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Transient Pressure Testing of Homogeneous and Heterogeneous Oil Reservoirs: A Simulation Study Using Assumed Data

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Abstract

A fluid flow test is performed on oil or gas wells to examine the change in the flow rate of the well and the pressure response as a function of time. The objectives of this study are to investigate the effect of reservoir heterogeneity and the effect of well location on well testing. In this study, a reservoir model was constructed, and the fluid and reservoir properties were then subjected to a well testing process (buildup test). The results indicate that the pressure during well testing increases with increasing time of testing until reaching the reservoir pressure. The location of the well affected the slope of the straight line. An increase in the slope of the straight line was observed when the well was located at the flank of the reservoir, and an effect on the pressure buildup period was also noted. In the case of increasing the permeability with depth, the slope of the straight line increases compared with that of a homogeneous reservoir well located at the crest, while if the permeability decreases with depth, the slope increases and the pressure buildup period decreases. This behavior was also observed in the alternating permeability case.

Keywords: Well test; Transient pressure; Well location; Heterogeneity; Permeability estimation.

1. Introduction

The upstream oil sector focuses on transient well testing (TWT) because of the valuable information it provides about reservoirs, which enables staff to make decisions throughout the entire production process [1]. Initially, groundwater hydrology required a technique for water well testing; after this technique proved successful, its application was transferred to petroleum reservoirs to assist in estimating formation permeability, wellbore conditions, and reservoir pressure [2]. Subsequently, transient testing proved capable of estimating the effective fracture extent along the reservoir and its accessibility, the extent of reservoir boundaries, and selecting the most viable flow behavior model of the reservoir [3]. Outputs from transient well testing have been routinely used to optimize drilling and completion processes, increasing oil production and enhancing the knowledge of reservoir engineers [4-6]. Analytical solutions that assume uniform reservoir characteristics throughout the area investigated by transient testing have considerably advanced transient well testing [7,8]. For example, specifying a single value for effective oil permeability was considered adequate when predicting reservoir performance using the material balance equation (MBE) and decline curve analysis [9]. With the advent of numerical simulation in recent decades, the capability of TWT to predict reservoir performance has improved [10].

Detailed information about the reservoir is necessary for staff to understand the current behavior and long-term performance of the reservoir. TWT is intended to provide a quantitative analysis of reservoir characteristics [11]. A transient test is essentially accomplished by creating a pressure disturbance in the reservoir and recording the response at the wellbore (i.e., the downhole flowing pressure, p_{wf} , as a function of time) [12].

A wide range of well test types and procedures is available, which can be classified according to the approach by which they are carried out [13]: whether they involve a single well or multiple wells [14], whether they are run by opening up or shutting in the production well [15], whether the well is a production or an injection well [16], and whether it is an exploration well or a well in a mature field [17]. These types include drill-stem, drawdown, buildup, step-rate, falloff, interference and pulse, layered-reservoir, and repeat/multiple-formation tests [18]. Pressure buildup data are used together with other beneficial tools to examine reservoir behavior [19]. Pressure buildup analysis characterizes the buildup of well pressure over time after a well is shut in. The main objective of this test is to determine the static reservoir pressure in a short time without waiting weeks or months for the pressure in the entire reservoir to stabilize [20]. The pressure buildup analysis can be extended to estimate the effective reservoir permeability, the extent of permeability damage around the wellbore, the presence of faults and, to some degree, the distance to faults, any interference between producing wells, and reservoir boundaries, because pressure buildup in a wellbore generally follows a specific trend [21]. Many factors affect the well test, such as reservoir heterogeneity [22-24], well location, type of oil (volatile or black oil), and type of reservoir (saturated or undersaturated reservoir) [25]. A new approach to the analysis of the pressure buildup curve obtained from a closed-in well was proposed based on the relationship between the bottom hole pressure (BHP) and the logarithm of the closed-in time [26].

A simple and practical method was identified to estimate effective permeability and reservoir pressure from the rise in downhole pressure when the well is drilled and closed [27]. A novel and simple method was identified, which eliminates the reliance on producing time effects and allows the user to take advantage of existing drawdown type curves to analyze pressure buildup data [28]. This method can also be used to analyze double- and multiple-rate tests and other types of tests by type curve methods in addition to traditional methods. The difference between the pressure in a producing well and the average pressure of its drainage area was studied [29]. The buildup time required to overcome this difference was then indicated. A method can be used to estimate the average drainage-area pressure from the Horner plot [30] (Figure 1). A method to calculate both the average tank pressure and the approximate distribution of pressure within a given reservoir was developed, known as the Matthews-Brons-Hazebroek (MBH) method [31] (Figure 2).

This study was conducted to investigate the effect of reservoir heterogeneity and the effect of well location on well testing. Owing to the absence of available field data and the difficulty of obtaining them, this study assumed many different scenarios using simulation models to understand the effects of reservoir heterogeneity and well location on the buildup test for oil reservoirs.

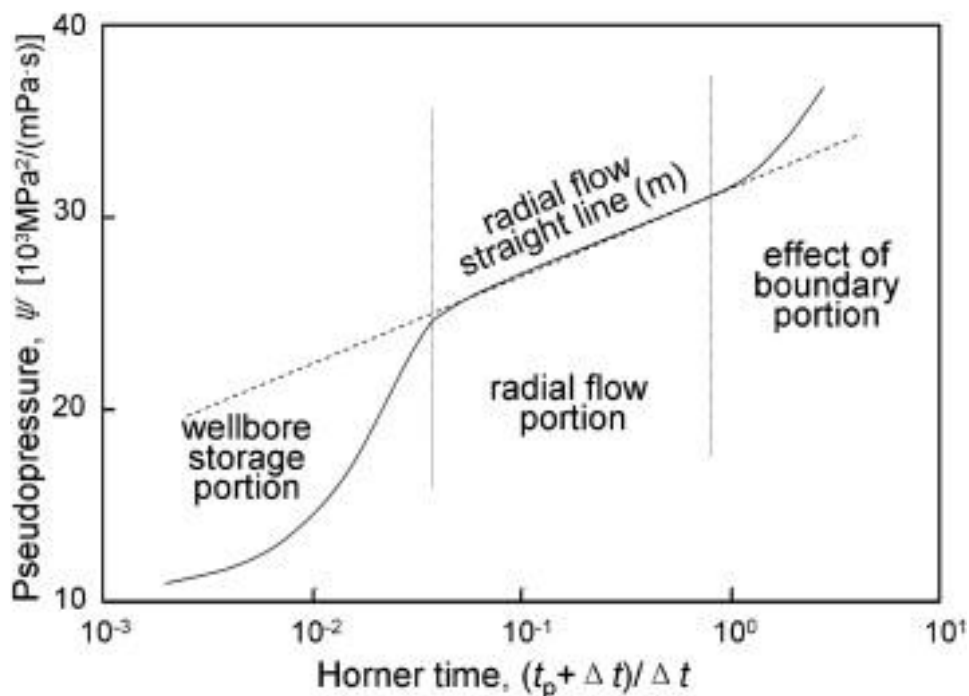


Figure 1: Pressure buildup analysis, Horner method [32]

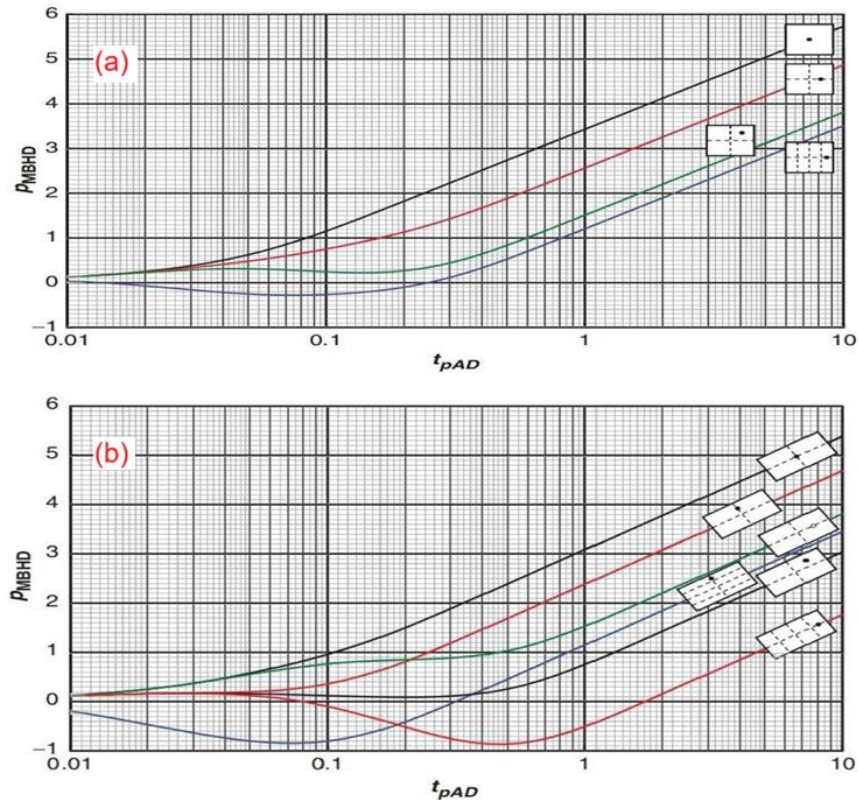


Figure 2 : Matthews-Brons-Hazebroek (MBH) method, a- for a square area. b- for a 2×1 rectangular drainage area [31]

2 .Data and Methods

2.1 Data

Researchers in the oil industry (especially those whose research requires measurements and field data) are aware of the difficulty of obtaining real information because official approvals are required to provide such data. The data collection process included reviewing numerous reference books on well testing and well test analysis methods, followed by collecting the reservoir properties required to build the static and dynamic models.

2.2 Methods

2.2.1 Static model

A static model was constructed using PetrelTM to establish an assumed reservoir length, width, with a depth equal to 9200 ft) consisting of nine layers for the five cases (Figure 3).

Table 1: Reservoir state, well location, porosity, and permeability (K) in the x, y, and z directions for the five assumed cases

Case No.	Reservoir state	Well location	Porosity (%)	Kx (md)	Ky (md)	Kz (md)
1	Homogeneous	At the crest	20	600	600	60
2	Homogeneous	At the flank	20	600	600	60
3	Reservoir alternating permeability	At the crest	20	K1= 300 K2= 700 K3= 300 K4= 700 K5= 300 K6= 700 K7= 300 K8= 700 K9= 300	K1= 300 K2= 700 K3= 300 K4= 700 K5= 300 K6= 700 K7= 300 K8= 700 K9= 300	10% of Kx and Ky
4	Permeability decreases with depth	At the crest	20	K1= 900 K2= 800 K3= 700 K4= 600 K5= 500 K6= 400 K7= 300 K8= 200 K9= 100	K1= 900 K2= 800 K3= 700 K4= 600 K5= 500 K6= 400 K7= 300 K8= 200 K9= 100	10% of Kx and Ky
5	Permeability increases with depth	At the crest	20	K1= 100 K2= 200 K3= 300 K4= 400 K5= 500 K6= 600 K7= 700 K8= 800 K9= 900	K1= 100 K2= 200 K3= 300 K4= 400 K5= 500 K6= 600 K7= 700 K8= 800 K9= 900	10% of Kx and Ky

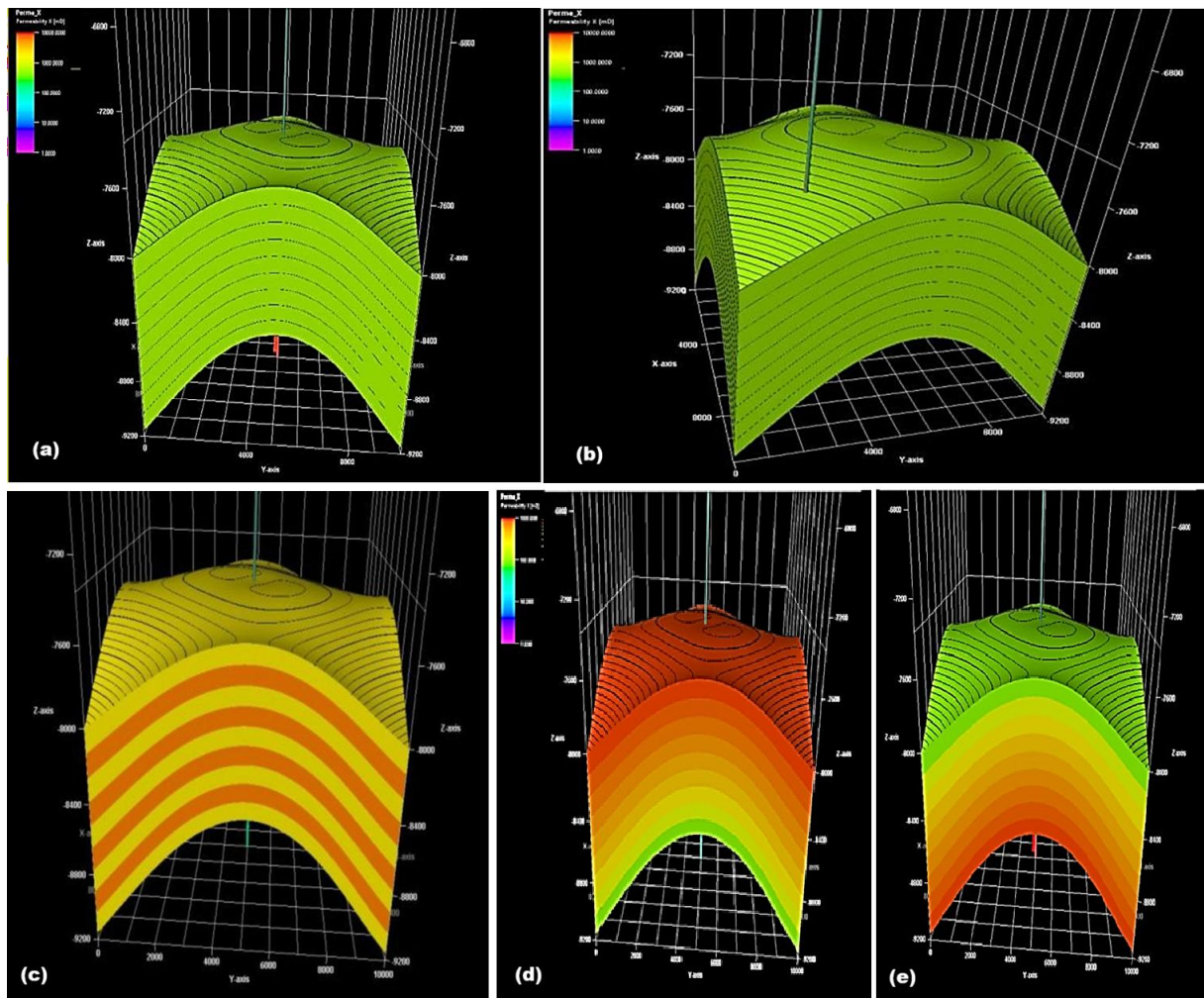


Figure 3: Static model built in Petrel TM: a- for case 1 (homogeneous reservoir, well at the crest), b- for case 2 (homogeneous reservoir, well at the flank), c- for case 3 (reservoir alternating permeability), d- for case 4 (reservoir permeability decreases with depth), and e- for case 5 (reservoir permeability increases with depth)

2.2.2 Dynamic model

The dynamic model was built by entering rock-fluid data, such as saturation, relative permeability, capillary pressure, and fluid contacts, followed by other processes, such as defining the development strategy, opening the well to production, and performing a buildup test to calculate the average effective permeability and skin factor. The data of the dynamic model are shown in Table 2. Table 3 shows the properties of the fluids. Table 4 presents the completion data of the well.

Table 2: Reservoir data of dynamic model

Parameter	Value
Maximum pressure	6275 psi
Minimum pressure	1980 psi
Reference pressure	15 psi
Bubble point pressure	1969 psi
Depth datum	-9000 ft
Gas-oil contact	-5000 ft
Water-oil contact	-9000 ft
Reservoir temperature	112 °F
Thickness of pay zone	60 ft

Table 3: Properties of the fluids

Property	Value
Viscosity of oil	7.7 cp
Oil formation volume factor	1.14 bbl/STB
Oil flow rate	5000 bbl/day
Gravity of oil	21.6 API
Gravity of gas	0.75 sg air
Oil-water surface tension	33.5 dyne/cm
Water salinity	30000 ppm
Viscosity of oil	7.7 cp

Table 4: Data on the completion of the well

Depth of well	9200 ft
Height from sea level	52 ft
Casing depth	8989.81 ft
Tubing depth	6300.93 ft
Height of packer	139.19 ft
Depth of plug	9022.14 ft
Top of perforation	7550.79 ft
Bottom of perforation	8197.54 ft

2.3 Development plan

The development plan was designed such that the well was opened for production on 1/1/2023 at a flow rate of 5000 bbl/day. On 1/1/2025, the well was shut in at the surface, and it was then reopened for production on 1/1/2026 at a flow rate of 5000 bbl/day. The well will continue producing at the same flow rate until 1/1/2040.

3. Results and Discussion

3.1 Case 1: Homogeneous reservoir, well located at the crest

Figure 4 shows the bottom hole pressure versus time for the buildup test of the homogeneous reservoir well located at the crest. It is observed that the pressure increased very rapidly from 5127.8 to 5257.9 psi within 1 hour. From Figure 5, the slope is equal to 200 psi/cycle. The average reservoir permeability calculated using $K = -\frac{162.6qB\mu}{mh}$ [27] is 594.7 md, whereas the reservoir permeability is 600 md, where K is the Effective permeability to the flowing fluid in md, q is the flow rate in STB/D, B is the Formation volume factor in RB/STB, μ is the Fluid viscosity in centipoise (cp), m is the slope of the semi-log straight line on a pressure vs. log-time plot in psi/cycle, and h is the net formation thickness in ft.

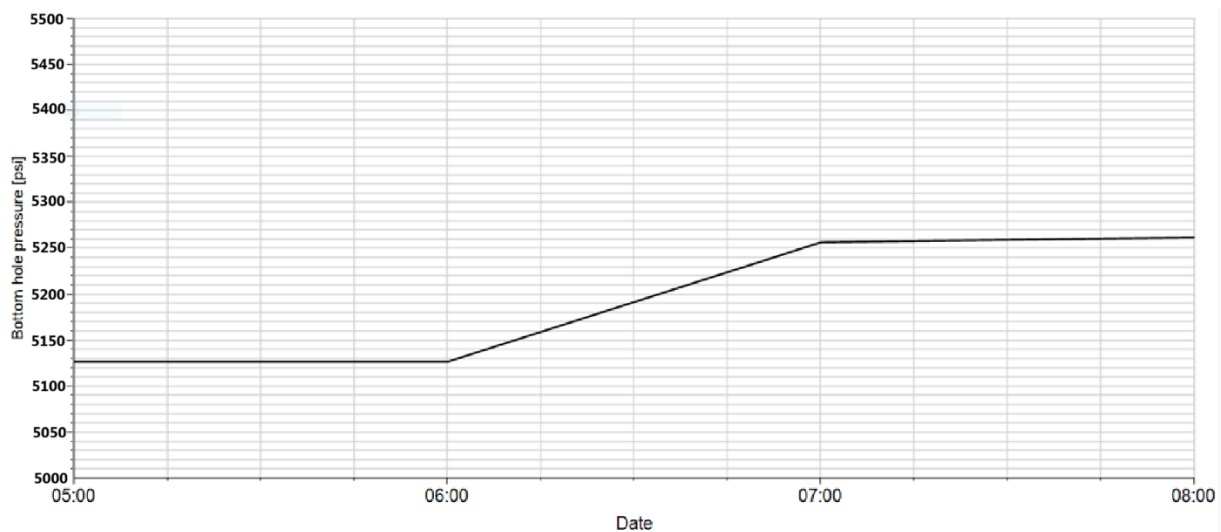


Figure 4: Buildup pressure curve for the homogeneous reservoir well located at the crest

3.2 Case 2: Homogeneous reservoir, well located at the flank

Figure 6 shows the bottom hole pressure versus time for the buildup test of the homogeneous reservoir well located at the flank. It is observed that the pressure increased very rapidly from 5128.6 to 5279.9 psi within 1 hour. From Figure 7, the slope is equal to 252 psi/cycle. The average reservoir permeability based on the Horner method is 471.99 md, whereas the reservoir permeability is 600 md.

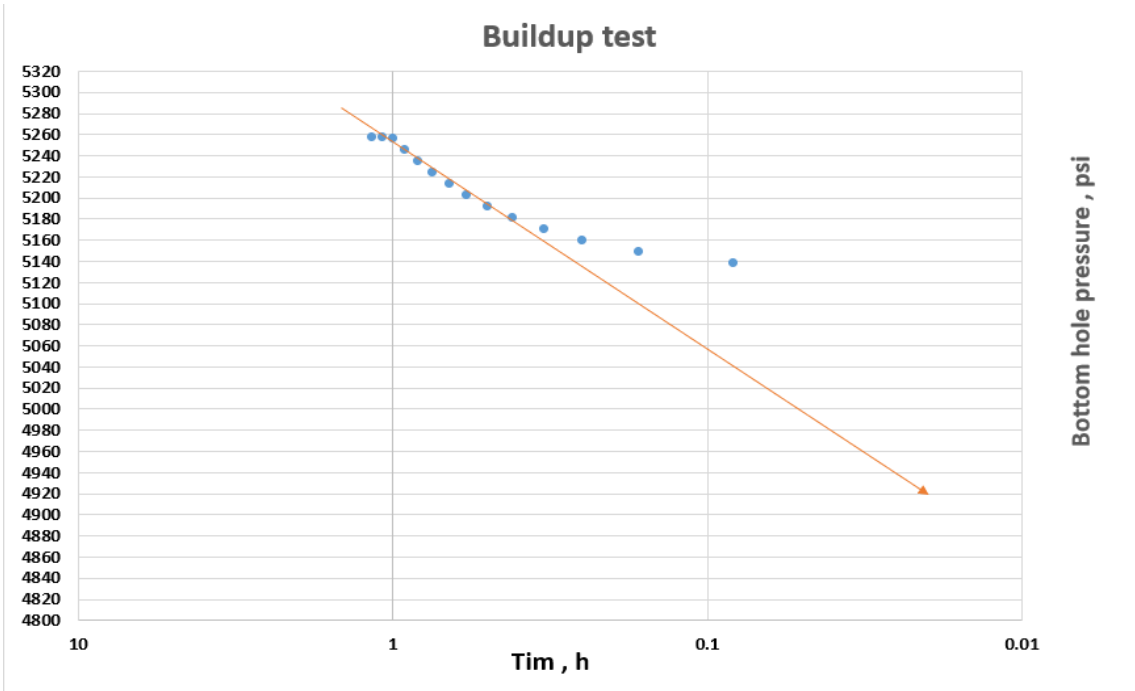


Figure 5: Semi-log graph of the buildup pressure test for the homogeneous reservoir well located at the crest

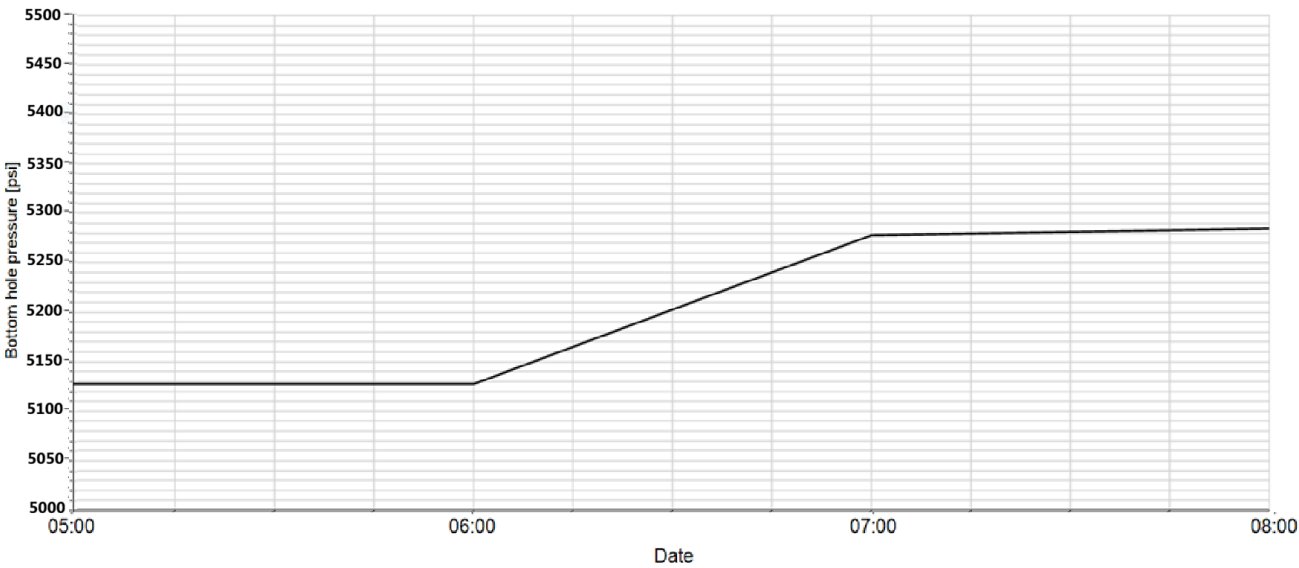


Figure 6: Buildup pressure curve for the homogeneous reservoir well located at the flank

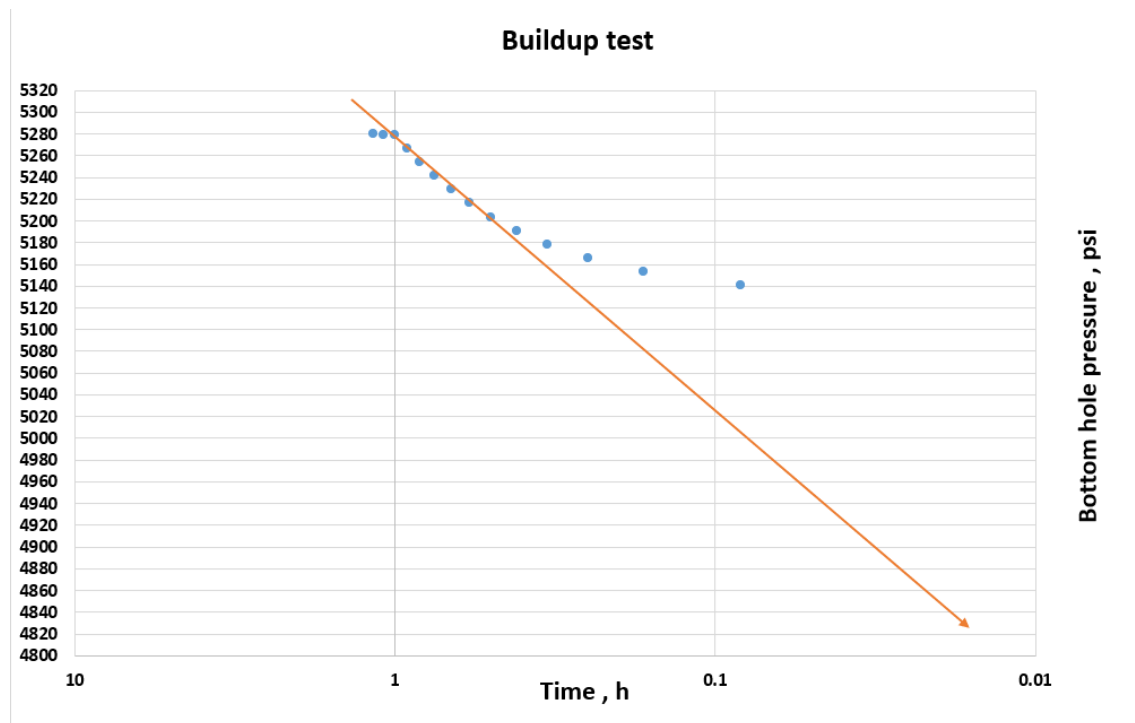


Figure 7: Semi-log graph of the buildup pressure test for the homogeneous reservoir well located at the flank

3.3 Case 3: Alternating permeability

Figure 8 illustrates the bottom hole pressure versus time for the buildup test of the alternating permeability case. It is observed that the pressure increased very rapidly from 5094.6 to 5245.7 psi within 1 hour.

From Figure 9, the slope is equal to 250 psi/cycle. The average reservoir permeability from the weighted method is 477.77 md, and the average reservoir permeability based on the Horner method is 475.76 md.

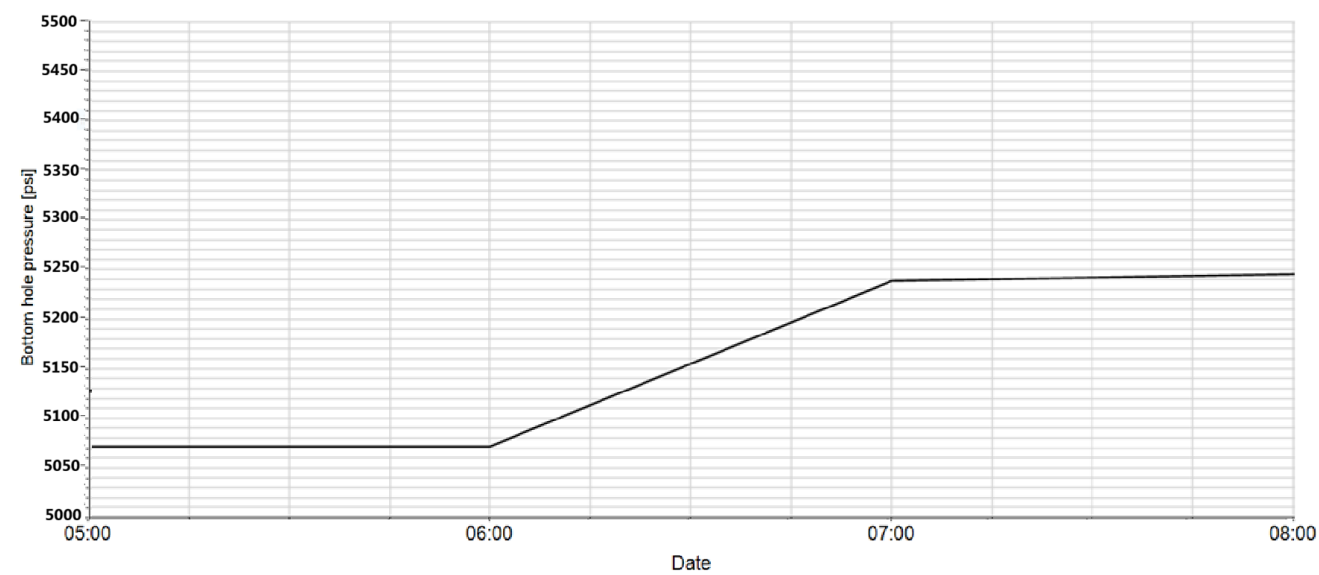


Figure 8 : Buildup pressure test for alternating change in permeability

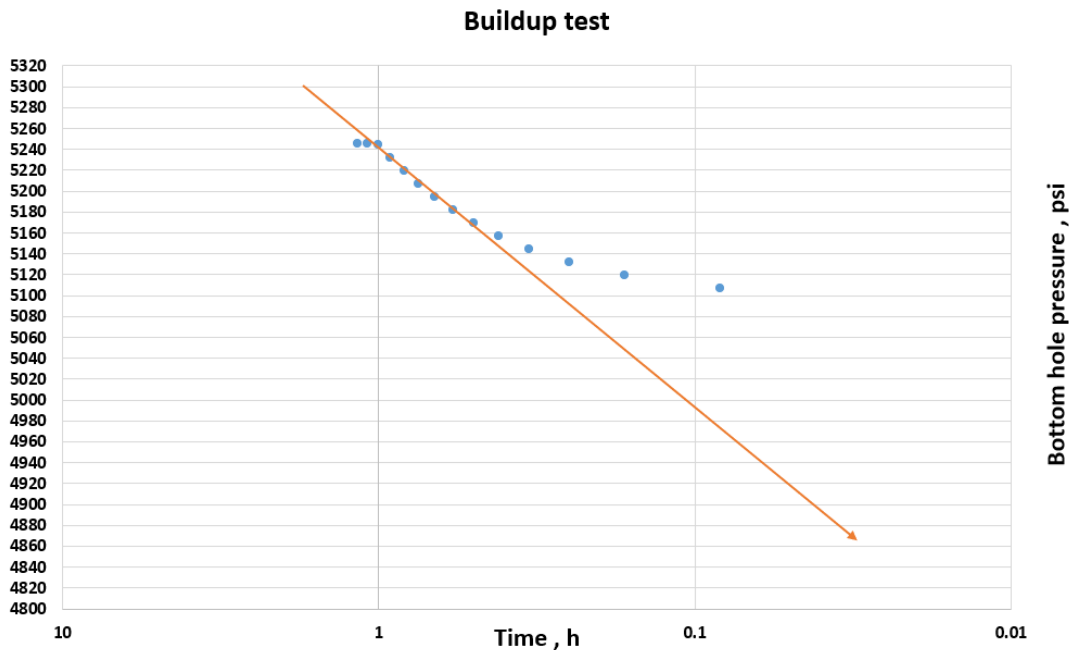


Figure 9: Semi-log graph of the buildup pressure for alternating change in permeability

3.4 Case 4: Permeability decreasing with depth

Figure 10 shows the bottom hole pressure versus time for the buildup test of the case in which permeability decreases with depth. It is observed that the pressure increased very rapidly from 5109 to 5251.7 psi within 1 hour.

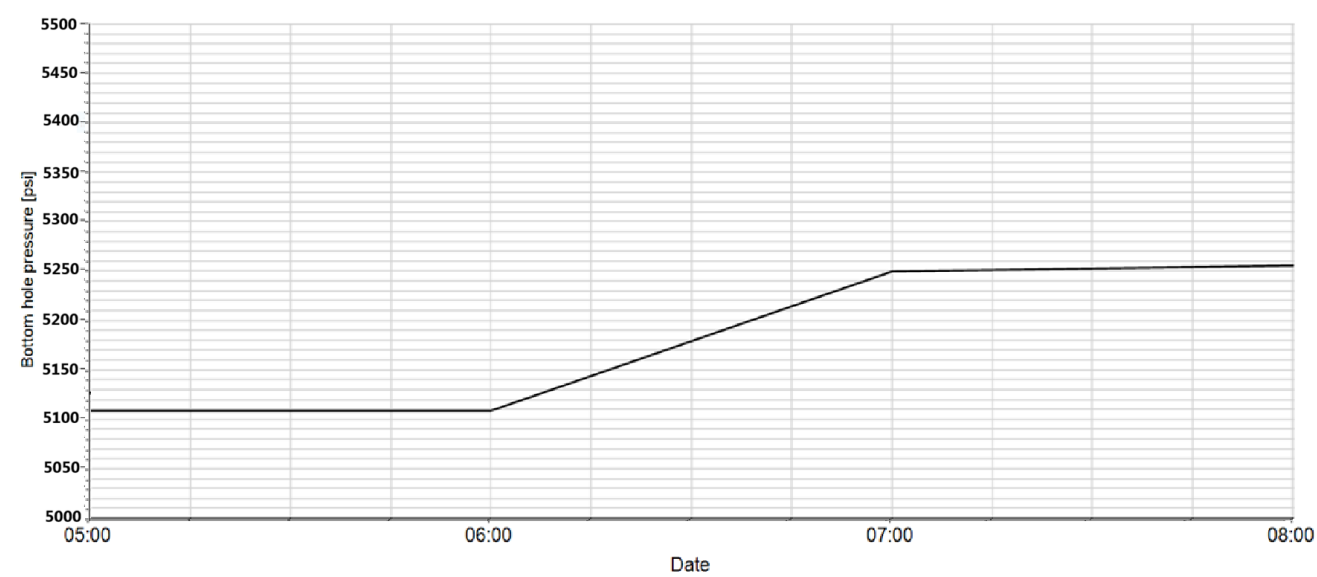


Figure 10: Buildup pressure curve of the case where the permeability decreases with
Buildup test

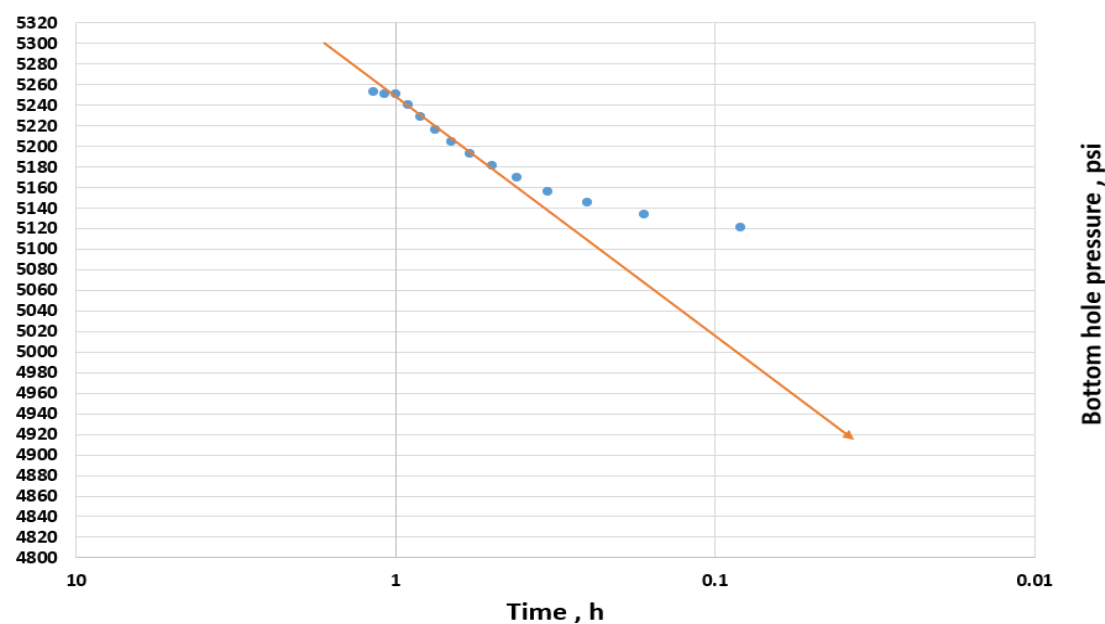


Figure 11: Semi-log graph of the buildup pressure test for alternating change in
permeability

From Figure 11, the slope is equal to 240 psi/cycle. The average reservoir permeability from the weighted method is 500 md, and the average reservoir permeability based on the Horner method is 495.59 md.

3.5 Case 5: Permeability increasing with depth

Figure 12 illustrates the bottom hole pressure versus time for the buildup test of the case in which permeability increases with depth. It is observed that the pressure increased very rapidly from 5072 to 5240 psi within 1 hour.

From Figure 13, the slope is equal to 260 psi/cycle. The average reservoir permeability from the weighted method is 500 md, and the average reservoir permeability based on the Horner method is 457.46 md.

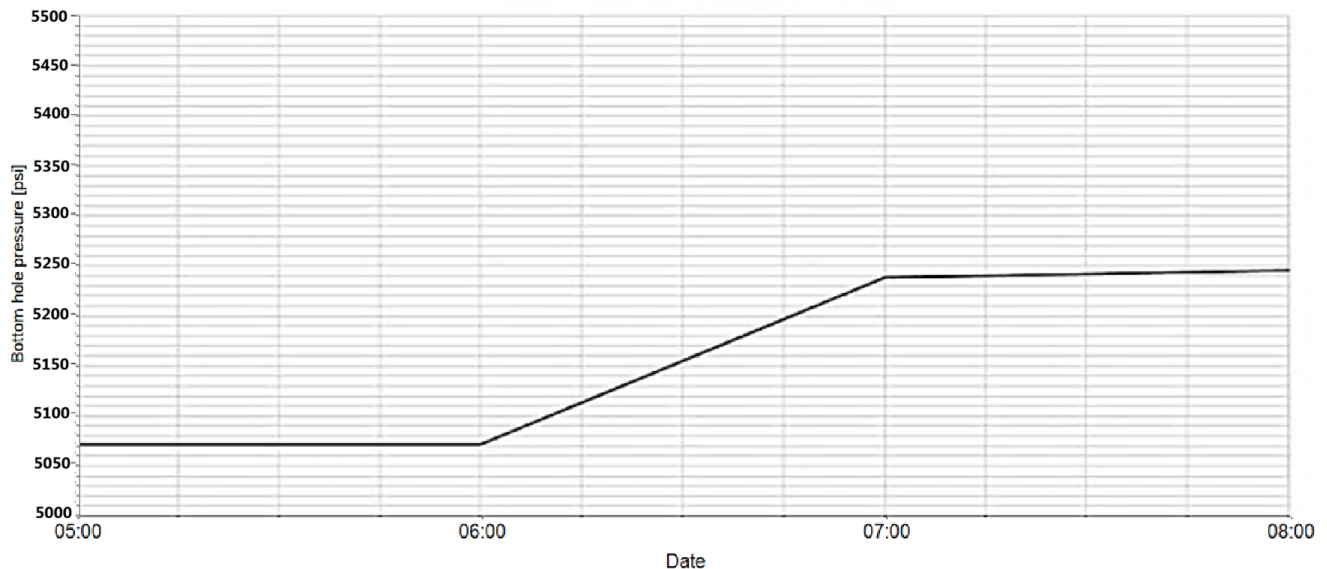


Figure 12 :Buildup pressure curve of the case where the permeability increases with depth

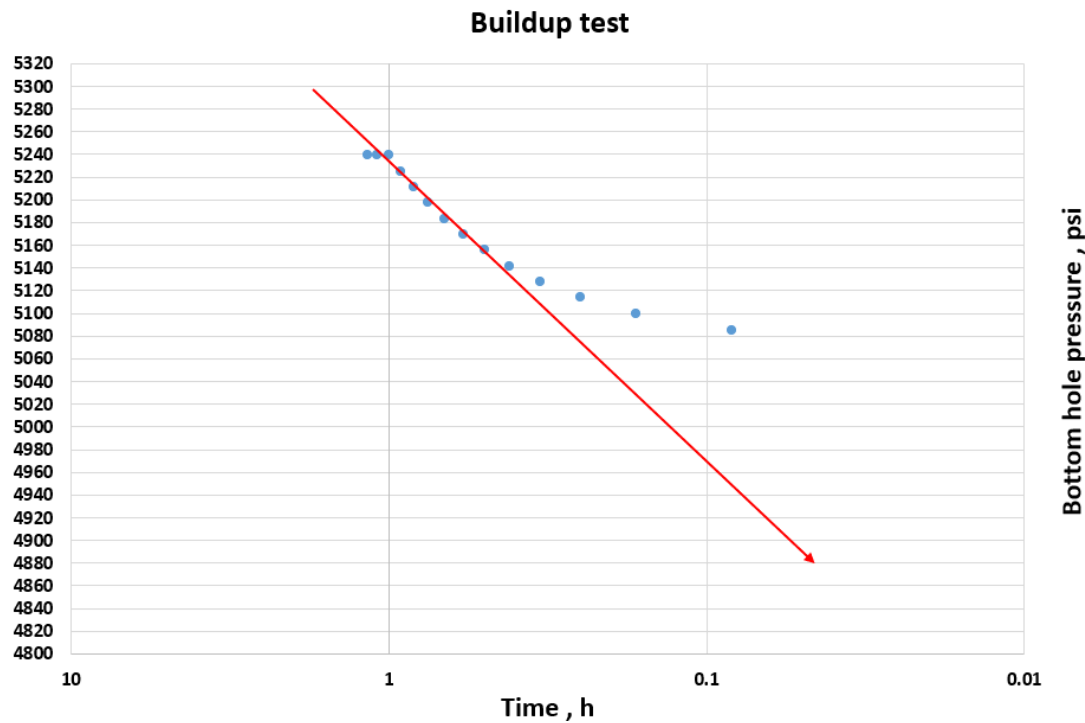


Figure 13: Semi-log graph of the buildup pressure test for the case of permeability increasing with depth

The results for the effect of wellbore storage and the middle region time are summarized in Table 5 and Figures 14 and 15.

Table 5 : Effect of wellbore storage and the middle region time for the five cases

Case No.	End time of wellbore storage effect (hour)	Start of the middle region time (hour)	End of the middle region time (hour)
1	0.65	0.65	1
2	0.70	0.70	1
3	0.70	0.70	1
4	0.75	0.75	1
5	0.75	0.75	1

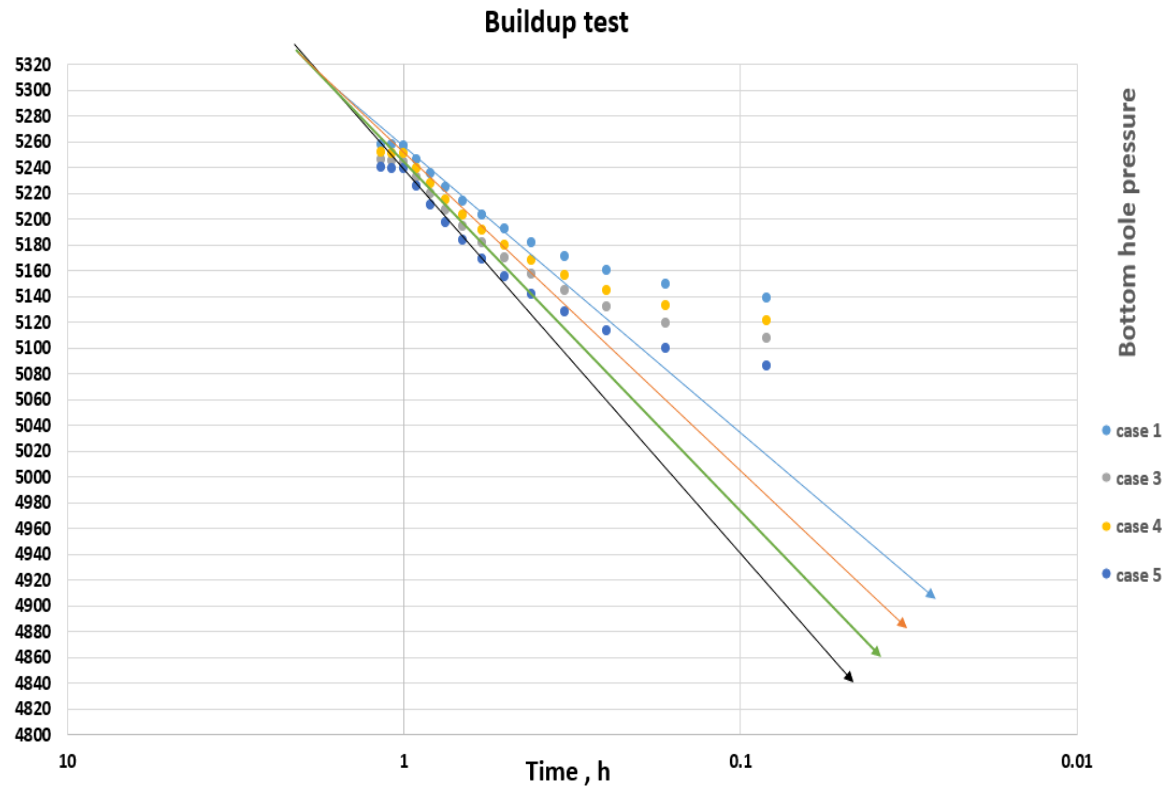


Figure 14: Semi-log graph of the buildup pressure test of the heterogeneity for the four cases

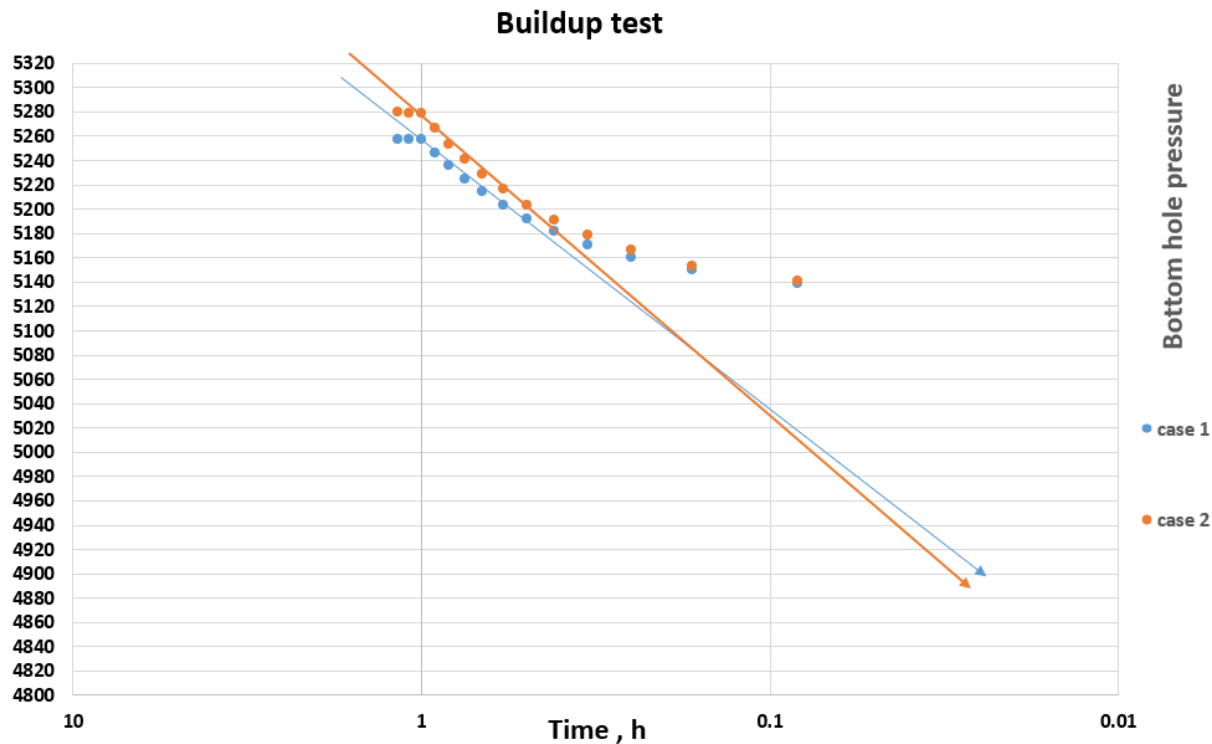


Figure 15: Semi-log graph of the buildup pressure test according to the location of the well for two cases

The results show that case 1 (homogeneous reservoir, well located at the crest) takes less time than the other cases to reach the middle region time and to end the wellbore storage effect, whereas case 4 (permeability decreasing with depth) and case 5 (permeability increasing with depth) require more time than the other cases to reach the middle region time and to end the wellbore storage effect.

Interbedded high- and low-permeability layers create a complex flow pattern with vertical crossflow (or lack thereof) and channeling. Alternating strata create heterogeneity-induced skin. Flow lines must converge, diverge, and thread through low-k "baffles" to access high-permeability bars. This creates a higher pressure drop than that in a homogeneous reservoir with the same average horizontal permeability. The effective radial flow is disturbed, resulting in a steeper semi-log slope. Regarding the shorter buildup period, the high-k layers provide pathways, increasing overall effective diffusivity. Pressure disturbances along these layers move quickly to the boundaries or to the wellbore. Meanwhile, the low-k bars act as local storage that slowly bleeds into the high-k layers. The pressure buildup test is dominated by the high-k layers, resulting in faster stabilization of the wellbore pressure. The test therefore detects a "pseudo" average pressure sooner.

The slope may increase, corresponding to a known fault or a known fining-upward sequence. This will be essential to match and certain for the real geological models.

4. Limitations and Uncertainties

The results of the current study should be applied to a specific reservoir, considering the complexity of reservoir geology, the effect of faults on flow and pressure, and the reservoir fractures. To fully understand the reservoir performance, a field history dominated by high-permeability layers, historical commingled production and injection, and the current development of reservoir intervals with uncertain or sparse production history should be considered. The saturated pressure (P_{sat}) versus depth trends for reservoir intervals can also be beneficial to reduce gas breakout at the reservoir boundaries when the bottom hole pressure (BHP) limit is estimated. Further limitations include sparse core and well test data, as usable core data are limited and only a few wells have potentially useful well tests.

5. Conclusion

The objective of this simulation study was to investigate the effects of heterogeneity and well location on the buildup test for oil reservoirs. The conclusions can be summarized as follows:

1. Locating the well at the flank of the reservoir increases the slope of the straight line and affects the pressure buildup period.

2. In the case of permeability increasing with depth, the slope of the straight line increases compared with that of a homogeneous reservoir well located at the crest, and the pressure buildup period decreases.
3. In the case of permeability decreasing with depth, the slope of the straight line increases compared with that of a homogeneous reservoir well located at the crest, and the pressure buildup period decreases.
4. In the case of alternating permeability, an increase in the slope of the straight line is observed compared with that of a homogeneous reservoir well located at the crest, together with a decrease in the pressure buildup period.

6. Recommendations for Future work

Future work should focus on a specific type of transient test (e.g., drill-stem test or pressure buildup test) or compare the results from multiple tests. The results of this study should also be implemented and tested on a real reservoir transient test.

Declaration of generative AI and AI-assisted technologies in the writing process

None

Disclosures

The authors have no conflicts of interest to declare in relation to this manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

μ	Viscosity
B	Formation volume factor
bbl	Barrel
BHP	Bottom Hole Pressure
h	Formation (pay-zone) thickness
K	Permeability
m	Slope
MBE	Material Balance Equation
MBH	Matthews-Brons-Hazebroek
md	millidarcy
Psat	Saturated pressure
Pwf	Downhole flowing pressure
q	Flow rate
TWT	Transient well testing

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اختبار الضغط العابر لمكامن النفط المتجانسة وغير المتجانسة: دراسة بيانات مفترضة باستخدام المحاكاة

الخلاصة: يُجرى اختبار تدفق السوائل على آبار النفط أو الغاز لفحص تغير معدل تدفق البئر واستجابة الضغط مع الزمن. تهدف هذه الدراسة إلى بحث تأثير عدم تجانس المكمن على اختبار البئر، وتأثير موقع البئر على اختبار البئر. في هذه الدراسة، تم بناء نموذج للمكمن، ثم خضعت خصائص السائل والمكمن لعملية اختبار البئر (اختبار تراكم الضغط). تشير النتائج إلى أن الضغط أثناء اختبار البئر يزداد مع ازدياد مدة الاختبار حتى يصل إلى ضغط المكمن. يؤثر موقع البئر على ميل الخط المستقيم. لوحظ ازدياد في ميل الخط المستقيم عندما يقع البئر على جانب المكمن، وكذلك تأثيره على فترة تراكم الضغط. في حالة ازدياد النفاذية مع العمق، يزداد ميل الخط المستقيم مقارنةً ببئر مكمن متجانس يقع على قمة المكمن، بينما إذا انخفضت النفاذية مع العمق، يزداد الميل، وتقل فترة تراكم الضغط. وقد تم توضيح هذا السلوك في حالة النفاذية المتناوبة.

الكلمات المفتاحية: اختبار البئر؛ الضغط العابر؛ موقع البئر؛ عدم التجانس؛ حساب النفاذية.