate has decreased from the initial production in 1989, when it produced about 10 m^3/day, to about 0.8 m^3/day in 2007, when the analysed build-up test was performed. According to INA's documentation (**INA, 2014**), well X is currently produces only 0.3 m^3/day of oil, and the water cut has also increased slightly compared to 2007.

Table 1: Results of the pressure build-up test analyses

Cases	PVT condition	**Results**	
		Permeability	Skin factor
		mD	-
1. analysis	Single-phase fluid	0.18	3.7
2. analysis	Two-phase fluid	0.3	4.0
3. analysis	Multiphase fluid	0.3	4.0

6. Conclusions

The main objective of the analysed well test is to determine the permeability of the rock and the skin factor after the well has been producing for a long period of time, so that the production possibilities of the reservoir and the well have changed and decreased compared to the initial period. In order to determine the most reliable results and compare them, three cases are analysed depending on the PVT properties of the fluid. In the first case, the fluid is assumed to be single-phase, in the second two-phase, and in the third case multiphase.

According to the interpretation of the associated log-log diagrams, all three analyses of the pressure build-up test indicate that the necessary stabilisation of the pressure at the end of the test is not completely fulfilled, which, according to the condition of the PTA, means that the IARF, i.e. the applied solutions of the specified analytical model, could give deviations in the accuracy of the results. It can be concluded from the diagram that the complete overlap of the measured and modelled curves most likely did not occur due to the proximity of the fault, but the modelled lines nevertheless describe the entire pressure curve and its derivative well, so that the results can be taken with sufficient accuracy.

The most reliable result is obtained in the first analysis and the permeability of the reservoir rock is determined to be 0.18 mD (1.78E-16 m^2), which is not very different from the results of the second and third analyses, where, however, a larger number of assumptions are made for the input of the PVT parameters, which increased their deviation.

The result for the skin factor is selected from the first analysis, which means that the well is a good candidate for hydraulic fracturing, as its production capacities have drastically decreased from an initial flow of about 10 m^3/day to about 0.8 m^3/day in 2007, when the analysed build-up test was performed.

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SAŽETAK

Mogućnosti analize testa porasta tlaka u vertikalnoj naftnoj bušotini sa smanjenjem proizvodnje

U radu je opisana analiza testa porasta tlaka vertikalne naftne bušotine s pomoću programa Saphir. Glavni cilj je odrediti propusnost stijene i skin faktor, a u svrhu dobivanja što pouzdanijih rezultata, analizirana su tri slučaja, ovisno o PVT svojstvima fluida. U prvom slučaju je pretpostavljeno da je fluid jednofazan, u drugom da je dvofazan i u trećem da je višefazan. Iako metoda Bourdet log-log dijagrama nije dosegla prijelaznu fazu ni u jednom od tri slučaja, jer nije bilo potpunog preklapanja mjerenih podataka tlaka i njegove derivacije s modeliranim krivuljama, rezultati se mogu prihvatiti s dovoljnom točnošću prema obrazloženjima u diskusiji rezultata. Najpouzdaniji rezultat dobiva se u prvoj analizi. Propusnost stijene je određena u iznosu od 0,18 mD (1.78E-16 m^2), a pripadajući skin faktor je 3,7.

Ključne riječi: analiza testa porasta tlaka; propusnost; skin faktor

Author’s contribution

Sonja Koščak Kolin (Assistant Professor, PhD) Formal analysis, Methodology, Interpretations and presentation of the results, Writing- Original draft preparation, Supervision, Writing – review & editing provided. **Vladislav Brkić** (Associate Professor, PhD) Investigation, Data validation, Interpretations and presentation of the results, Writing – review & editing provided. **Nikola Jukić** (Mag.ing.petrol., Petroleum engineer) Data curation, Methodology, Formal analysis, Interpretations and presentation of the results. **Sonja Buti Njie** (Mag.ing.petrol., Oil and gas production expert) Data validation, Writing – review & editing provided.