Effect of Natural Fractures on the Pressure Transient Behavior of Multilayered Reservoirs

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

Petroleum Engineering

December 2012

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Mr. Rami Ahmed Al-Abdulmohsin** under the direction of his thesis advisor and approval by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN PETROLEUM ENGINEERING**.

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ACKNOWLEDGEMENT

I would like to express my gratitude to Dr. Hasan S. Al-Hashim for his continuous guidance, advice and encouragement throughout the course of the study. Also, I would like to thank Dr. Hasan Y. Al-Yousef and Dr. Mohammed B. Issaka for their valuable support and advice. All models used in this study were built in Ecrin well testing software.

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ABSTRACT

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TITLE: EFFECT OF NATURAL FRACTURES ON THE PRESSURE TRANSIENT BEHAVIOR OF MULTILAYERED RESERVOIRS

MAJOR FILED: PETROLEUM ENGINEERING

DATE OF DEGREE: DECEMBER 2012

Analysis of well test data from multilayered reservoirs can be quite complicated, especially when one considers the possibility of cross flow between the layers. Moreover, when one or more of the layers are naturally fractured, another degree of complexity is added. The permeability of the different layers, as well as the properties of the natural fractures can result in pressure and pressure derivative behavior that is quite different from the behavior of a single layer reservoir. Natural fracture parameters such as the storativity ratio, (ω), and the interporosity flow parameter, (λ), may have a significant effect on the pressure buildup behavior, especially when both layers are fractured.

In this study, a numerical approach is used to investigate the effect of permeability variation, as well as the storativity ratio and the interporosity flow parameter, on the pressure transient behavior of two-layered reservoirs, where one layer is homogeneous, while the other layer is naturally-fractured. Alternatively, both layers could be naturally-fractured with different fracture density.

Results from this study show that the variation of the fractured layer parameters, λ and ω, revealed different pressure behavior responses, and in some cases, the response is seen only when the well is shut-in for a very long period. Short shut-in tests of the well may lead to the wrong estimates of the parameters for each layer, which may affect the understanding of the whole system.

خلاصة الرسالة

اسم الطالب :رامي أحمد علي العبدالمحسن

عنوان الرسالة : تأثير التكسرات الطبيعية على استجابة الضغط في الماكامن متعددة الطبقات

التخصص : هندسة البترول

تاريخ الدرجة : صفر 1434هـ

يمكن ان يكون تحليل إختبار الآبار معقداً جداً وخصوصاً عند إمكانية تدفق النفط بين الطبقات. وعلاوة على ذلك، يتم إضافة درجة آخرى من التعقيد عندما تكون طبقة من الطبقات أو أكثر من الطبقات تعاني من التكسرات بشكل طبيعي. نفاذية الطبقات المختلفة، فضلا عن خصائص الكسور الطبيعية، يمكن أن تؤدي إلى تغير الضغط و مشتقة الضغط التي هي مختلفة تماما عن سلوك المكمن المكون من طبقة واحدة. خصائص الطبقات التي تعاني من التكسرات بشكل طبيعي مثل خاصية نسبة تخزين النفط في التكسرات (ω) وخاصية تبادل النفط بين التكسرات وبين الطبقة ذاتها (λ) قد يكون لها تأثير كبير على بناء الضغط، وخصوصاً عندما يكون هناك أكثر من طبقة بها إنكسارات طبيعية.

في هذه الدراسة، تم استخدام نهج العددية لدراسة تأثير اختلاف نفاذية الطبقة، وكذلك نسبة تخزين النفط في التكسرات وخاصية تبادل النفط بين التكسرات وبين الطبقة ذاتها ، على سلوك الضغط في المكامن المكونة من طبقتين، حيث تكون واحدة من الطبقات متجانسة، في حين أن الطبقة الأخرى فيها إنكسارات طبيعية. بدلا من ذلك، كل من هذه الطبقات ممكن ان تكون متكسرة بشكل طبيعي مع كثافة تكسرات مختلفة.

النتائج من هذه الدراسة تظهر أن التغير في خصائص التكسرات، λ وω، أظهرت إستجابات مختلفة في سلوك الضغط، وفي بعض الحالات، تتم ملاحظة الاستجابة فقط عندما يتم إغلاق البئر لفترة طويلة جداً. الإختبارات القصيرة المدة قد تؤدي إلى تقديرات خاطئة لخصائص كل طبقة، والتي قد تؤثر على فهم النظام برمته.

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CHAPTER 1

INTRODUCTION

Numerous studies have investigated the pressure transient behavior of a single layer homogeneous reservoir, a single layer fractured reservoir, and multilayered reservoirs. For multilayered reservoirs, the previous studies have considered models with, or without, crossflow between the layers. Those studies did not combined homogeneous layers along with fractured layers and did not investigate the effect of the homogeneous layer permeability variation on the total system behavior. Moreover, the previous studies did not study the effect of fractures density variation of the fractured layer on the total system response.

Permeability of each layer and fracture properties have a great effect on the pressure transient behavior. The interpretation of that behavior is used to describe the reservoir properties and well condition. The analysis can be done by utilizing the pressure versus time plot. Several methods are used to carry out these analyses, such as the straight line on portions of the data to get the slope, or type curve matching.

Prijambodo et al. [2] studied the performance of a well in a multilayered system with crossflow and concluded that the early time responses are identical for both cases of commingled systems with, and without, crossflow when the properties are the same. The interlayer flow affects the transition period at intermediate time. However, the late time response is similar to that of a single layer system.

Kuchuk et al. [3] presented generalized analytic formulation for pressure transient behavior of a commingled system without crossflow including hydraulic fractures and natural fractures. They discussed the effects of variation of flow rate and the wellbore storage effect. They concluded that their method can be applied to any multilayer system without crossflow with different number of layers, different reservoir properties, different initial pressure, and different initial flow rates. Also, their solutions have been derived both in the Laplace transform and real time domains.

Al-Ajmi et al. [6] presented a method to estimate and calculate the storativity ration (ω) of multi-layer reservoir with cross flow by utilizing the pressure transient data and its derivative. This method depends on the analytical derived formula for the storativity ratio in term of the separation between the two straight lines on the pressure derivative early time and late time. This is used to develop the correlation in their study to estimate the storativity ratio. As a result, an improved definition of interporosity flow coefficient was developed for a layered reservoir with a dual-permeability system.

Slimani et al. [8] presented the effect of partial penetration on the pressure and pressure derivatives. The study identified the characteristics of the different flow regimes in different completions and obtained the reservoir parameters such as vertical and horizontal permeability, fracture properties, and skin factor for both fractured and non-fractured reservoir. Moreover, the effect of the storage coefficient (ω) and the interporosity flow coefficient (λ) was presented. They concluded that the transition period of the fracture-matrix flow can happen in early time when the flow is not radial due to the partial penetration. Also, the position of the flow interval in a well and the value of penetration ratio can develop transitional spherical or hemispherical flow.

Al-Ghamdi et al. [17] presented new models to differentiate between the microfractures and the macrofractures in dual fracture (triple porosity) system (pseudosteady state model). Dual fracture system is a more realistic alternative to the dual porosity models. Also, the similarities and the differences between the support from the tight matrix and that of the more permeable microfractures were presented. The model showed that macrofracture system will respond first at the very early time of the pressure transient test. The response of the microfracture system can be observed and can be distinguished only if the ratio of the microfracture permeability to that of the macrofracture system is small ($\lambda_f \leq 0.001$). At early time of the pressure derivative plot, the presence of microfractures can form a transition zones which may be interpreted as matrix support by mistake.

The aim of this study is to investigate the pressure transient behavior of two-layer reservoirs, one of which is homogeneous, while the other is naturally-fractured. The effect of permeability variation of one layer (the homogeneous layer) on the pressure response and the derivative of the pressure is considered and analyzed. The effect will be analyzed for commingled systems with or without crossflow. Moreover, the study includes the effect of fracture density of the layers on the pressure transient analysis for a two-layer reservoir, where both layers are fractured (with and without crossflow). The fracture density of one of the layers will be varied in order to study its effect.

Four models are considered in this study. The first two models will have two layers, where one of them is homogeneous and the other one is naturally fractured (with and without crossflow). In the last two models, the model will have two naturally-fractured layers (with and without crossflow) and the effect of the fracture density (Omega, ω and Lambda, λ) variation on the pressure transient behavior will be investigated.

CHAPTER 2

LITERATURE REVIEW

As stated earlier, homogeneous layer permeability has a great effect on the total multi-layers system behavior. Also, the fracture density affects the response of the total multi-layers system response. This section reviews the concept of multilayer systems and the latest work done in the following areas:

1) Multi-layers pressure behavior with and without crossflow.
2) Method to estimate and calculate the storativity ration (ω) of multi-layer reservoir.
3) The effect of partial penetration on the pressure and pressure derivatives.
4) Models to differentiate between the microfractures and the macrofractures in dual fracture system.
5) Dual porosity system behavior.

Robert C. Earlougher, K. M. Kersch, and W. J. Kunzman(1974) [1]used simulated data to present the behavior of pressure buildup in a multilayered reservoir without communication. The pressure buildup behavior is compared to that of a single layer reservoir. It was found that based on layer properties, the pressure response may look like one for the single layer. Also, it was found that the shape of the pressure drawdown curve for a multilayered system is indistinguishable from that for a single layer, if the skin factor is the same in both layers. Moreover, the time to reach pseudosteady state depends on the layers properties and the number of layers.

R. Prijambodo, R. Raghavan, and A. C. Reynolds (1985) [2] presented the performance of a well in a multilayer system with crossflow. The mathematical model used is a two-layer cylindrical reservoir, which is enclosed at the top and bottom, with both layers being homogeneous. The outer boundaries are impermeable. They concluded that the early time responses are identical for both cases of commingled systems with, and without, crossflow when the properties are the same. The interlayer flow affects the transition period at intermediate time. However, the late time response is similar to that of a single layer system.

Fikri J. Kuchuk and David J. Wilkinson(1991) [3] presented generalized analytic formulation for pressure transient behavior of a commingled system without crossflow including hydraulic fractures and natural fractures. Effects of variation of flow rate (surface and downhole) were discussed. Wellbore storage effect is discussed too. Their method can be applied to any multilayer system without crossflow with different number of layers, different reservoir properties, different initial pressure, and different initial flow rates. Their solutions have been derived both in the Laplace transform and real time domains.

Christine A. Ehllg (1993) [4] presented a new form of multilayer transient (MLT) test measurements that is analogous to the log-log plot used for model diagnosis of conventional transient test. Different ways of test were presented including a field example of 2-layer water injection well in a naturally fracture reservoir. The paper concluded that the reciprocal pressure-normalized rate (RPNR) and its derivative can be considered equal to the log pressure and its derivative which is used for a single-layer test.

John P. Spivey, Ahmed M. Aly, and W. john lee (1998) [5] showed the pressure behavior of layered system with crossflow. Also, they showed the pressure behavior of the commingled system without crossflow. Their study analyzed the pressure behavior of the commingled system with and without crossflow and described why that behavior is observed during each period of the production. As a result of the study, multi-layered system with crossflow behaves similar to a naturally fractured reservoir. At early time, the behavior is the same as that of homogeneous layer where kh corresponds to the high permeable layer only. When crossflow started, both layers contribute to the production and kh reflects the total kh of both layers. Moreover, it is not possible to estimate permeability and skin factor for individual layers from only total flow rate and wellbore pressure. Rates of individual layers must be captured in order to estimate individual layers' properties.

N. M. Al-Ajmi, H. Kazemi, and E. Ozkan (2003) [6] presented a method to estimate and calculate the storativity ration (ω) of multi-layer reservoir with cross flow by utilizing the pressure transient data and its derivative. This method depends on the analytical derived formula for the storativity ratio in term of the separation between the two straight lines on the pressure derivative early time and late time. This is used to develop the correlation in this study to estimate the storativity ratio. Also, examples are presented to show the calculation of the individual layer properties. As a result, an improved definition of interporosity flow coefficient was developed for a layered reservoir with a dual-permeability system.

F. Medeiros Jr., E. Ozkan, and H. Kazemi(2006) [7] presented a semi-analytical model for the pressure transient analysis of horizontal well in composite, layered, and compartmentalized reservoirs. They applied their solutions to horizontal well in compartmentalized reservoir, high permeability streak along the horizontal well path, and horizontal well in locally fractured reservoir. This led to obtaining a new method for pressure transient solutions for heterogeneous systems where different characteristics are observed in different sections of the reservoir.

K. Slimani, D. Tiab, and K. Moncada(2006) [8] presented the effect of partial penetration on the pressure and pressure derivatives. The study identified the characteristics of the different flow regimes in different completions and obtained the reservoir parameters such as vertical and horizontal permeability, fracture properties, and skin factor for both fractured and non-fractured reservoir. Moreover, the effect of the storage coefficient (ω) and the interporosity flow coefficient (λ) was presented. It was found that the transition period of the fracture-matrix flow can happen in early time when the flow is not radial due to the partial penetration. Also, the position of the flow interval in a well and the value of penetration ratio can develop transitional spherical or hemispherical flow.

B. Ramirez, H. Kazemi, and E. Ozkan (2007) [9] studied the retrograde condensation behavior in natural fractures and in the near wellbore region of a naturally fractured reservoir. They include the combined effect of non-Darcy flow in presence of retrograde condensation and wellbore damage on pressure transient analysis of naturally fractured reservoir. A single well compositional model was constructed to evaluate early-time and late-time characteristics of the pressure transient data. The solution is presented for one layer reservoir. It was concluded that the skin damage is increased due to fluid condensation and condensate accumulate inside the fractures.

Arash Soleimani, Byung Lee, and Yahya Ghuwaidi(2009) [10] investigated the modeling and interpretation of pressure transient responses of multiple hydraulic fractured horizontal wells using a numerical reservoir model. Pressure transient response signatures are produced.

The effects of the following parameters are discussed: number of fractures along the horizontal well, fracture conductivity ($k_f w$), half length of the fracture, and the effect of fracture spacing. Case study was provided. The model showed that increasing the number of fractures along the well resulted in increasing productivity. Also, increasing the fractures conductivity resulted in decreasing the duration of the early time radial flow regime. But, lowering the fractures conductivity delays the fracture interference and makes the radial flow last longer.

J. E. Warren and P. J. Root (1963) [12] developed a model to study the behavior of dual porosity system where part of the medium is contributing significantly to the pore volume and the other part is contributing negligibly to the flow capacity (primary and secondary porosity). In this model, the unsteady state flow is described mathematically. From this study, a technique was suggested to analyze the buildup data in order to evaluate the model parameters. They concluded that dual porosity medium deviates in behavior from the homogeneous medium by two additional parameters which are Omega (ω) and Lambda (λ).

H. L. Najurieta (1980) [13] developed a technique to calculate the unsteady state behavior in the fractures of the homogeneously fractured reservoirs. It is used for analysis of the pressure buildup and drawdown for block-shaped fractured reservoirs. In the model, the reservoir is made up of two porous media which are the matrix and the fractures and both of them are homogeneous and isotropic. Also, it assumes that the fluid is slightly compressible and the flow toward the wellbore is from the fractures only. As a result, four parameters can describe the pressure behavior in the system which are the fracture transmissivity, fracture storage, matrix storage, and a parameter that gives information about the size and the diffusivity of the matrix blocks.

G. E. Crawford, A. R. Hagedorn, A. E. Pierce (1976) [14] combined previously published model (Warren and Root) with a nonlinear, least-squares regression techniques to analyze the pressure buildup behavior of naturally fractured reservoirs. The model is used to determine the effective formation permeability and to describe the buildup response. From the analysis of the study cases, it was found that the presence of the natural fractures causes multi-slope behavior of the pressure buildup curves. Also, Warren and Root model for naturally fractured reservoir was found to be useful in obtaining the initial formation pressure and the effective formation permeability.

De Swaan (1976) [15] developed an unsteady state theory that describes the well pressure response in naturally fractured reservoirs especially for reservoirs of high permeable fractures and tight matrix blocks. The model showed a good agreement between the computed results of the theoretical curves with the numerical model. It was concluded that the fractures' kh and the average of the matrix porosity can be evaluated using the two straight-line well pressure plot .

A. C. Gringarten (1984) [16] summarized the current knowledge of dual porosity reservoir (naturally fractured reservoir) behavior along with multilayered reservoir with high permeability contrast between layers. Available solutions such as the solution to the diffusivity equation for double-porosity reservoirs are presented. Also, methods for solving the inverse problem (dual porosity behavior and evaluating reservoir parameters) are discussed. They concluded that naturally fractured reservoir and multilayered reservoir with high permeable contrast between layers have the same dual porosity behavior. Also, using dual porosity type curve can provide the reservoir properties. Moreover, fractured reservoir can be distinguished from multilayered reservoir only if the well is not damaged or acidized.

A. Al-Ghamdi and I. Ershaghi (1996) [17] presented new models to differentiate between the microfractures and the macrofractures in dual fracture (triple porosity) system (pseudosteady state model). Dual fracture system is a more realistic alternative to the dual porosity models. Also, the similarities and the differences between the support from the tight matrix and that of the more permeable microfractures were presented. The model showed that macrofracture system will respond first at the very early time of the pressure transient test. The response of the microfracture system can be observed and can be distinguished only if the ratio of the microfracture permeability to that of the macrofracture system is small ($\lambda_f \leq 0.001$). At early time of the pressure derivative plot, the presence of microfractures can form a transition zones which may be interpreted as matrix support by mistake.

R. Aguilera (2000) [18] studied and compared the geometric mean fracture permeability with the permeability from well testing data in naturally fractured layered reservoir. 10-layered reservoir (with crossflow between layers) with increasing, decreasing, and random fracture permeability was used in this study. It was found that the fractured permeability calculated from the test is larger than the geometric mean permeability from all layers. Also, they can be larger than the arithmetic average permeability from all layers.

C. O. Bennett, R. G. Camacho, A. C. Reynolds, and R. Raghavan: (1985) [19] derived new analytical solutions for the response of a hydraulically fractured well in a multilayered reservoir. The model assumes that the well is producing at a constant flow rate or constant pressure without communication between layers. The well is located at the center of the reservoir and the center of the fracture. Also, the top, bottom, and outer boundaries of the reservoir are assumed to be impermeable. Each layer has different properties than the other one.

D. Bourdet (1985) [20] presented a new analytical solution which describes the pressure response of layered reservoir with crossflow with alternating beds of relatively high permeability contrast. The presented solution is general and it includes homogeneous reservoir solution, two layers without crossflow solution, and the dual porosity pseudosteady state interporosity flow solution as limiting forms. It was concluded that the dual permeability response shows three characteristic flow regimes. At early time, it shows two layers without crossflow behavior. Then, a transition period occurs. After that, a homogenous behavior is observed which is representing the total system behavior.

K. Serra, A. C. Reynolds, and R. Raghavan (1983) [21] presented new methods for analyzing pressure drawdown and buildup data for a well producing from naturally fractured reservoir. The model assumes unsteady-state fluid transfer from the matrix to the fracture system and infinite acting reservoir. They concluded that the pressure response in naturally fractured reservoir may follow three distinct semi-log flow regimes. The first and the third regimes correspond to the familiar early and late time semi-log straight lines. The second flow regime at intermediate time is characterized by the existence of a semi-log straight line that has a slope of approximately one-half that of the straight lines in the first and third regimes.

H. A. Al-Ahmadi and R. A. Wattenbarger (2011) [22] presented a triple porosity model where fractures are considered to have different properties. In the presented triple porosity model, it consists of three porous media which are a matrix, microfractures (less permeable), and macrofractures (more permeable). The model assumed that the flow is flowing in the direction of the increased permeability and only macrofractures provide the flow. It is proven that the solutions can be utilized for radial flow geometry and also can be used for gas flow using the real gas pseudo-pressure and normalized time.

T. W. Engler (1996) [23] proposed a new method (direct synthesis) to interpret pressure tests in naturally fractured reservoir. The method is presented for single-well pressure tests in an infinite acting naturally fractured reservoir with pseudosteady state interporosity flow. Also, the method includes the effects of wellbore storage and skin. This method utilizes the slopes of different straight lines from the log-log plot of the pressure and the pressure derivative and links them with analytical solution in order to estimate reservoir parameters. He concluded that the direct synthesis method is applicable for buildup and drawdown tests and it can be used without type curve matching since type curve matching is a trial and error method. Moreover, he identified different points and lines from the pressure derivative curve and coupled them linked them with the analytical solution to produce accurate results of ω and λ.

K. Slimani and D. Tiab (2005) [24] proposed a method to obtain various reservoir properties such as vertical and horizontal permeability, skin factors, and fracture properties by identifying the unique characteristics of the different flow regimes in partially and complete penetration vertical wells in naturally fractured reservoirs. They concluded that the transition period of fracture-matrix flow can occur in early time in partially penetrated wells when the flow is not radial in the reservoir. Also, they concluded that the transitional spherical or hemispherical flow depends on the position of the producing interval (top, bottom, or center). In addition, they proposed three empirical equations of pseudo skin in homogeneous and naturally fractured reservoir as an alternative to the manual type curve matching.

CHAPTER 3

STATEMENT OF THE PROBLEM AND OBJECTIVE OF THE STUDY

The transient pressure behavior of a single-layered homogeneous reservoir is quite different from that of a single-layered naturally-fractured reservoir. Moreover, the complexity of the pressure response increases if the reservoir consists of multilayers. Parameters like permeability, storativity ratio, and the interporosity flow have a significant influence on the pressure response and its derivative. In addition, crossflow between layers can affect the pressure response. Different studies carried out before showed the response of a single homogeneous layer, a single fractured layer, and multilayered systems with, and without crossflow. However, no study has shown the transient pressure performance of combination of a fractured and a homogeneous layer. Also, no study before combined several naturally fractured layers and presented the impact of the fractures intensities on the transient pressure behavior.

The aim of this study is to investigate the effect of reservoir rock properties variation on well test interpretation for multilayer (2 layers) reservoirs with and without crossflow between the layers. Different cases were considered where the two layers are both naturally fractured, as well as cases where one layer is naturally fractured, while the other is homogeneous. The study will investigate the effect on the pressure transient analysis for systems with different values of permeability for the homogeneous layers. Moreover, the study will also investigate the effect of fracture density variation on two-layer reservoirs with crossflow and without crossflow.

3.1 Objective of the study

The general objectives of this work are:

1. To investigate the effect of permeability variation of the homogeneous layer on the transient pressure behavior of the naturally fractured layer, in the presence and absence of crossflow between layers.
2. To investigate the effect of fracture interporosity flow coefficient (λ) and storativity ratio (ω) variation of each layer on the pressure transient behavior of a two- layer fractured reservoir in the absence, and presence of the crossflow between the two fractured layers.

To accomplish these objectives, numerical models were used to:

1. Build two-layer models, where one of the layers is homogeneous and the other one is fractured. Cases with and without crossflow between layers are investigated.
2. Build two-layer models, where both layers are fractured. Cases with and without crossflow between layers are investigated.
3. Study the impact of different permeability values of the homogeneous layer in the first two models.
4. Compare the pressure buildup and the pressure derivative responses for each model for different permeability values.
5. Study the impact of the fracture density variation in the two-layer fractured system.
6. Compare the pressure buildup and the pressure derivative responses for each model after changing the fracture density of one of the fractured layers.

CHAPTER 4

WELL TESTING OF MULTI-LAYER RESERVOIR AND ONE-LAYER FRACTURED RESERVOIR

This section presents a brief review of transient pressure behavior of multi-layer (two-layer) reservoirs and one-layer fractured reservoir. Generally, the pressure derivative behavior of Multi-layer (dual-permeability) system looks like that of the one-layer fractured (dual-porosity) system [5].

4.1 Dual-Permeability system

When a well is producing from a two-layer reservoir, the first contribution will be from the high permeable layer. Then, the low permeable layer will start to contribute. As a result, the pressure derivative shows different flow periods corresponding to [2]:

1. High permeable layer response (Early time),
2. Transition period, and
3. Total system response (late time)

Figure 4.1 shows the expected behavior of a dual-permeability system. This system consists of two homogeneous layers with cross flow between them. Table 4.1 shows the properties of each layer and Table A.1 shows the fluid properties used to generate the results presented in Figure 4.1. One of the layers has low permeability and the other one has high permeability compared to the first one. Communication between the two layers is handled in Saphir software by using a leakage factor of 50%.

By inspecting Figure 4.1, it is clearly seen that the high permeability homogeneous layer start contributing first. This is represented by the first flattening of the pressure derivative. After some time, the second low permeability layer starts contributing. This is represented by the second dip [6]. Then, the total system response is observed which is represented by a flat line at the late time.

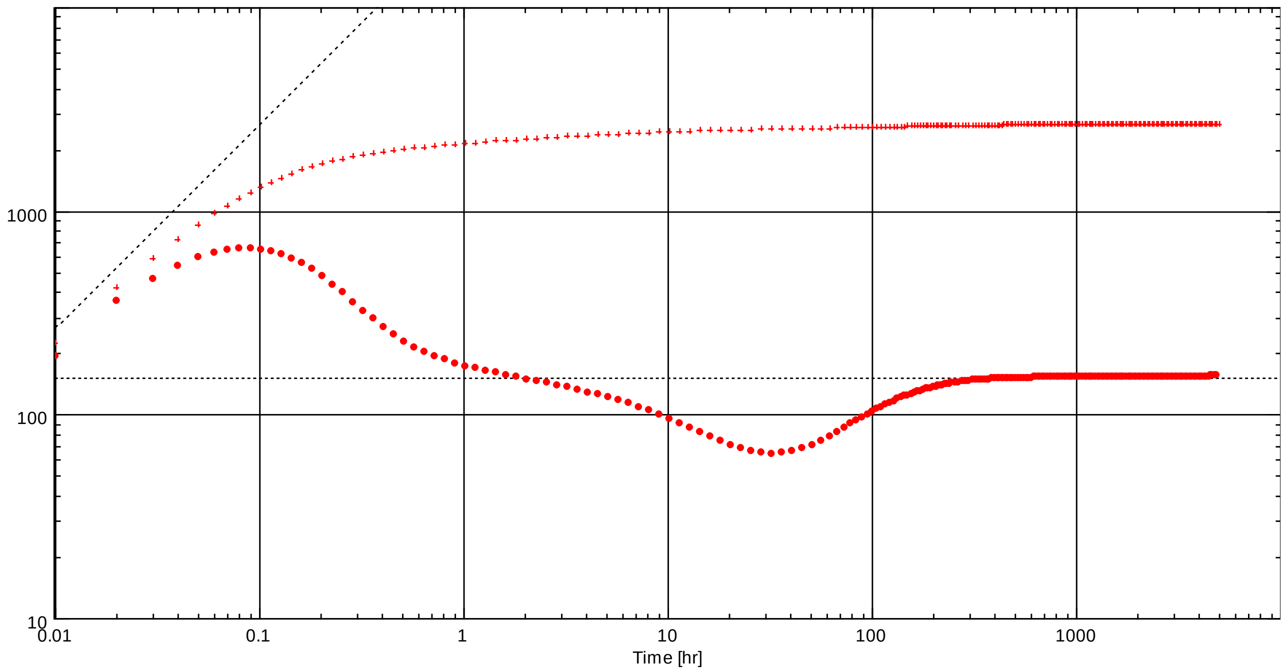

Figure 4.1: A typical dual-permeability transient pressure behavior

Table 4.1: Dual-permeability system properties

layer	Layer Type	Permeability (md)	Porosity (%)	Thickness ft
1	Homogeneous	1	10	100
2	Homogeneous	100	10	30

4.2 Dual-Porosity System (single fractured layer)

In dual-porosity systems, the first contribution will come from the fractures since they have high permeability. After that, the matrix will start to contribute to the production [1, 11]. The response of the matrix is highly dependent on the matrix permeability. Because of the permeability difference between the fractures and the matrix, the pressure derivative will show three periods corresponding to [2]:

1. Fracture response, a flat line in the pressure response. This flat line may be masked by wellbore storage,
2. Transition period. This is reflected by a dip in the pressure response due to the flow from the matrix into the fractures, and
3. Total system response. This is a flat line at late time reflecting the total system response.

Warren and Root [12] introduced two parameters that can be used to describe the dual-porosity reservoirs. The parameters are Omega (ω) and Lambda (λ) which are the main parameters of the fractured layer, in addition to the usual single-porosity parameters. Omega (ω) is storativity ratio (fracture storage)/(total system storage). In other words, it is the fraction of the fracture storage compared to the total system storage.

It is defined as [6]:

$$\omega = \frac{\varphi_f \, c_f}{\varphi_f \, c_f + \varphi_m \, c_m}$$

where:

φ_f is the porosity of the fractures.

c_f is the fracture compressibility, psi^{-1}

φ_m is the porosity of the matrix.

c_m is the matrix compressibility, psi^{-1}

Therefore, the more porosity available in the fractures, the more fracture storage.

Lambda (ƛ) is defined as the fluid exchange parameter between the matrix and the fracture.

It is defined as [6]:

$$ƛ = \alpha r_w^2 \frac{k_m}{k_f}$$

where the subscript "f" refers to the fractures, while "m" refers to the matrix.

r_w is the wellbore radius, ft

k_m is the matrix permeability, md

k_f is the fractures' permeability, md

From the definition, when the matrix has higher permeability, ƛ will be higher and the flow exchange between the matrix and the fractures is more.

Figure 4.2 shows the expected behavior of a dual-porosity system. Table 4.2 shows the properties of the dual-porosity system and Table A.1 shows the fluid properties. Table A.2 and Table A.3 show detailed parameters used to calculate ω and ƛ used to generate Figure 4.2. The fractures response is seen first which is represented by the flattening of the pressure derivative at early time. After that, the transition period occurred when the flow starts from the matrix into the fractures which is represented by a dip in the pressure derivative. Then, the entire system behavior is seen at late time and it is represented by a flat line. Analysis of the early time will provide the fractures properties and analysis of the late time straight line will provide the dual-porosity total system properties.

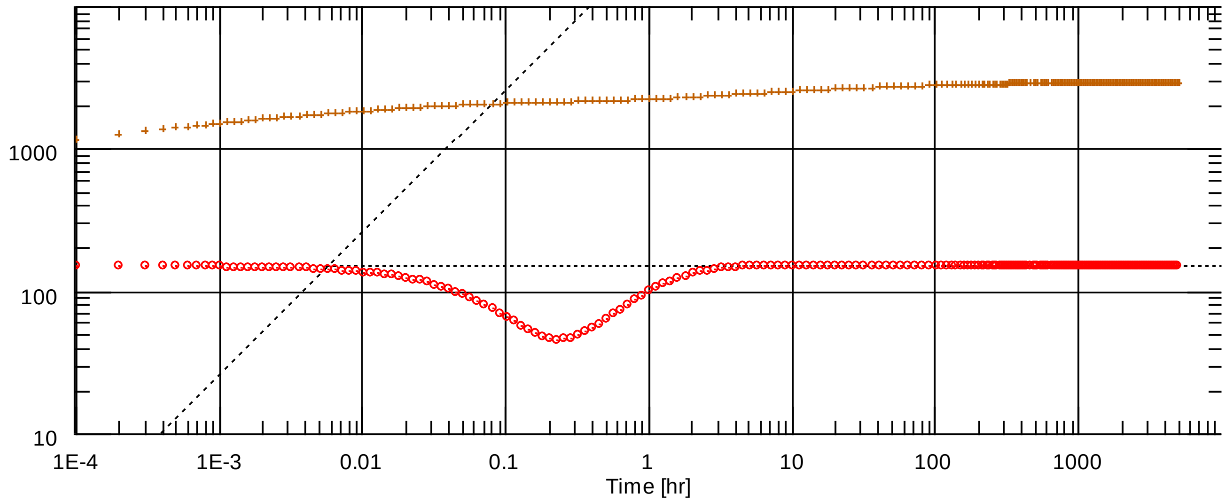

Figure 4.2: A typical dual-porosity transient pressure behavior

Table 4.2: Dual-porosity system properties

Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	λ
Fractured	100	10	100	0.1	$1X10^{-6}$

There are many models that have been developed to describe naturally fractured reservoir. However, the two common used models are the pseudosteady state model and the transient flow model.

The Pseudosteady state model assumes that at all points, the pressure in the matrix is decreasing at the same rate at any given time [11]. So, the difference between the matrix pressure and the adjacent fracture is what is controlling the flow from the matrix to the fractures.

Transient flow model assumes an increasing pressure drawdown that starts at the matrix/fracture interface. Then with time increasing, it moves farther into the matrix. The pseudosteady state is achieved only at late time if external boundary conditions necessitate.

CHAPTER 5

MODELS VALIDATION

5.1 Single fractured layer validation (Slimani et al. model [8])

The generated numerical models in Saphir well testing software were validated using the Slimani et al. model [8]. A model, similar to that used by Slimani et al., was generated using Saphir and the results were compared. It should be noted that the Slimani et al model included the following assumptions:

1. One layer system,
2. Infinite reservoir and constant thickness,
3. Matrix and fractures have uniform properties,
4. Matrix is isotropic,
5. Impermeable top and bottom boundaries,
6. Single phase,
7. No wellbore storage,
8. Well bottom area flow is negligible. No flow comes through the bottom area of the well, and
9. The reservoir is partially penetrated, with flow to the well occurring at the top.

Figure 5.1 shows the single layer model used by Slimani et al, while Figure 5.2 shows the effect of ω variation on the pressure derivative response [8]. The model is considered to be penetrated at the top. Table 5.1 and table 5.2 show the layer properties and the fluid properties used to generate the model response.

The generated model response in Figure 5.3 shows similar results and performance of the Slimani model. It can be seen clearly that with increasing value of ω, the derivative curve tends to be shallower at late time. In order to compare the results of Slimani et al model with the generated model, the pressure and time of the generated model were changed to dimensionless values and the comparison is presented in Figure 5.4.

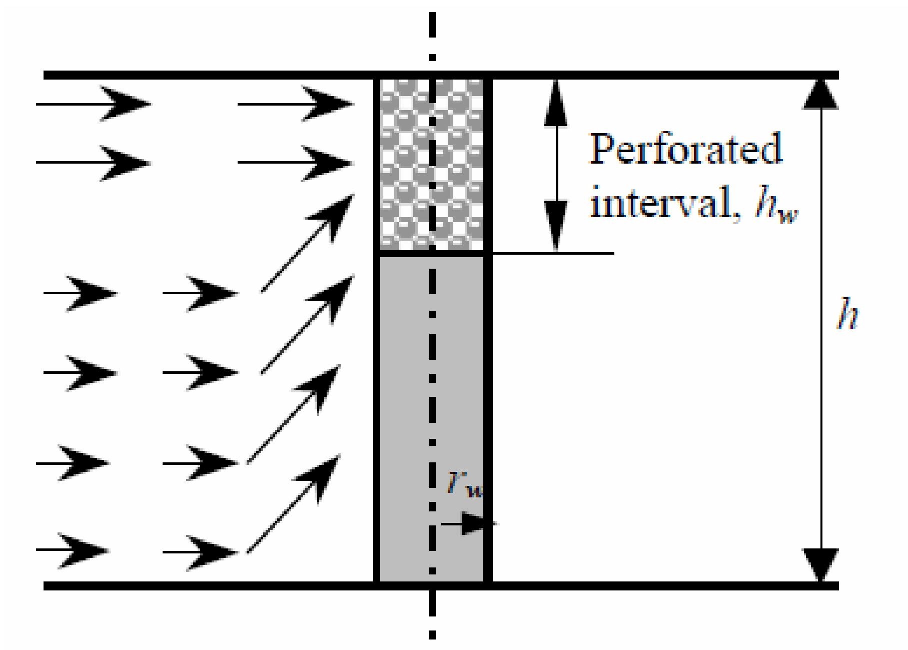

Figure 5.1: Slimani layer model [8]

Table 5.1: Layer properties of Slimani et. al. model [8]

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	ג
Case 1	Fractured	100	10	200	0.001	$1X10^{-8}$
Case 2	Fractured	100	10	200	0.005	$1X10^{-8}$
Case 3	Fractured	100	10	200	0.01	$1X10^{-8}$
Case 4	Fractured	100	10	200	0.05	$1X10^{-8}$
Case 5	Fractured	100	10	200	0.1	$1X10^{-8}$
Case 6	Fractured	100	10	200	0.5	$1X10^{-8}$

Table 5.2: Fluid properties

Property	Value
Oil compressibility c_o, psi^{-1}	$3X10^{-6}$
Oil viscosity μ, cp	1.2
Oil formation volume factor B_o, RB/STB	1.29
Total oil rate (bbl/d)	5000

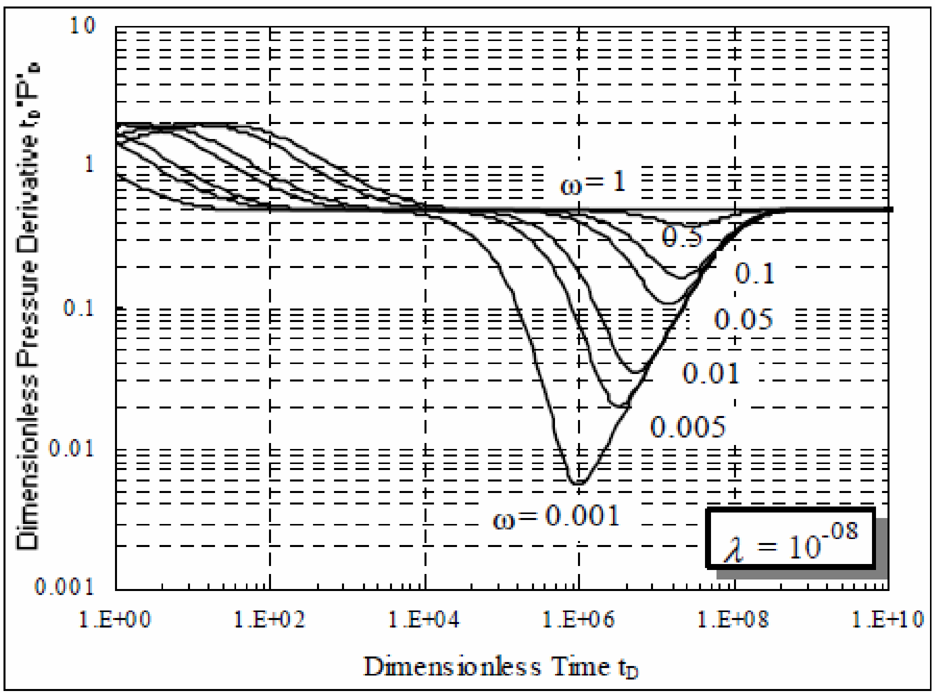

Figure 5.2: Effect of storativity ratio on the pressure derivative in Slimani model [8]

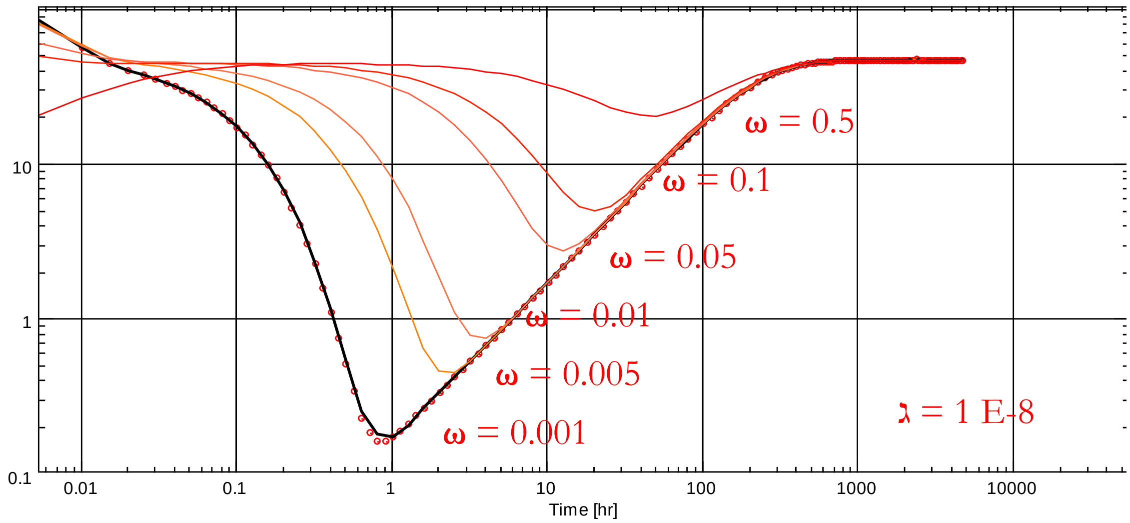

Figure 5.3: Effect of storativity ratio on the pressure derivative response in the validation model

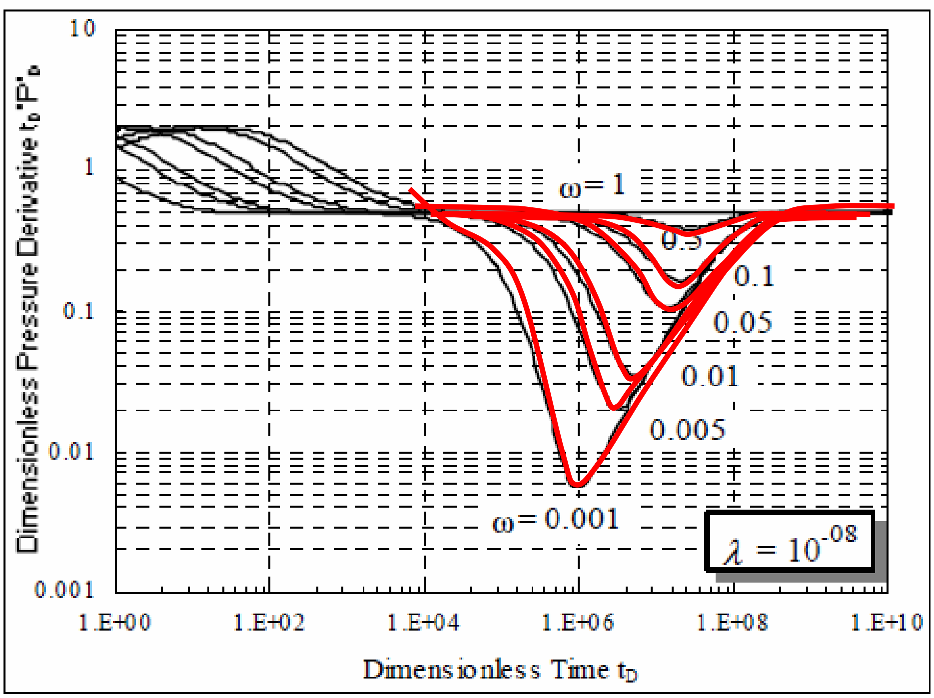

Figure 5.4: Slimani et al model vs simulated model

5.2 Two fractured layers with crossflow validation

The numerical models generated in Saphir are validated for a layered system. A two-layer system with both layers fractured was considered. The two layers have different thickness and reservoir properties as shown in Table 5.3. The fluid properties used are presented in Table 5.4.

Figure 5.5 shows a schematic of the two-layer system with crossflow, and Figure 5.6 presents the effect of ω variation on the pressure derivative. The model is considered to be penetrated at the top. The penetration is considered to be 20%.

Table 5.3: Two fractured layers properties

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	λ
Case 1	Fractured	10	10	270	0.001	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 2	Fractured	10	10	270	0.005	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 3	Fractured	10	10	270	0.01	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 4	Fractured	10	10	270	0.05	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 5	Fractured	10	10	270	0.1	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 6	Fractured	10	10	270	0.5	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$

Table 5.4: Fluid properties

Property	Value
Oil compressibility c_o, psi^{-1}	$3X10^{-6}$
Oil viscosity μ, cp	1
Oil formation volume factor B_o, RB/STB	1.29
Total oil rate (bbl/d)	5000

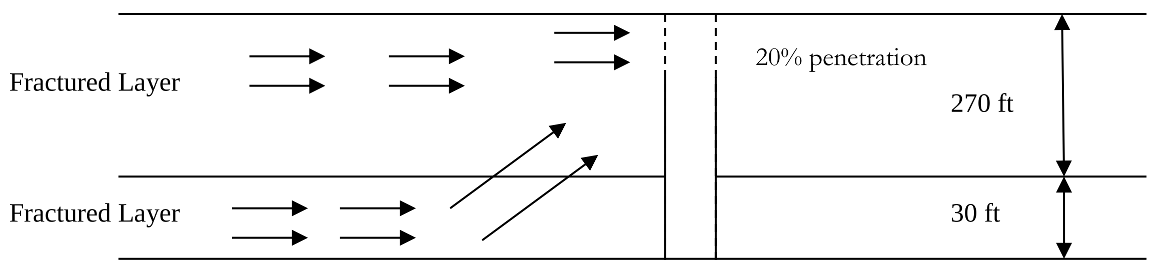

Figure 5.5: Schematic of two fractured layers model with cross flow

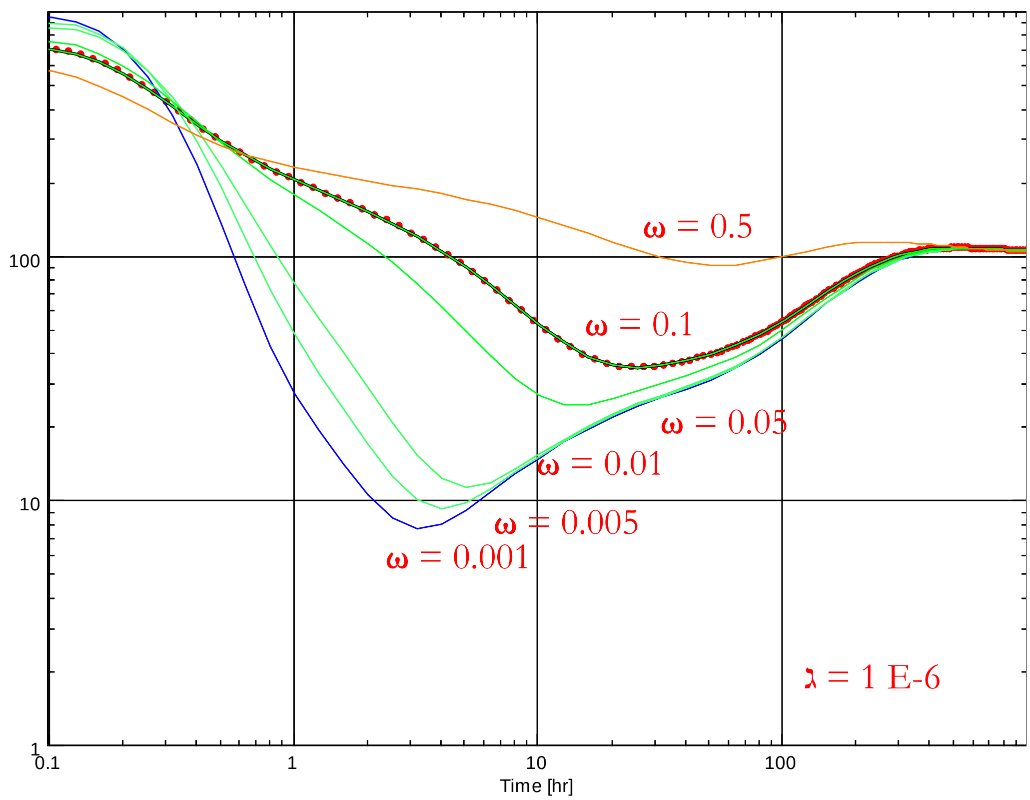

Figure 5.6: Effect of storativity ratio on the pressure derivative in the two fractured layers model

The response generated for the two fractured layer model, Figure 4.5, shows similar results to that of the Slimani model. It can be seen clearly that with increasing value of ω, the valley in the derivative curve tends to be shallower at late time.

CHAPTER 6

NUMERICAL MODELING AND CASE STUDIES

The Saphir numerical well testing application is used to generate all the model responses used in this study. The selection of the layers properties (thickness, permeability, and porosity) was done based on the maximum effect on the pressure response which can demonstrate the objective of this study. Below are the assumptions used for all the generated models:

1. All models are numerical models,
2. Reservoir is infinite,
3. Matrix is isotropic and homogeneous, i.e. $k_x = k_y = k_z$,
4. Pseudosteady state model is used,
5. Two-layer reservoir,
6. A vertical producing well is completed across both layers with full penetration,
7. In case of crossflow, leakage factor is 50% for all cases,
8. Pressure is uniformly distributed in the reservoir and equal to the initial reservoir pressure at t = 0, and
9. The well is producing at constant rate from t = 0 with constant wellbore storage and no skin effects.

6.1 Homogeneous layer and fractured layer

6.1.1 No cross flow

A two-layer reservoir model is considered in this case. A vertical producing well is completed across both layers. One of the layers is homogeneous, while the other one is fractured. Table 6.1 shows the properties of each layer for the different cases used in this study. Table A.1 shows the fluid properties and Figure 6.1 shows a schematic of the layered model.

In this case, the production is from both layers with no cross flow. The study in this case considers the variation of permeability in the homogeneous layer, where all other parameters in table A.1 are the same in the fractured layer. Table A.2 and Table A.3 show detailed parameters used to calculate ω and λ.

Three numerical models were built for this case using Saphir software. Each model has the same properties in the homogeneous layer and the fractured layer, except that the permeability of the homogeneous layer was changed in each model as shown in Table 6.1. The Saphir application has an option to select if there is a crossflow between layers through the leakage factor.

Figure 6.2 shows the effect of permeability variation in the homogeneous layer on this model response.

Table 6.1: Layers properties of homogeneous layer and fractured layer with no cross flow

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	λ
Case 1	Homogeneous	1	10	270	-	-
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 2	Homogeneous	10	10	270	-	-
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 3	Homogeneous	100	10	270	-	-
	Fractured	100	10	30	0.1	$1X10^{-6}$

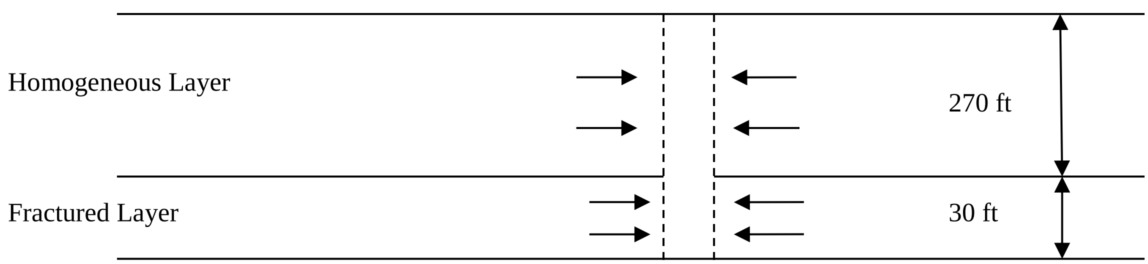

Figure 6.1: Schematic of a two-layer reservoir for homogeneous layer and fractured layer with no cross flow

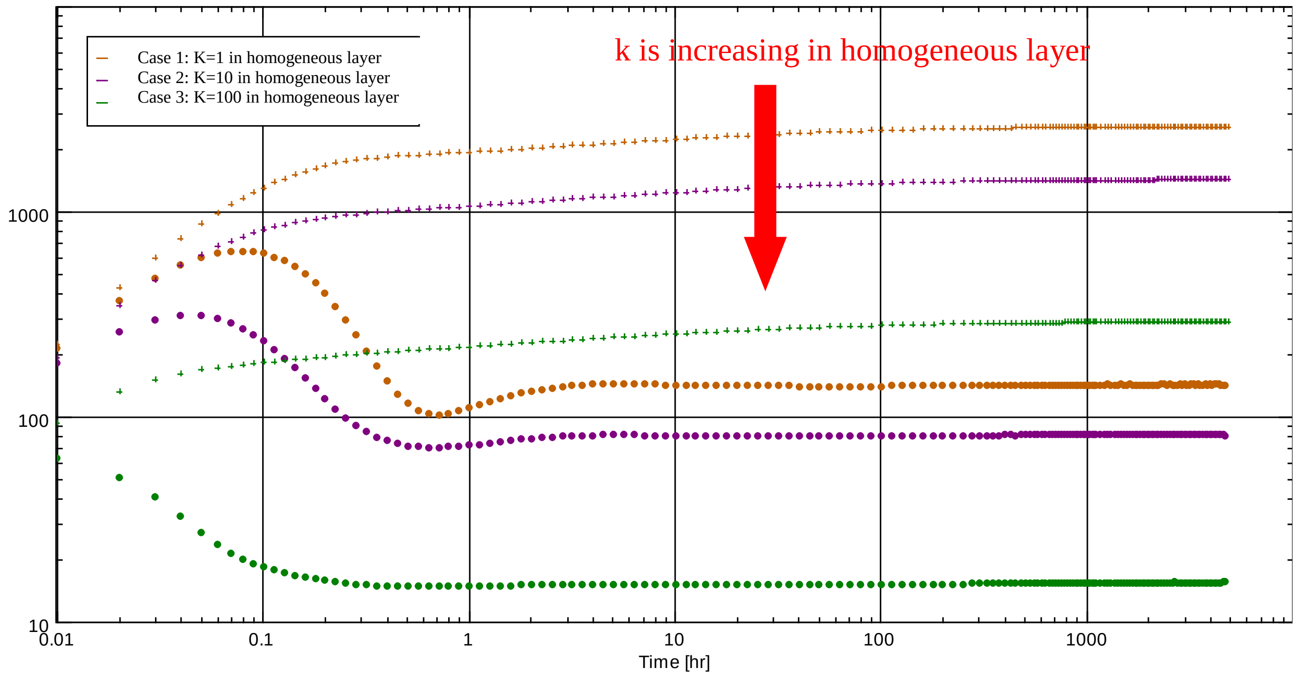

Figure 6.2: Homogeneous layer and fractured layer with no cross flow results

6.1.2 Case results analysis (No crossflow)

For a fractured formation, the expected pressure response of the fractures is seen at early time as a flat line. In the presence of wellbore storage, this flat line may be masked. After that, the transition period occurs which is represented by a dip reflecting the flow from the matrix into the fractures. Then, at late time, the pressure derivative will flatten again and become as a straight line which is a reflection of the total system response. This will happen when the entire formation (matrix and fractures) produce at the same time as one equivalent reservoir [2, 23].

Figure 6.2 shows that, in the case of a low permeable homogeneous layer (k=1 md) is comingled with a fractured layer, the high permeable fracture layer will start to contribute first and then the homogeneous low permeable layer will contribute later.

The comingled model with low homogeneous layer permeability clearly shows this behavior where a dip of the pressure derivative can be seen first at early time confirming the response of the high permeable fractured layer. After that, the homogeneous layer starts contributing.

When the permeability of the homogeneous layer is increased (k = 10 md and 100 md), the homogeneous layer starts to contribute at early time, at the same time as the fractured layer contribution. This effect is clearly seen at early time since the dip of the pressure derivative that shows the response of the high permeable fractured layer is not seen in the case (k=100 md in the homogeneous layer).When the permeability of the homogeneous layer is increased more, the homogeneous layer starts to dominate and the pressure response behaves as one homogeneous layer, while the effect of the fractured layer cannot be seen. Gringarten [16] showed the response of a single homogeneous layer and a single fractured layer. For the same kh value, the single homogeneous layer showed no dip in its pressure derivative and it tends to flatten whereas the single fractured layer showed a dip reflecting the fractures response. This can be related to this model since for low permeable homogenous layer, the layer response is delayed and it is observed later after the fractured layer response. But, when the homogeneous layer permeability increases, its response is seen earlier and it masks the fractured layer response.

6.1.3 Cross flow

Similar to the previous case, a two-layer reservoir model is considered. A vertical producing well is completed across both layers. One of the layers is homogeneous and the other one is fractured layer. Table 6.2 shows the properties of each layer, Table A.1 shows the fluid properties and Figure 6.3 shows a schematic of the layered model. Table A.2 and Table A.3 show detailed parameters used to calculate ω and λ.

In this case, the production is from both layers with cross flow from the low permeable layer to the high permeable one. Similar to the previous case, the permeability of the homogeneous layer was varied, but with cross flow between the two layers. Communication between the two layers is handled in Saphir by using a leakage factor of 50%.

Four numerical models were built for this case using Saphir software. Each model has the same properties in the homogeneous layer and the fracture layer, except that the permeability of the homogeneous layer was changed from low to high value (k= 0.1 md, k= 1 md, k= 10 md, and k= 100 md) in each model as presented in Table 6.2.

Figure 6.4 shows the results of these models.

Table 6.2: Layers properties of homogeneous layer and fractured layer with cross flow

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	ג
Case 1	Homogeneous	0.1	10	270	-	-
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 2	Homogeneous	1	10	270	-	-
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 3	Homogeneous	10	10	270	-	-
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 4	Homogeneous	100	10	270	-	-
	Fractured	100	10	30	0.1	$1X10^{-6}$

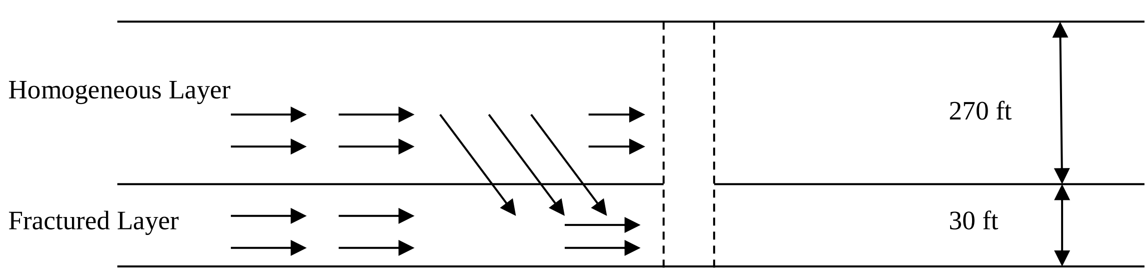

Figure 6.3: Schematic of a two-layer reservoir for homogeneous layer and fractured layer with cross flow

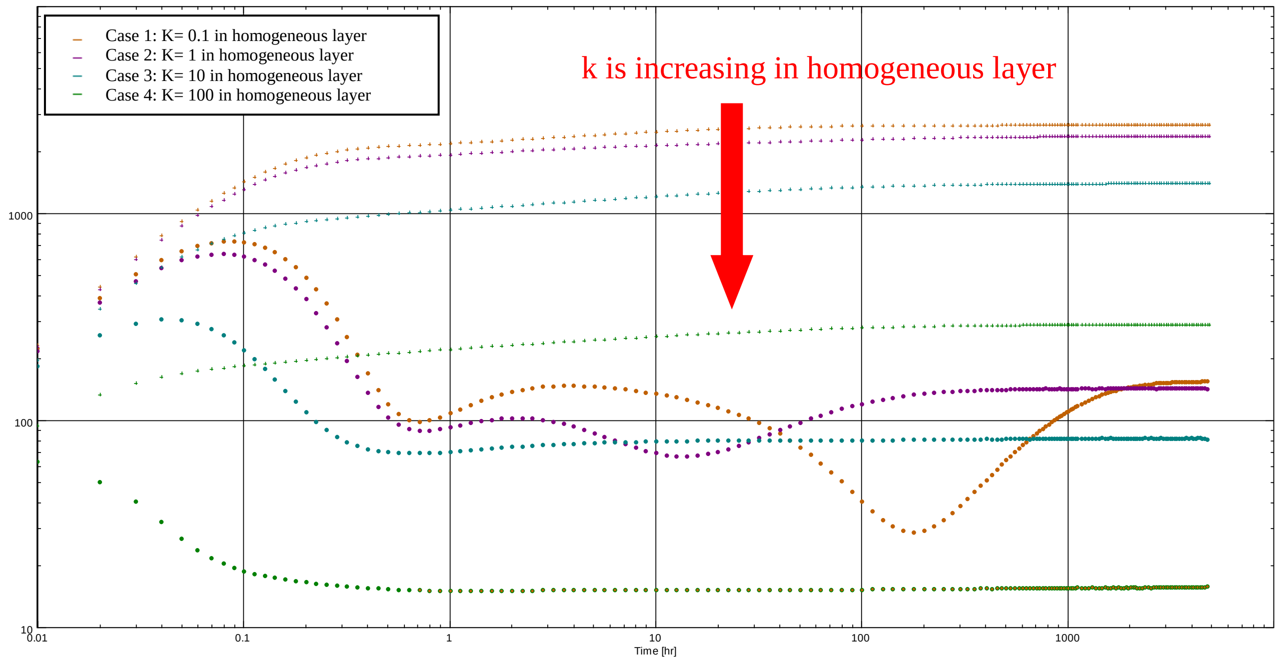

Figure 6.4: Homogeneous layer and fractured layer with cross flow results

6.1.4 Case results analysis (crossflow)

In this case, since the fractured layer has higher permeability, it will start to flow first and hence, its pressure response is seen first at early time. The fractures response is a flat line which is masked by the wellbore storage in this case. It is followed by the first dip representing the transition period of the high permeability fractured layer where the flow starts from matrix into the fractures. After the transition period, the pressure derivative shows a flat line representing the fractured layer total response. Analysis of that straight line will provide the properties of the fractured layer.

In this case, the homogeneous layer is not flowing to the wellbore only, it flows to the wellbore and to the high permeable fractured layer since there is crossflow between the homogeneous layer and the fractured layer. So, it is feeding the fractures and the matrix of the fractured layer.

Due to the crossflow, the results of the numerical models show that for low permeability homogeneous layer (0.1 and 1 md), the fractured layer response is seen first at early time and it is masked by the wellbore storage. The first dip in the pressure derivative reflects the transition period of the high permeable fractured layer. After that, the pressure tends to stabilized reflecting the response of the high permeable fractured layer. Then, the low permeable homogeneous layer starts contributing and this is where the second dip is seen followed by flattening reflecting the total system response.

In Figure 6.4, the second dip is clearly seen when the homogeneous layer has very low permeability (k= 0.1 md and k= 1 md). Once its permeability increases to higher values (k= 10 md and k= 100 md), the homogeneous layer will start to contribute earlier, and it masks the fractured layer behavior since both of them are flowing at the same time. Moreover, with higher permeability in the homogeneous layer, the system behaves like one fractured layer with high ω. This is clearly seen in Case 4 (Table 6.2) where k= 100 in the homogeneous layer.

Bourdet [20] presented similar results in his model for layered systems with high permeability contrast between layers. His model showed the early time response where both layers contribute to the wellbore. Then, a transition period occurs where the low permeable layer flows and feeds the high permeable one. After that, the late time shows the total system. This is similar to this case. However, in the cases of high permeability contrast between the homogeneous and fractured layers, the fracture contribution is seen earlier (first dip). Then, the transition period occurs where the homogeneous layers starts contributing.

Alghamdi et al. [17] presented results for a triple porosity model that are similar to the results of this case. The similarity is that their model considers the flow from the matrix to the wellbore, and to the microfractures and macrofractures whereas this model considers the flow from the high permeable layer matrix to the fractures and also from the low permeable homogeneous layer to the high permeable fractured layer.. There is a large permeability contrast between the microfractures and macrofractures in Alghamdi model similar to this case. The pressure response showed two dips corresponding to the different time of contribution for the matrix and the fractures.

Figure 6.5, Table 6.3 and Table 6.4 show the analysis of one of the models (Case 1 in Table 6.2) where the homogeneous layer permeability is low (0.1 md).

The analysis of the total system response (late time) showed that the calculated total permeability of the system is very close to the input permeability. The calculated ω also is very close to the input value of the analyzed case. However, if the well is not shut-in long enough during the buildup test, as in Figure 6.6, this may lead to wrong results especially the calculation of ω. Figure 6.7, Table 6.5, and Table 6.6 show the analysis of Case 1 where k=0.1 in the homogeneous layer and the well is not shut-in long enough. The analysis of this case shows wrong estimation of ω.

Therefore, the design of the well test is very important. If the well is not flowed for enough time or the test and data gathering for the shut-in period is stopped earlier than needed, this may lead to wrong test results and wrong estimates of the layers properties.

The weighted average permeability is calculated as follows [6, 11]:

$$\overline{\mathbf{k}} = \frac{\mathbf{k_1 h_1} + \mathbf{k_2 h_2}}{\mathbf{h_1}+\mathbf{h_2}}$$

ω is calculated from the plot as follows [16]:

$$\delta P = -m \log \frac{1}{\omega}$$

Therefore

$$\omega = 10^{-(\delta P/m)}$$

where m is the slope of the line in Figure 6.5 and δP is the difference between the two parallel lines.

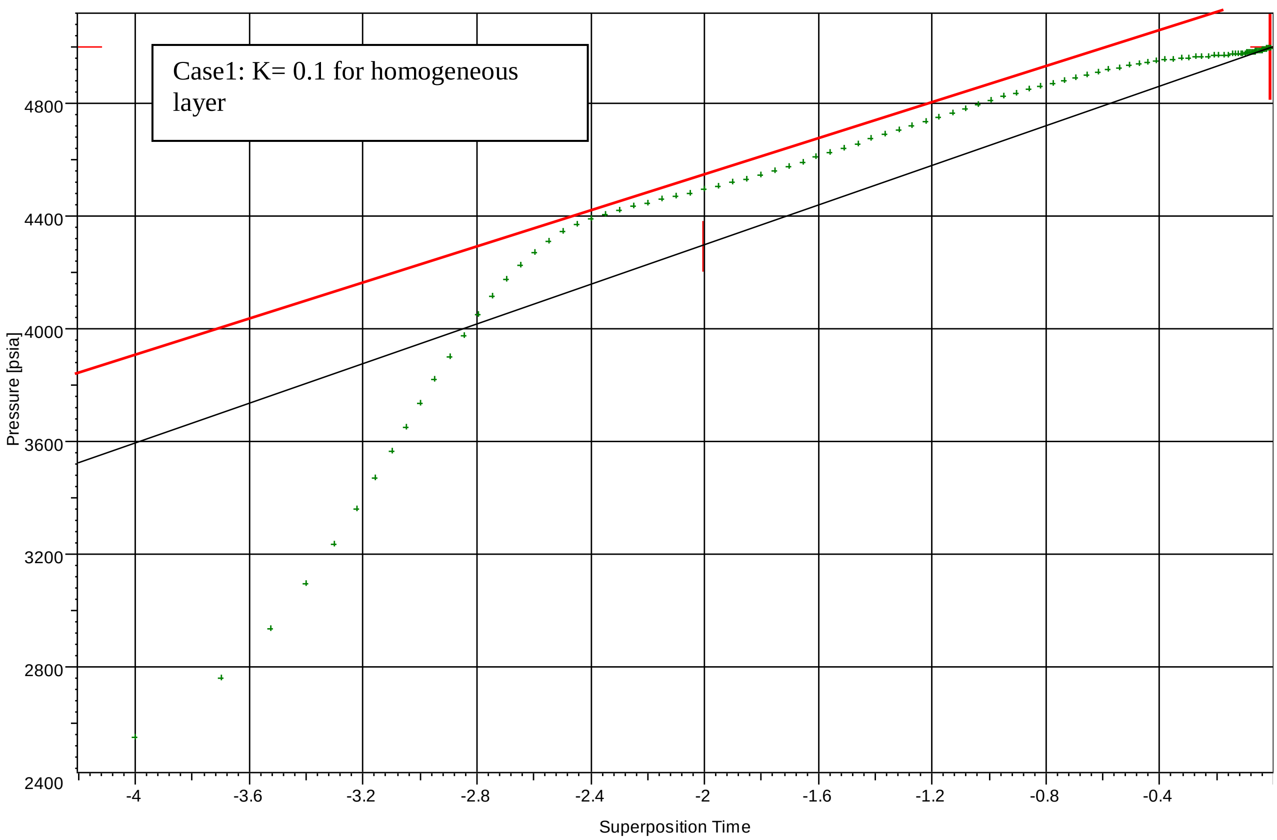

Figure 6.5: Homogeneous layer and fractured layer with cross flow analysis

Table 6.3: Homogeneous layer and fractured layer with cross flow analysis results

Name	Value	Unit
C	0.01	bbl/psi
Pi	5000	psia
Derived & Secondary Parameters		
Rinv	11800	ft
Test. Vol.	2090.7	MMB
Delta P (Total Skin)	0	psi
Semilog Line (K0.1_with_CrossFlow build-up #1)		
From	3182.07	hr
To	4610.07	hr
Slope	351.649	psi
Intercept	4999.97	psia
P@1hr	4295.16	psia
PMatch	0.00327	[psia]-1
k.h	2980	md.ft
k	9.94	md
p*	4999.97	psia
Skin	0.003	--
Delta P Skin	102.495	psi

Table 6.4: Homogeneous layer & fractured layer with cross flow analysis results

$\overline{K}$ (md)	10.1
Calc k (md)	9.94
Slope (m)	351
δP	291
ω (Calculated)	0.14
Model ω	0.1

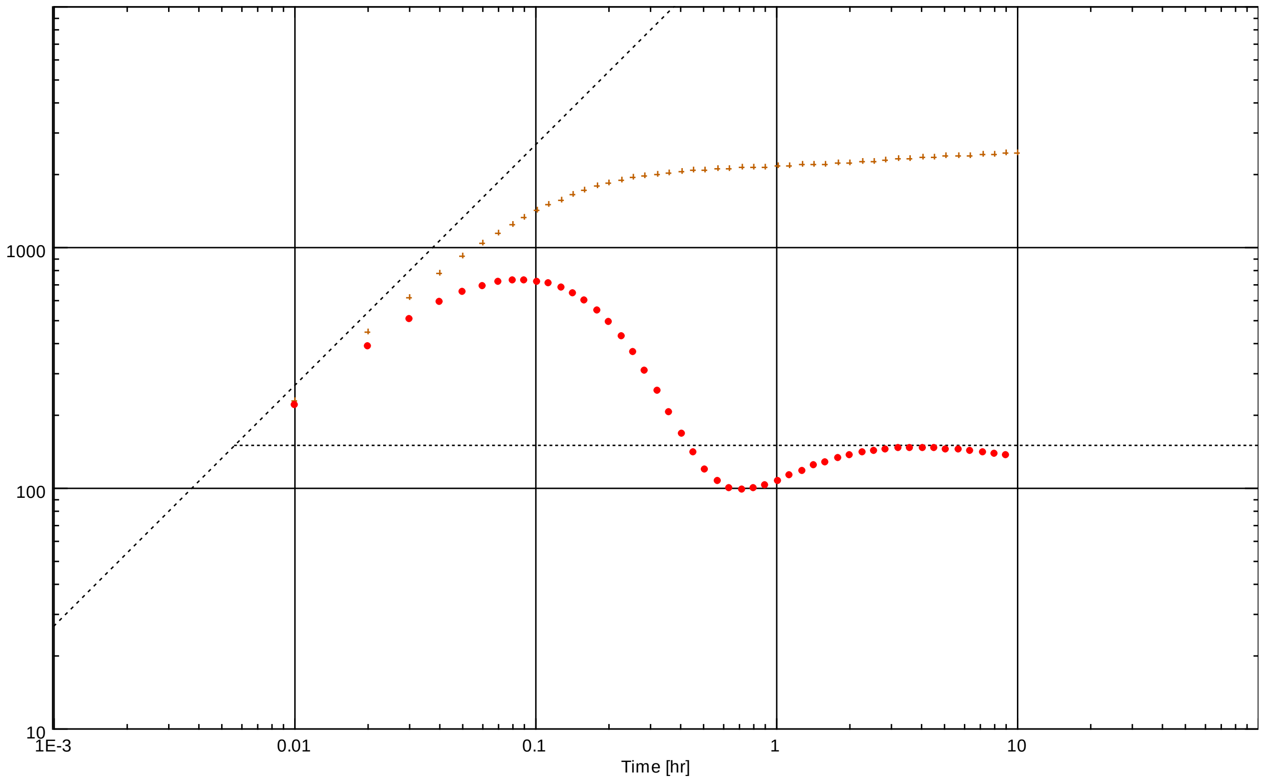

Figure 6.6: k=0.1 Homogeneous layer and fractured layer with cross flow results with short shut-in time

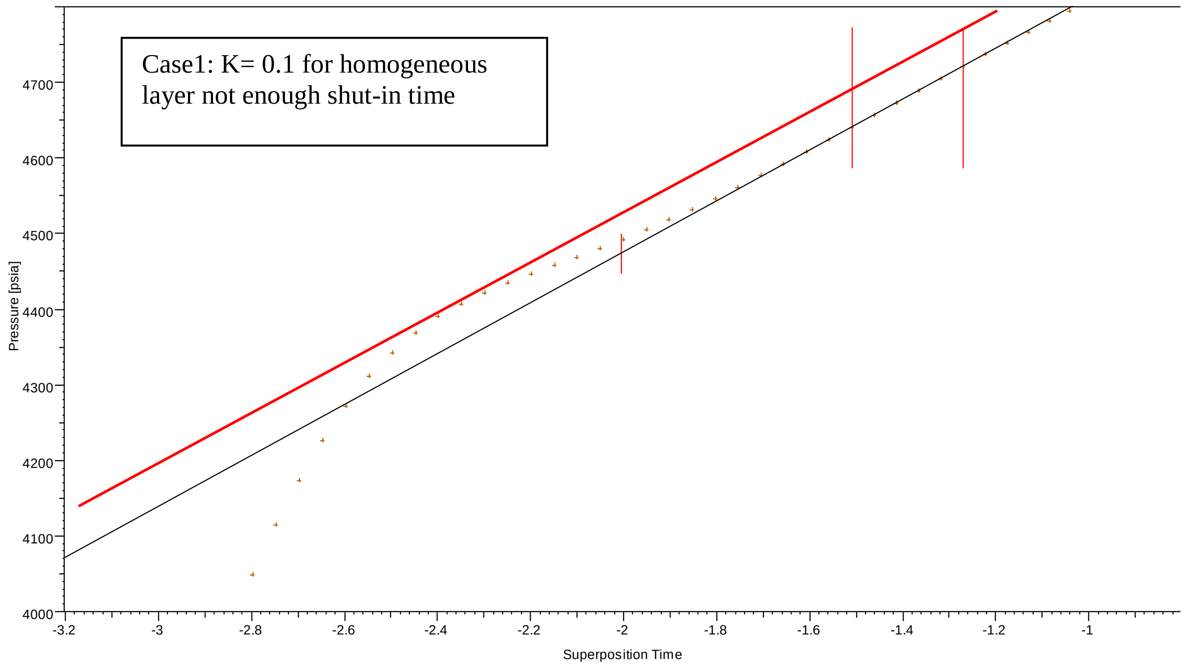

Figure 6.7: k=0.1 Homogeneous layer and fractured layer with cross flow with short shut-in time analysis

Table 6.5: k=0.1 Homogeneous layer and fractured layer with cross flow with short shut-in time analysis results

Name	Value	Unit
C	0.01	bbl/psi
Pi	5000	psia
Derived & Secondary Parameters		
Rinv	532	ft
Test. Vol.	4.27322	MMB
Delta P (Total Skin)	0	psi
Semilog Line (Test Design 1 build-up #1)		
From	103.193	hr
To	105.679	hr
Slope	336.244	psi
Intercept	5147.82	psia
P@1hr	4473.88	psia
PMatch	0.00342	[psia]-1
k.h	3120	md.ft
k	10.4	md
p*	5147.82	psia
Skin	0.0037	--
Delta P Skin	356.927	psi

Table 6.6: k=0.1 Homogeneous layer and fractured layer with cross flow with short shut-in time analysis results

$\overline{K}$ (md)	10.1
Calc k (md)	10.4
Slope (m)	336
δP	54
ω (Calculated)	0.69
Model ω	0.1

6.1.5 Homogeneous layer and fractured layer, with and without cross flow comparison

The analyses of the previous cases showed that the permeability of the homogeneous system has a significant effect on the pressure derivative behavior. Also, the crossflow between layers has an effect. Figure 6.8 compares the results for cases of crossflow and no crossflow between the homogeneous layer and the fractured layer.

For low permeability homogeneous layer (k=1 md), when there is no crossflow, the fractured layer response is seen at early time and then the pressure derivative tends to stabilize since the flow of the homogeneous layer goes to the wellbore only. This is why only one dip is seen in the derivative. In other words, the homogeneous layer is flowing only to the wellbore and does not feed the fractures in the second layer.

However, for the same conditions but with cross flow, the fractured layer response is not seen at early time because of wellbore storage. The response of that layer is followed by the transition period reflected by the first dip where the flow starts from the matrix of that layer into the fractures followed by a straight line reflecting the fractured layer total response. After that, the low permeable homogeneous layer starts contributing not only to the wellbore, but also to the fractured layer, causing a second dip to appear later followed again by flat straight line reflecting the total system response..

But, with higher homogeneous layer permeability, the pressure behavior is almost similar between the cross flow case and no cross flow case. This is due to the higher permeability of the homogeneous layer which causes more flow to the wellbore instead to the fractured layer resulted in the system behaving as a single homogeneous layer.

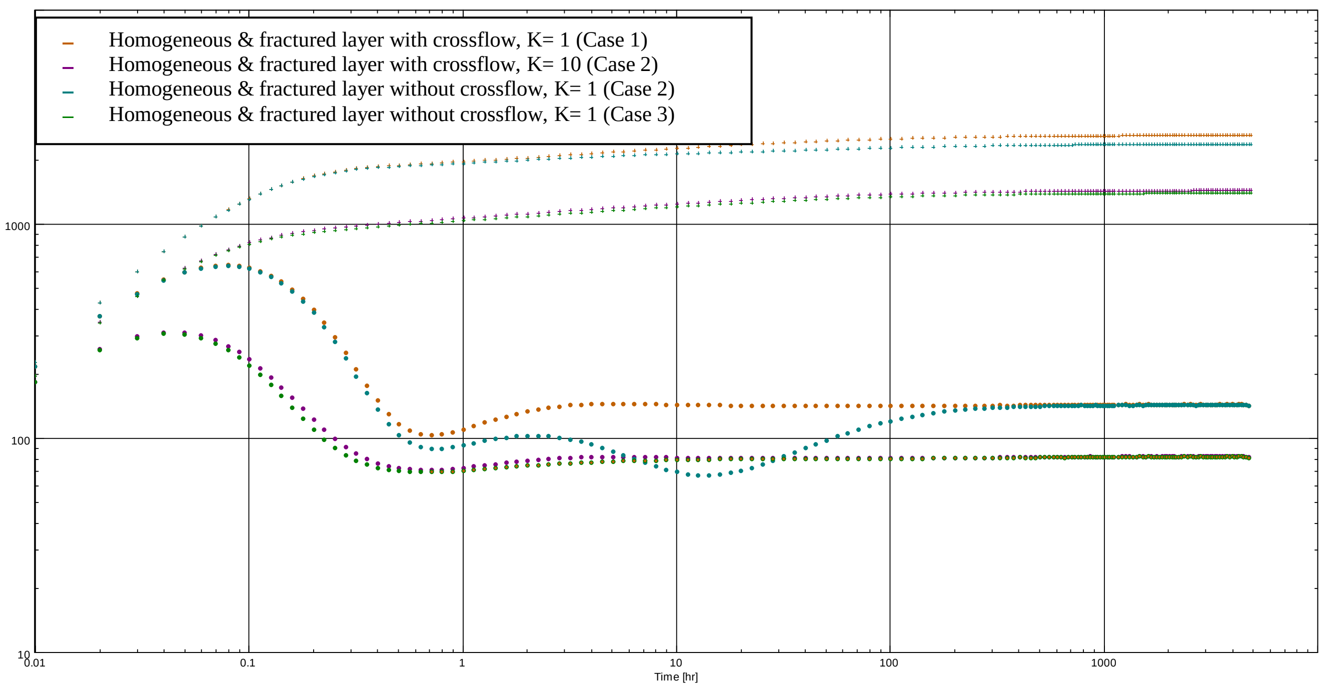

Figure 6.8: Homogeneous layer and fractured layer with and without cross flow comparison

6.2 Two fractured layers (ω variation)

6.2.1 No cross flow

In this case, a two-layer reservoir model is considered. A vertical producing well is completed across both layers. Both of the layers are fractured. Table 6.7 shows the properties of each layer. Table A.1 shows the fluid properties and Figure 6.9 shows a schematic of the total system. Table A.2 and Table A.3 show detailed parameters used to calculate ω and λ.

In this case, both layers are contributing with no cross flow between them. The study in this case considers the variation of omega (ω) in the low permeable fractured layer.

Four numerical models were built for this case using Saphir software. The first fractured layer has lower permeability (total permeability) than the second fractured layer. Variation of ω is carried out in the first low permeable fractured layer. Figure 6.10 shows the results for these models.

Table 6.7: Layer properties of two fractured layers (ω variation) with no cross flow

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	λ
Case 1	Fractured	10	10	270	0.01	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 2	Fractured	10	10	270	0.1	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 3	Fractured	10	10	270	0.3	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 4	Fractured	10	10	270	0.5	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$

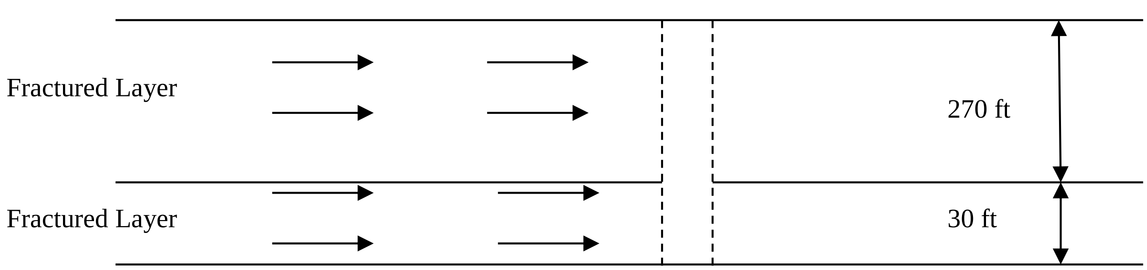

Figure 6.9: Schematic of a two-layer reservoir for two fractured layers (ω variation) with no cross flow

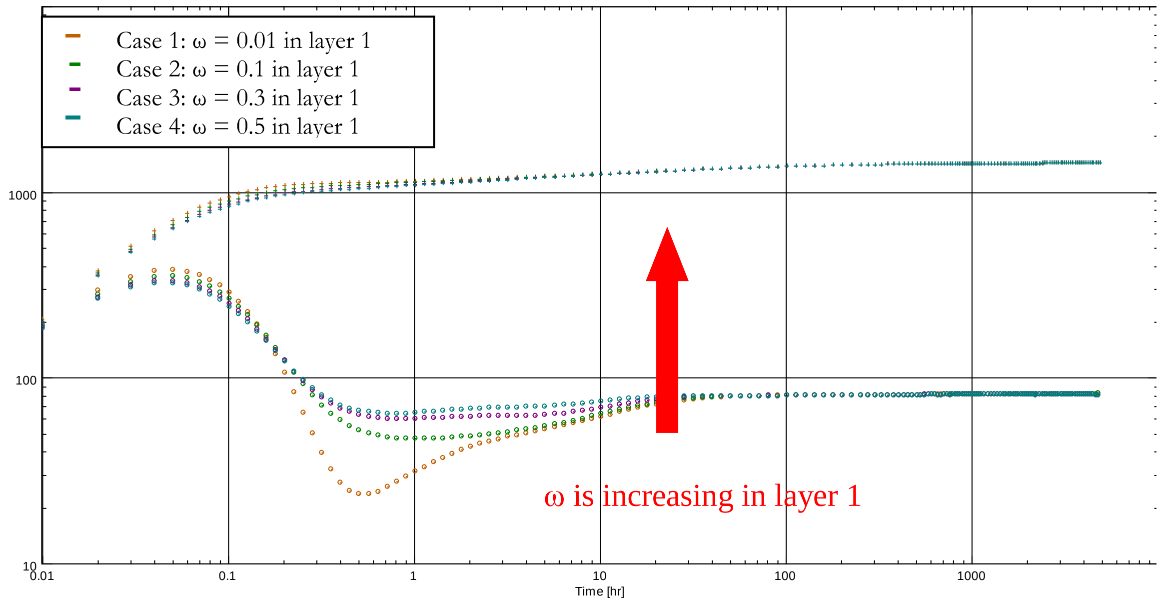

Figure 6.10: Two fractured layers (ω variation) with no cross flow

6.2.2 Case results analysis (No crossflow)

By definition, ω is the ratio of the fracture storage with respect to the total system storage. Normally, the pressure derivative signature of one layer fractured system has a dip at the early time which is the sign of the presence of fractures. The fractures response is a flat line, which is usually masked by the wellbore storage as in the case presented here. This flow period is followed by a dip representing the transition period that is following the fracture response where the flow starts from the matrix into the fractures. This is followed by a flat line reflecting the fractured layer total response. As can be seen from Figure 6.10, in the presence of another lower permeability fractured layer in addition to the main high permeable fractured layer (2-layer fractured system), the fractures in both layers flow simultaneously to the wellbore at early time. For each layer, its matrix flows to the layer's fractures only since there is no crossflow between the layers. Due to that, the two layers' pressure response is similar to that one of a single fractured layer for low values of ω (0.01) in the low permeability fractured layer.

When ω increases in the low permeability fractured layer, the fractures flow to the wellbore for longer time since the fractures have more storage. Due to that, the dip tends to flatten compared to the sharp dip of the one-layer fractured system. Therefore, as ω increases in the low permeability fractured layer, the dip tends to flatten more and more which results in less transition period. As a result, there was a doubt that maybe the production is coming only from the high permeable fractured layer and the low permeable one is not contributing at all. In order to validate this, those cases were compared to one-layer fractured system that has the same properties as the generated models. Figure 6.11 shows the comparison between 2-layer fractured system with variation of ω compared to one-layer system with the same properties. The results prove that the production is coming from both layers in the 2-layer fractured system since the pressure response is different from that of the single layer fractured system. The one-layer fractured system showed the dip that represents a signature of the fractured layer where the transition period occurs whereas the 2-layer fractured signature is different.

Analysis is carried out for one model where $\omega = 0.5$ in the low permeable fractured layer and $\omega = 0.1$ in the high permeable fractured layer (Case 3 in Table 6.7). The calculated permeability from the plot is almost similar to the input system permeability. For ω, it tends to be high and it is more close to the higher ω layer (calculated $\omega = 0.42$). This is demonstrated in Figure 6.12 and Table 6.9. The analysis results are shown in Table 6.8.

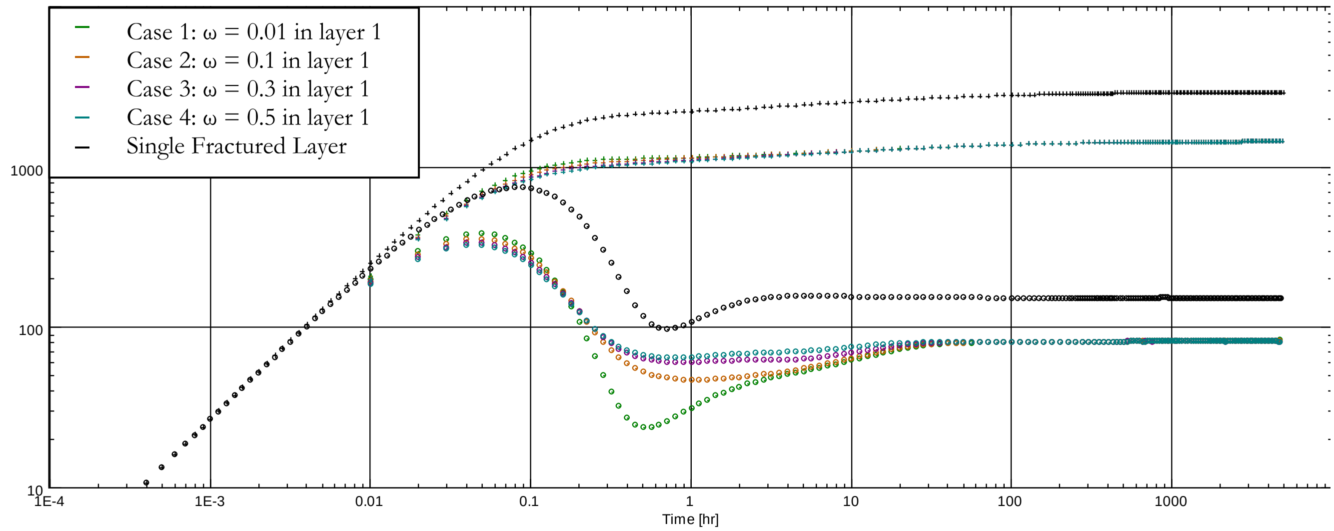

Figure 6.11: Two fractured layers (ω variation) with no cross flow comparison with single fractured layer

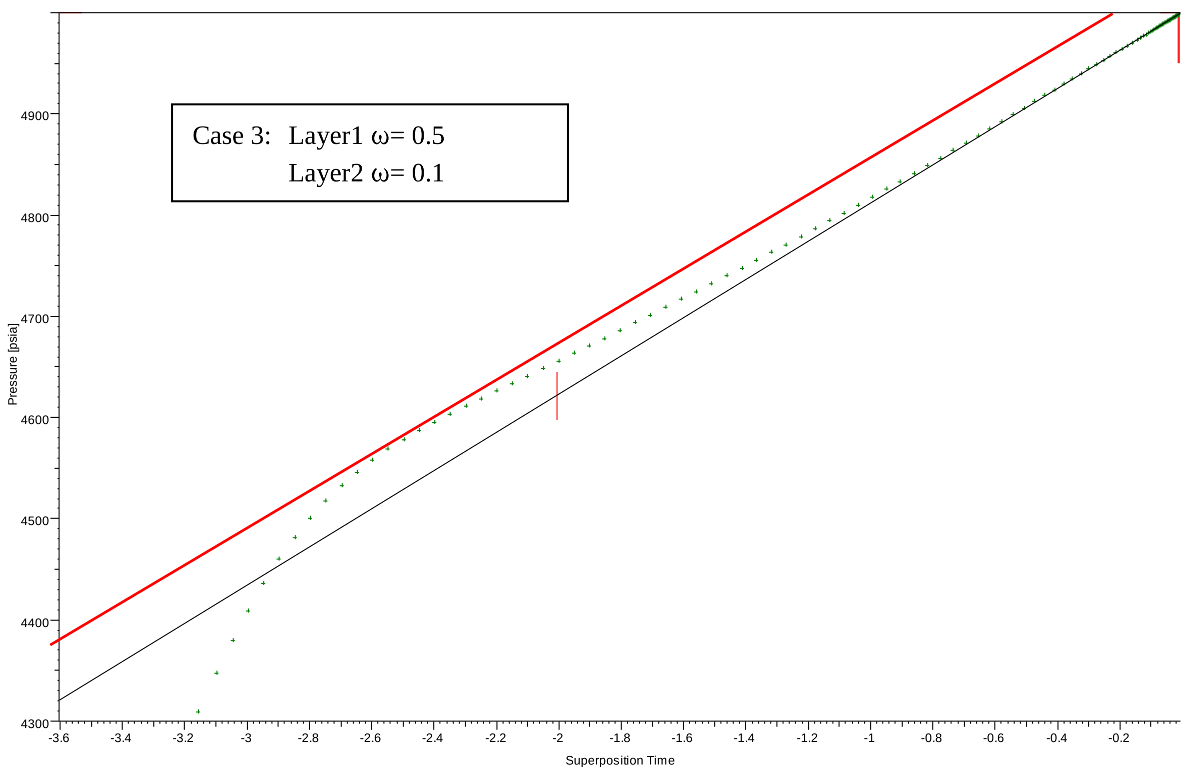

Figure 6.12: Two fractured layers (ω variation) with no cross flow analysis analysis where layer1 ω = 0.5 and layer2 ω = 0.1

Table 6.8: Two fractured layers (ω variation) with no cross flow analysis results

Name	Value	Unit
C	0.01	bbl/psi
Pi	5000	psia
Derived & Secondary Parameters		
Rinv	16100	ft
Test. Vol.	3936.9	MMB
Delta P (Total Skin)	0	psi
Semilog Line (W0.5_No_CrossFlow build-up #1)		
From	3029.07	hr
To	4610.07	hr
Slope	188.701	psi
Intercept	5000	psia
P@1hr	4621.78	psia
PMatch	0.0061	[psia]-1
k.h	5560	md.ft
k	18.5	md
p*	5000	psia
Skin	-0.00379	--
Delta P Skin	-0.620643	psi

Table 6.9: Two fractured layers (ω variation) with no cross flow analysis results

$\overline{K}$ (md)	19
Calc k (md)	18.5
Slope (m)	188
δP	69
ω (Calculated)	0.42

6.2.3 Cross flow

A two-layer reservoir model is considered in this case. A vertical producing well is completed across both layers. Both of the layers are fractured. Table 6.10 shows the properties of each layer, Table A.1 shows the fluid properties and Figure 6.13 shows a schematic of the layered model. Table A.2 and Table A.3 show detailed parameters used to calculate ω and λ.

In this case, the model is built to have the production from both layers with cross flow between the layers. The leakage factor between layers is set to be 50%. The study in this case considers the variation of omega (ω) in the low permeability fractured layer.

Three numerical models were built for this case using Saphir software. The first fractured layer has lower permeability (total permeability) than the second fractured layer. Variation of ω is carried out in the first low permeability fractured layer (ω= 0.1, ω= 0.3, and ω= 0.5).

Figure 6.14 shows the results of these models.

Table 6.10: Layers properties of two fractured layers (ω variation) with cross flow

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	λ
Case 1	Fractured	10	10	270	0.1	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 2	Fractured	10	10	270	0.3	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 3	Fractured	10	10	270	0.5	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$

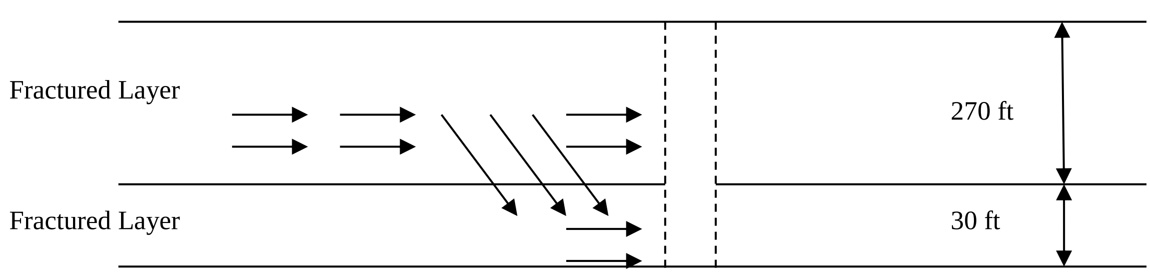

Figure 6.13: Schematic of a two-layer reservoir of two fractured layers (ω variation) with cross flow

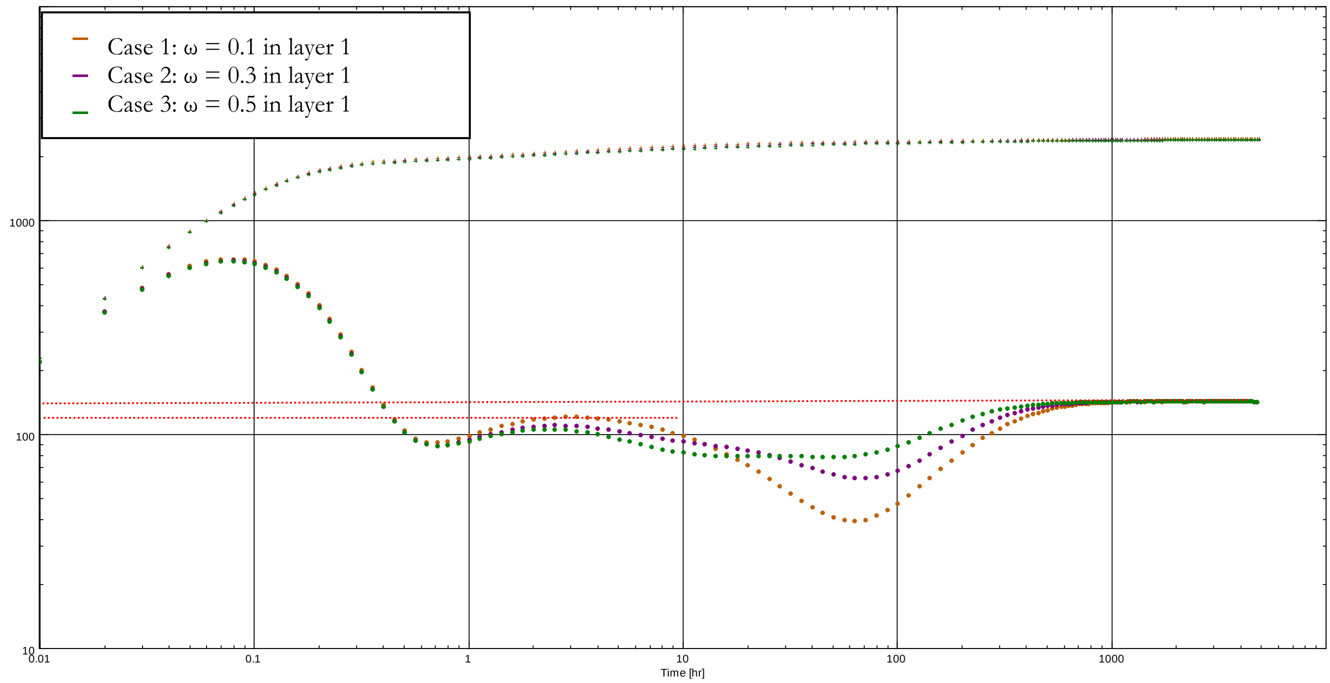

Figure 6.14: Two fractured layers (ω variation) with cross flow

6.2.4 Case results analysis (Crossflow)

In these models, the pressure response shows a dip which is a signature of the higher permeability fractured layer response. At early time, wellbore storage is masking the flat line that is corresponding to the fractures response of that layer. The first dip reflects the transition period where the flow starts from the matrix into the factures. Then, it is followed by a flat line reflecting the high permeability fractured layer total response. After that, the lower permeability fractured layer response is observed. The response of that layer is represented by the second dip where the dip represents the transition period of that layer corresponding to the flow from its matrix into the fractures. This is followed by a flat line reflecting the total system response. By drawing two horizontal lines reflecting the first layer response and the total system response, it is observed that the total system response is higher than the first layer response. This is an indication that the total system permeability is less than the first layer permeability.

Lower ω (0.1) in the low permeability fractured layer causes the second dip reflecting that layer response at late time to be sharper and deeper. Increasing ω to 0.3 and 0.5 in the low permeability fractured layer causes the second dip to be shallower with no effects on the first dip that represents the signature of the high permeability fractured layer which is seen at early time. With increasing ω, the fractures storage in the first layer is more. This resulted in less transition period which is indicated by the shallower dip.

Slimani et al. [8] showed the pressure response of a single fractured layer with variation of ω. As ω increases, the dip reflecting the response of the transition period is getting shallower. This is similar to the response found in this model. When ω is varied in the low permeability fractured layer, the second dip reflecting the matrix flow into the fractures (transition period for this layer) of that layer gets shallower.

Analysis has been carried out for two models out of the models considered above (Case 1 and Case 3 in Table 6.10). The first analysis is done for the model where both layers have the same ω value of 0.1 (Case 1) which is demonstrated in Figure 6.15 and Table 6.12. The analysis results are shown in Table 6.11. The second analysis is done for the model where the high permeable fractured layer has $\omega = 0.1$ and the low permeable fractured layer has $\omega = 0.5$ (Case 3) which is demonstrated in Figure 6.16 and Table 6.14. The analysis results are shown in Table 6.13.

For Case 1, where both fractured layers have $\omega = 0.1$, the analysis showed that the calculated permeability from the plot is very close to the input system permeability. The calculated ω from the system also is very close to the input system ω (initial $\omega = 0.1$ and calculated $\omega = 0.11$).

In Case 3 analysis where ω = 0.5 in the low permeability fractured layer and ω = 0.1 in the second layer, the analysis showed that the calculated permeability from the plot is very close to the input system permeability. The calculated ω from the system is also very close to the initial system ω, but it is higher than the previous case where ω = 0.1 in both layers (calculated ω = 0.16). It can be concluded from this analysis that Case 3 total system ω is higher than Case 1 total system ω due to the more fractures storage. The low permeability layer in Case 3 has higher thickness and since ω in higher in that layer, the total system fractures storage is higher in Case 3 compared to Case 1.

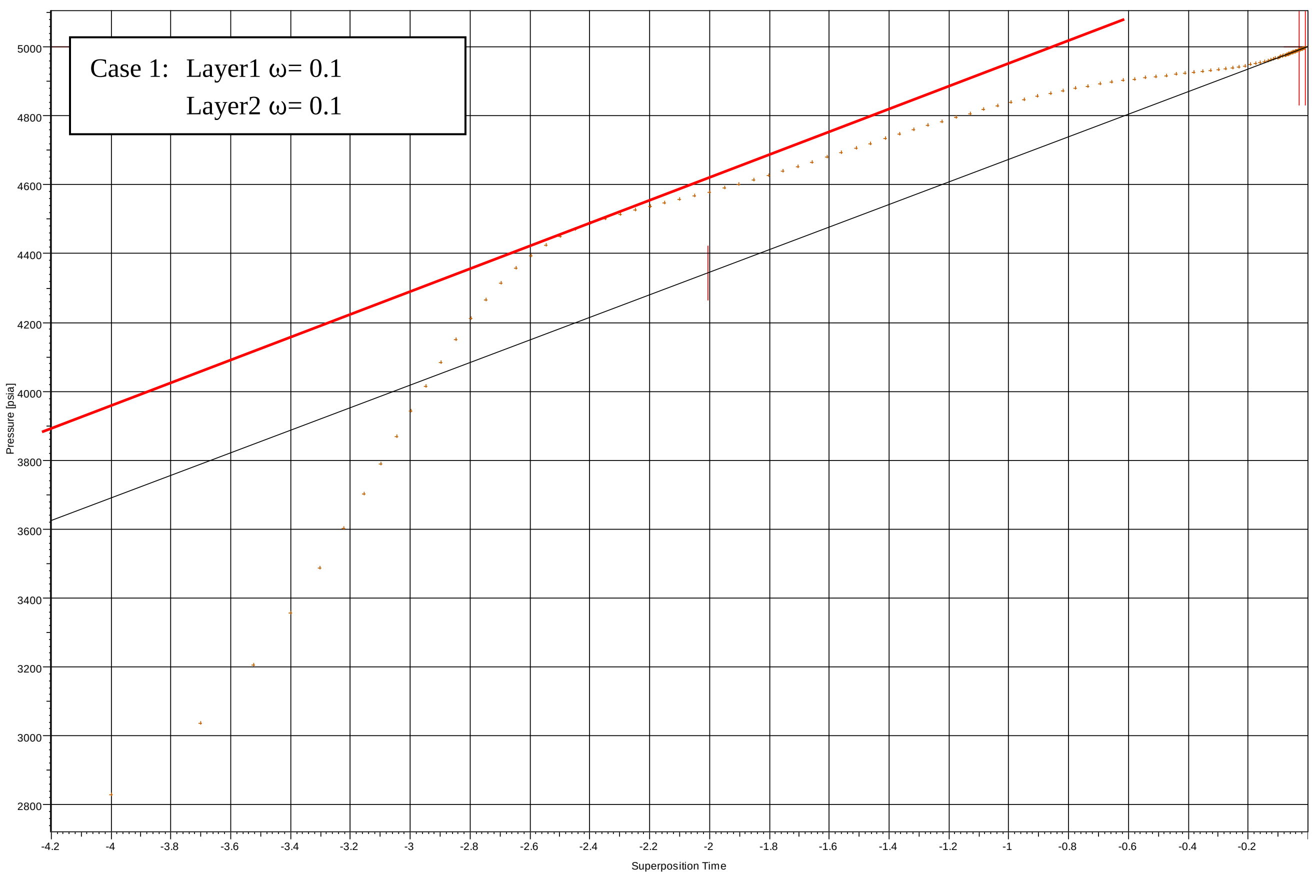

Figure 6.15: Two fractured layers (ω variation) with cross flow analysis where ω = 0.1 in both layers

Table 6.11: Two fractured layers (ω variation) with cross flow analysis where ω = 0.1 in both layers

Name	Value	Unit
C	0.01	bbl/psi
Pi	5000	psia
Derived & Secondary Parameters		
Rinv	12200	ft
Test. Vol.	2258.54	MMB
Delta P (Total Skin)	0	psi
Semilog Line (Test Design 1 build-up #1)		
From	1473.57	hr
To	4406.07	hr
Slope	327.395	psi
Intercept	4999.99	psia
P@1hr	4343.78	psia
PMatch	0.00352	[psia]-1
k.h	3200	md.ft
k	10.7	md
p*	4999.99	psia
Skin	-0.0493	--
Delta P Skin	-14.036	psi

Table 6.12: Two fractured layers (ω variation) with cross flow analysis results

$\overline{K}$ (md)	10.9
Calc k (md)	10.7
Slope (m)	327
δP	311
ω (Calculated)	0.11
Model ω	0.1

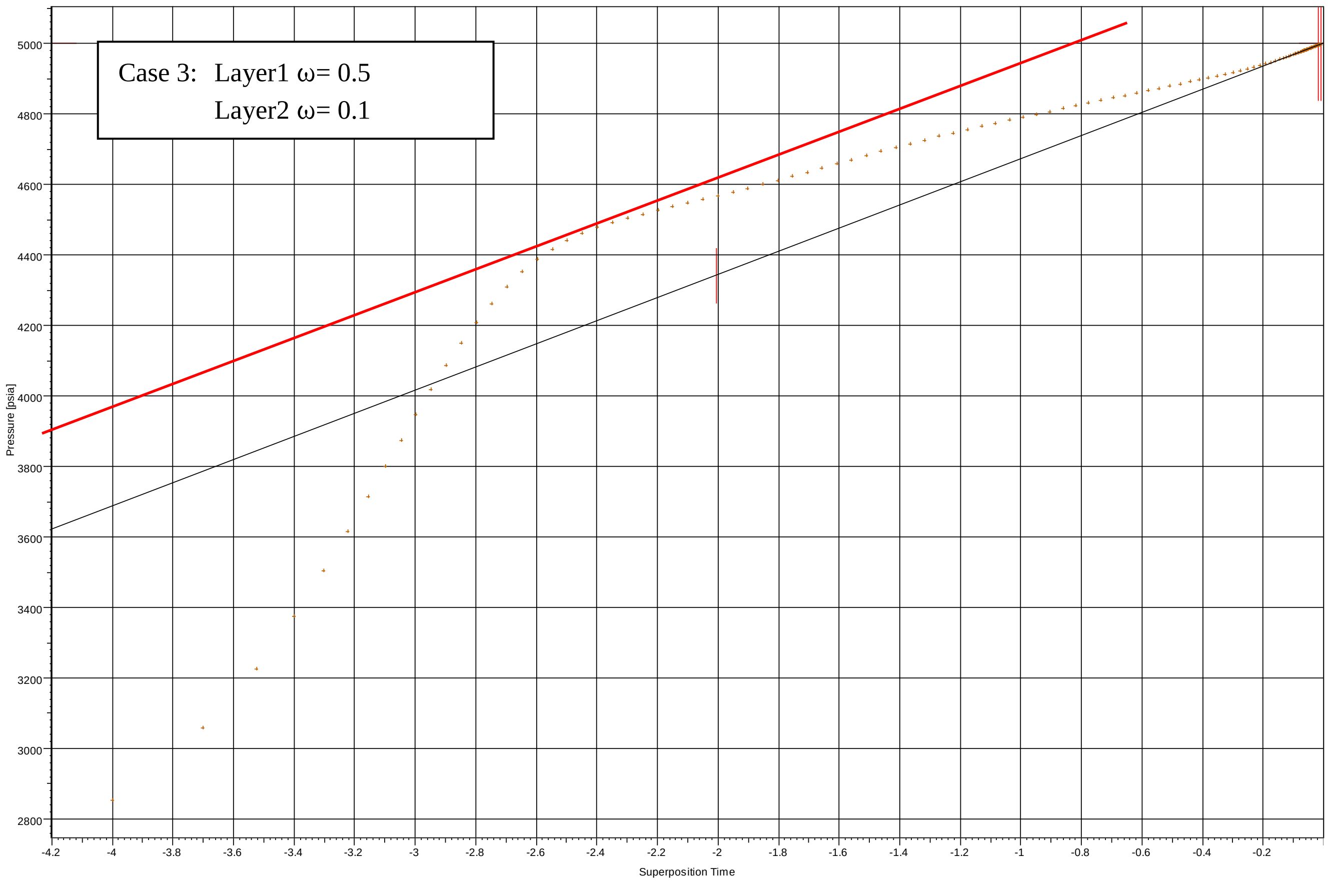

Figure 6.16: Two fractured layers (ω variation) with cross flow analysis where layer 1 ω = 0.5 and layer 2 ω = 0.1

Table 6.13: Two fractured layers (ω variation) with cross flow analysis where layer 1ω = 0.5 and layer 2 ω = 0.1

Name	Value	Unit
C	0.01	bbl/psi
Pi	5000	psia
Derived & Secondary Parameters		
Rinv	12200	ft
Test. Vol.	2258.54	MMB
Delta P (Total Skin)	0	psi
Semilog Line (Test Design 1 build-up #1)		
From	2570.07	hr
To	4610.07	hr
Slope	327.85	psi
Intercept	5000	psia
P@1hr	4342.88	psia
PMatch	0.00351	[psia]-1
k.h	3200	md.ft
k	10.7	md
p*	5000	psia
Skin	-0.15	--
Delta P Skin	-42.5861	psi

Table 6.14: Two fractured layers (ω variation) with cross flow analysis results

$\overline{K}$ (md)	10.9
Calc k (md)	10.7
Slope (m)	327
δP	261
ω (Calculated)	0.16
Model ω	0.1

6.3 Two fractured layers (λ variation)

6.3.1 No cross flow

Again, a two-layer reservoir model is considered. A vertical producing well is completed across both layers. Both of the layers are fractured. Table 6.15 shows the properties of each layer, Table A.1 shows the fluid properties and Figure 6.17 shows a schematic of the layered model. Table A.2 and Table A.3 show detailed parameters used to calculate ω and λ.

In this case, both layers are contributing with no cross flow between them. The study in this case considers the variation of lambda (λ) in the low permeability fractured layer.

Three numerical models were built for this case using Saphir software. The first fractured layer has lower permeability than the second fractured layer. Variation of λ is carried out in the first low permeable fractured layer.

Figure 6.18 shows the results of these models.

In order to study the effect of λ on the pressure behavior and to verify that it does not affect the total permeability of the system, a single fractured layer model was built to show the effect of λ as in Figure 6.19. From the model results**,** λ tends to affect and delays the fracture response. In other words, when λ is decreasing in a single layer fractured model, it delays the fractures response and hence it shifts the dip of the pressure derivative to the right [8]. Furthermore, to confirm that both layers are contributing, the model was compared to a single layer fractured model with the same properties to show that the pressure response is indeed different, and both layers are contributing as shown in Figure 6.20. The pressure derivative of the single layer fractured model showed the normal single layer response, which is a dip reflecting the transition period followed by a flat line reflecting the total system. However, the two-layer models showed different response, where two dips representing the response of both layers are observed.

Table 6.15: Layers properties of two fractured layers (λ variation) with no cross flow

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	λ
Case 1	Fractured	10	10	270	0.1	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 2	Fractured	10	10	270	0.1	$1X10^{-7}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 3	Fractured	10	10	270	0.1	$1X10^{-8}$
	Fractured	100	10	30	0.1	$1X10^{-6}$

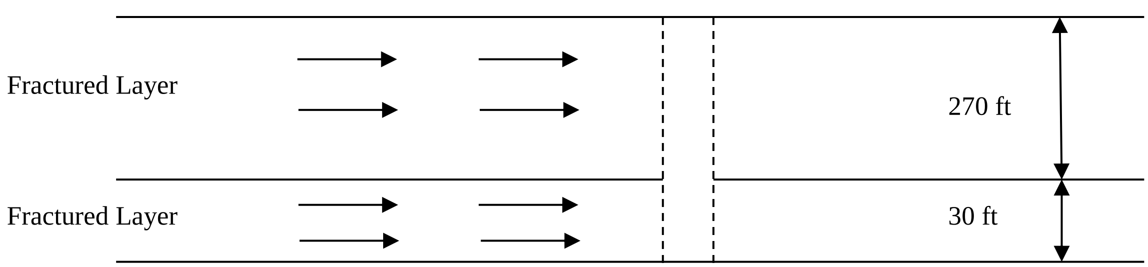

Figure 6.17: Schematic of a two-layer reservoir of two fractured layers (λ variation) with no crossflow

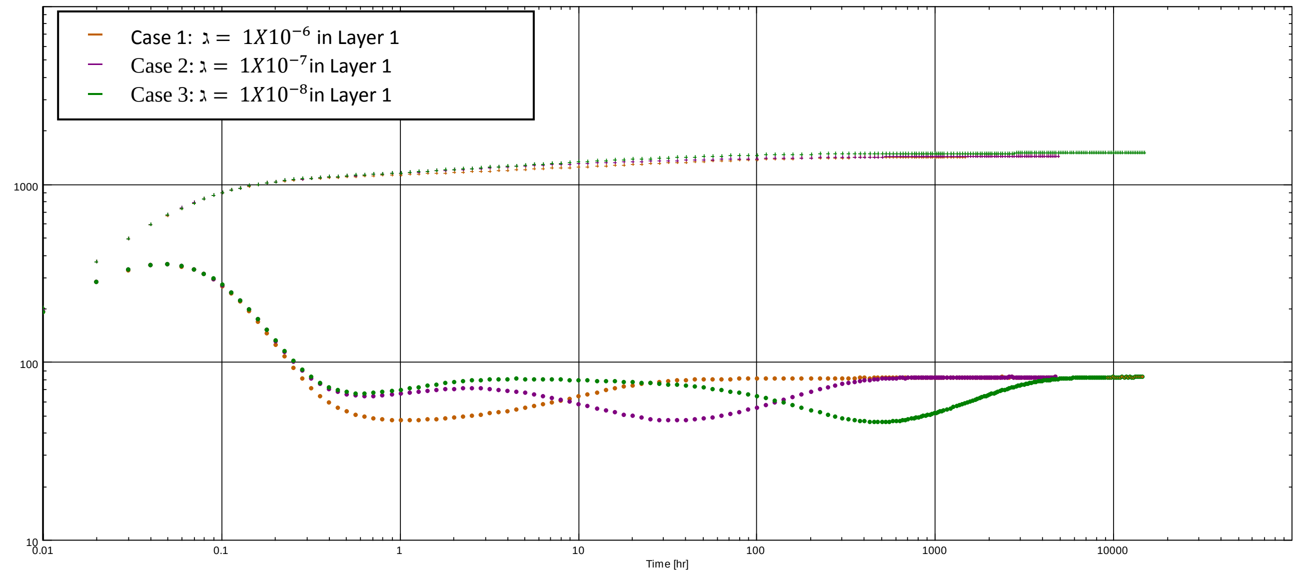

Figure 6.18: Two fractured layers (ג variation) with no cross flow

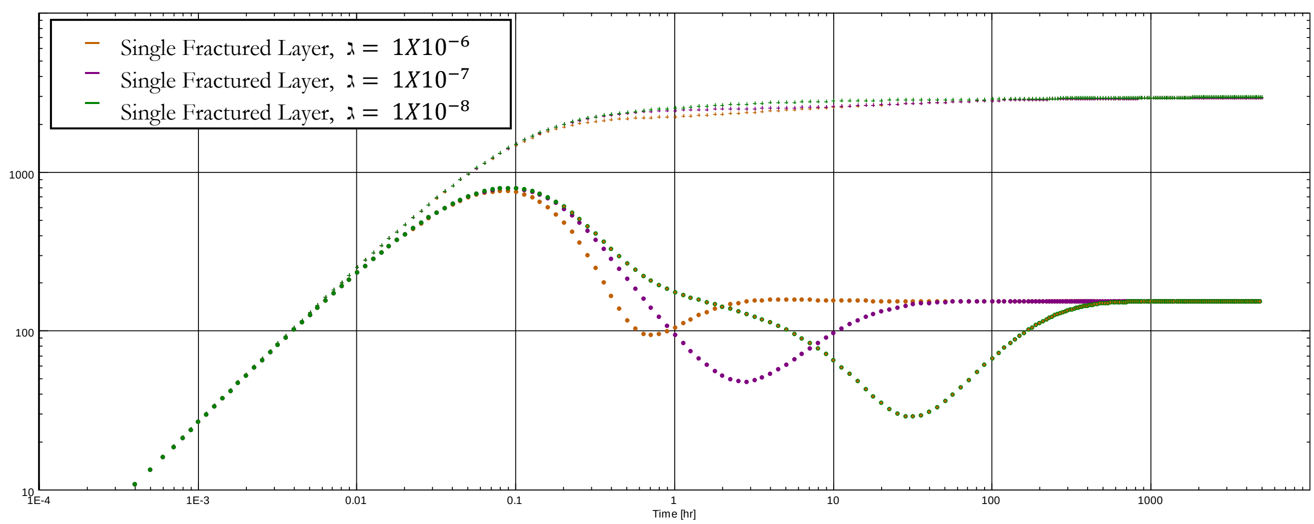

Figure 6.19: Single layer pressure response with ג variation

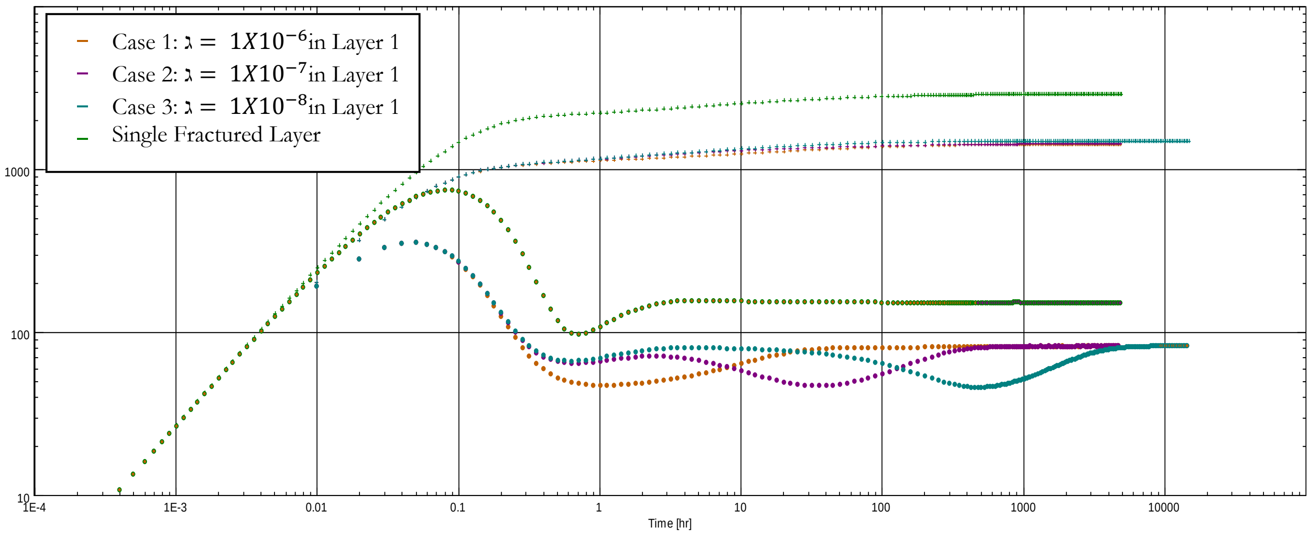

Figure 6.20: Two fractured layers (ג variation) with no cross flow and one fractured layer comparison

6.3.2 Case results analysis (No crossflow)

The results of this model show that the flat line corresponding to the high permeability fractured layer is masked by the wellbore storage. Then, two dips in the pressure derivative response are observed. The first dip reflects the transition period of the high permeability fractured layer where the matrix starts flowing into the fractures. This dip is followed by a short flattening period reflecting the total system response of the high permeability fractured layer. The second dip reflects the transition period of the low permeability fractured layer where its matrix starts flowing into the fractures. Then, a flat pressure derivative straight line is seen at late time reflecting the total system response.

When ג is decreased, this change affects the time between the high permeability fractured layer and the low permeability fractured layer responses which makes that time longer resulting in delaying the low permeability fractured layer response. As a result of that, the second dip that shows the transition period of low permeability fractured layer is delayed and shifted to the right. As λ decreases further ($\lambda = \mathbf{1X10^{-8}}$), it takes more time to see the total system behavior on the pressure derivative.

When both layers have the same λ, they act like one single fractured layer. This can be seen from the pressure derivative response where only one dip can be seen.

Slimani et al. [8] presented the expected behavior when λ is varied for a single layer. As λ decreases, the dip reflecting the transition following the fractures response shifts to the right. This is similar to what is found in this model. The lower permeability fractured layer transition period represented by the second dip is shifted to the right when λ decreases.

Analysis of the model where the low permeability fractured layer $\lambda = \boldsymbol{1X10^{-7}}$ and the high permeability fractured layer $\lambda = \boldsymbol{1X10^{-6}}$ has been carried out, and is demonstrated in Figure 6.21 and Table 6.17. The results of the analysis are shown in Table 6.16. The analysis shows that the calculated permeability is almost equal to the input system permeability. However, it seems that the change of λ affects the total system ω since the input ω = 0.1 is calculated to be ω = 0.22 from the analysis.

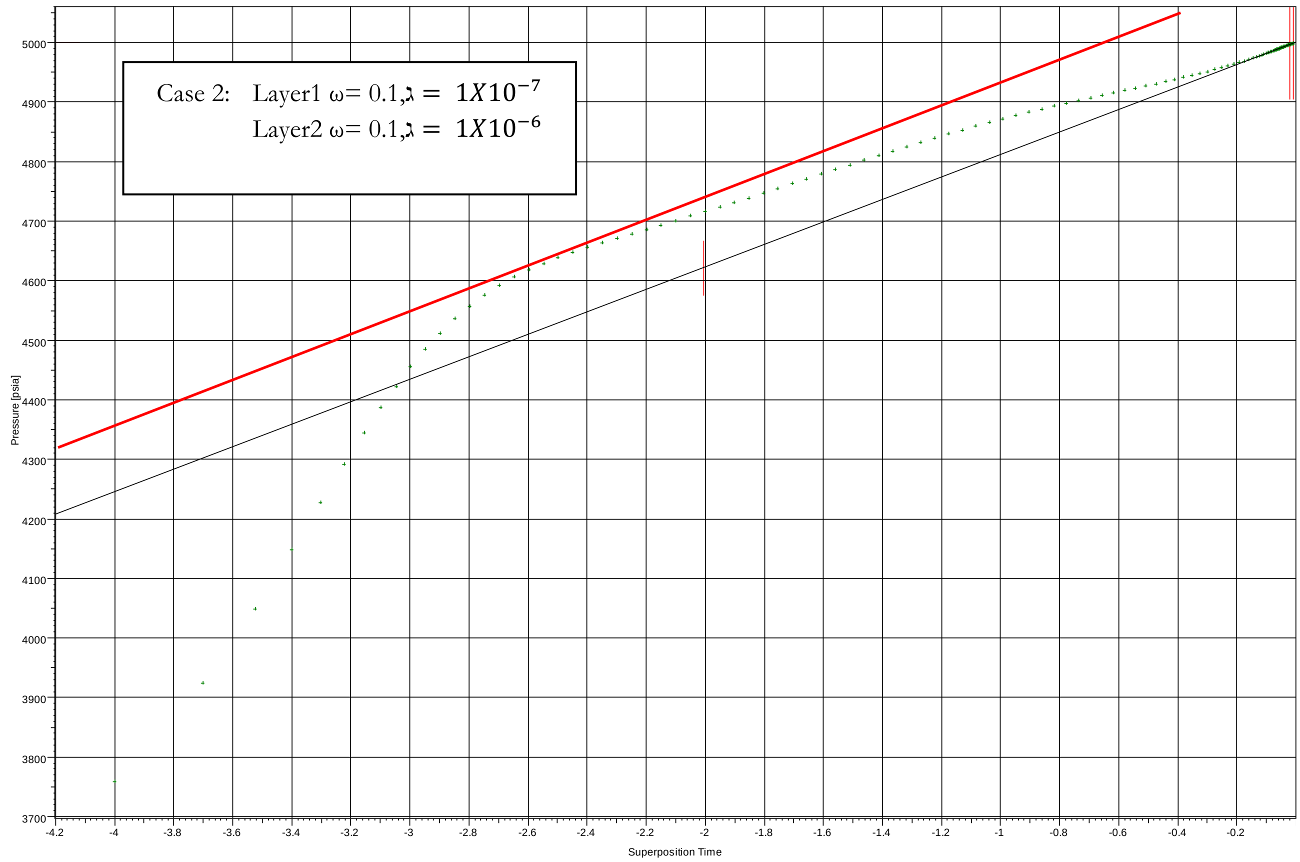

Figure 6.21: Two fractured layers (λvariation) with no cross flow analysis

Table 6.16: Two fractured layers (λ variation) with no cross flow analysis results

Name	Value	Unit
C	0.01	bbl/psi
Pi	5000	psia
Derived & Secondary Parameters		
Rinv	16100	ft
Test. Vol.	3936.9	MMB
Delta P (Total Skin)	0	psi
Semilog Line (Landa-7_No_CrossFlow build-up #1)		
From	2289.57	hr
To	4508.07	hr
Slope	188.702	psi
Intercept	5000	psia
P@1hr	4621.78	psia
PMatch	0.0061	[psia]-1
k.h	5560	md.ft
k	18.5	md
p*	5000	psia
Skin	0.05	--
Delta P Skin	8.19931	psi

Table 6.17: Two fractured layers (ג variation) with cross no flow analysis results

$\overline{K}$ (md)	19
Calc k (md)	18.5
Slope (m)	188
δP	123
ω (Calculated)	0.22

6.3.3 Cross flow

In this case, a two-layer reservoir model is considered. One vertical producing well is completed across both layers. Both of the layers are fractured. Table 6.18 shows the properties of each layer, while Table A.1 shows the fluid properties and Figure 6.22 shows a schematic of the total system. Table A.2 and Table A.3 show detailed parameters used to calculate ω and **ג**.

In this case, both layers are contributing with cross flow between them. The leakage factor is set to 50%. This case investigates the impact of the variation of lambda (ג) in the low permeability fractured layer.

Three numerical models were built for this case using Saphir software. The first fractured layer has lower permeability than the second fractured layer. Variation of ג is carried out in the first low permeable fractured layer.

Figure 6.23 shows the results of these models.

Table 6.18: Layers properties of two fractured layers (ג variation) with cross flow

	Layer Type	Permeability (md)	Porosity (%)	Thickness ft	ω	ג
Case 1	Fractured	10	10	270	0.1	$1X10^{-6}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 2	Fractured	10	10	270	0.1	$1X10^{-7}$
	Fractured	100	10	30	0.1	$1X10^{-6}$
Case 3	Fractured	10	10	270	0.1	$1X10^{-8}$
	Fractured	100	10	30	0.1	$1X10^{-6}$

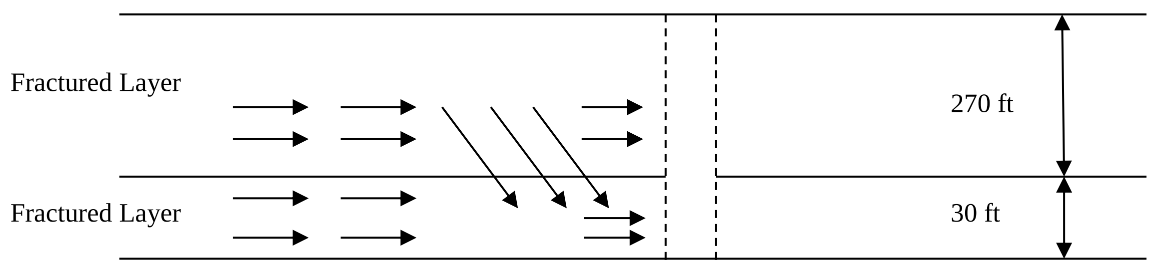

Figure 6.22: Schematic of a two-layer reservoir of two fractured layers (ג variation) with crossflow

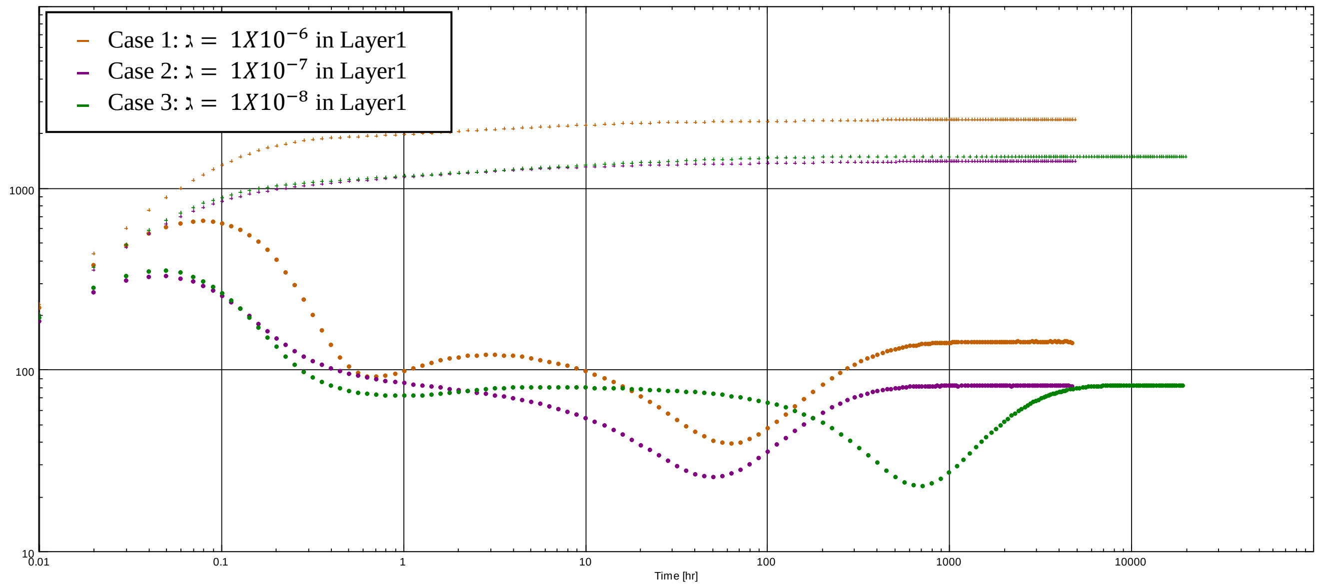

Figure 6.23: Two fractured layers (λ variation) with cross flow

6.3.4 Case results analysis (Crossflow)

Analysis of this model shows that the pressure response of both fractured layers acts like one single fractured layer when λ is the same in both fractured layers. Both of the layers are contributing almost at the same time. The low permeable layer is contributing to the wellbore and to the high permeability layer. When λ is decreased in the low permeable layer, the fluid exchange between the fractures and the matrix is lower. This causes a delay in the low permeability fractured layer contribution and this is why the pressure derivative shows a dip at first reflecting the transition period of the high permeable fractured layer and then after that, another dip is seen reflecting the transition period of the low permeable fractured layer followed by final flattening pressure derivative reflecting the total system response.

Al-Ghamdi et al. [17] presented the expected behavior when λ is varied where the matrix and microfracture contribute to the macrofractures and the macrofractures only flow to the wellbore. As λ decreases, the dip reflecting the transition, following the fractures response, shifts to the right. This is similar to what is found in this model. The lower permeability fractured layer transition period represented by the second dip is delayed when λ decreases.

Analysis of the model where the low permeability fractured layer $\lambda = \mathbf{1X10^{-7}}$ and the high permeability fractured layer $\lambda = \mathbf{1X10^{-6}}$ has been carried out, and is demonstrated in Figure 6.24 and Table 6.20. The results of the analysis are shown in Table 6.19. As a result of the analysis, the calculated permeability is almost equal to the input system permeability. However, similar to the previous case where there is no cross flow, it seems that the change of λ is affecting the total system ω, since the input ω = 0.1, while the calculated ω = 0.24 from the analysis.

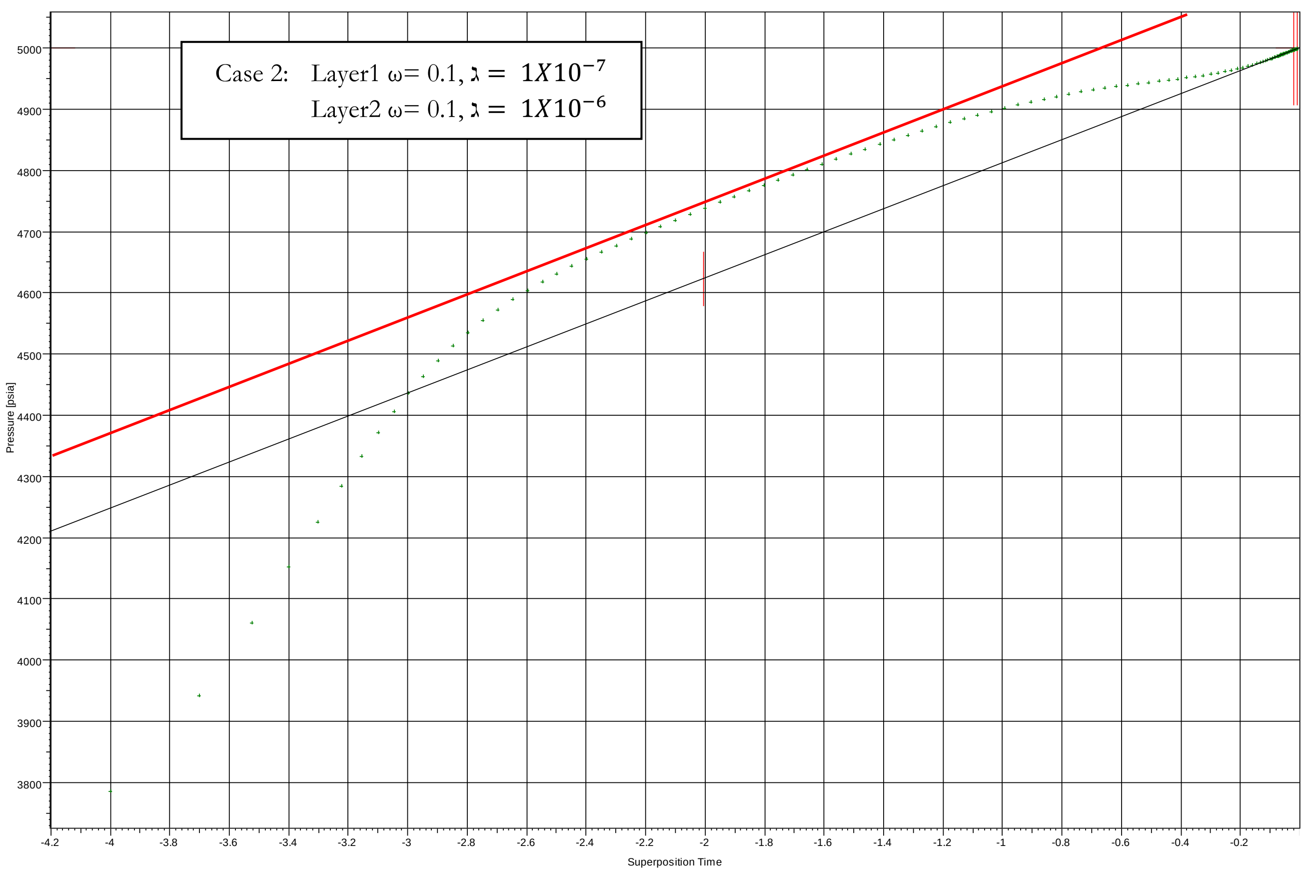

Figure 6.24: Two fractured layers (λ variation) with cross flow analysis

Table 6.19: Two fractured layers (ג variation) with cross flow analysis results

Name	Value	Unit
C	0.01	bbl/psi
Pi	5000	psia
Derived & Secondary Parameters		
Rinv	16100	ft
Test. Vol.	3936.9	MMB
Delta P (Total Skin)	0	psi
Semilog Line (Landa-7_With_CrossFlow build-up #1		
From	2034.57	hr
To	4508.07	hr
Slope	188.03	psi
Intercept	5000	psia
P@1hr	4623.12	psia
PMatch	0.00612	[psia]-1
k.h	5580	md.ft
k	18.6	md
p*	5000	psia
Skin	-0.118	--
Delta P Skin	-19.2857	psi

Table 6.20: Two fractured layers (ג variation) with cross flow analysis results

$\overline{K}$ (md)	19
Calc k (md)	18.6
Slope (m)	188
δP	116
ω (Calculated)	0.24

6.4 General comparison between no cross flow and cross flow cases in the two fractured layered models

Models and analysis for the two fractured layers with cross flow and without cross flow were discussed in the previous section. The discussion and analysis included the results of variation of ω and λ and their effect on the pressure transient behavior.

In this section, a comparison is done between the cross flow and no cross flow models when both ω and λ are varied.

6.4.1 Two fractured layers (ω variation) with and without cross flow

Figure 6.25 shows all the models with cross flow and without cross flow, with the variation of ω in the low permeable fractured layer. When there is no cross flow between the low and high permeability fractured layers (with variation of ω in the low permeable layer), the effect and contribution of the fractures in both layers happen in the same time since both of them flow to the wellbore only in the same time. For low value of ω (0.01) in the low permeability fractured layer, the two layers act like one system and their response is similar to that one of one single fractured layer. As ω increases in the low permeable fractured layer, the dip tends to flatten more and more.

On the other hand, when there is crossflow between the two layers, the pressure response shows a dip which is a signature of the high permeability fractured layer response which is reflecting the transition period of that layer where the matrix starts flowing into the factures. The presence of wellbore storage at early time masked the flat line corresponding to the fractures response of that layer. Then, the first dip is followed by another flat line reflecting the high permeability fractured layer total response. After that, the lower permeability fractured layer response is observed. The response of that layer is reflected by the second dip where the dip represents the transition period of that layer which corresponds to the flow from its matrix into the fractures. This is followed by a final flat line reflecting the total system response.

Lower ω in the low permeability fractured layer causes the second dip (which reflects the transition period of the lower permeability fractured layer) to be sharper. This is due to the lower storage of the fractures in the low permeability fractured layer resulting in longer transition period. Increasing ω causes the second dip to be shallower, with no effects on the first dip that reflects the transition period of the high permeability fractured layer.

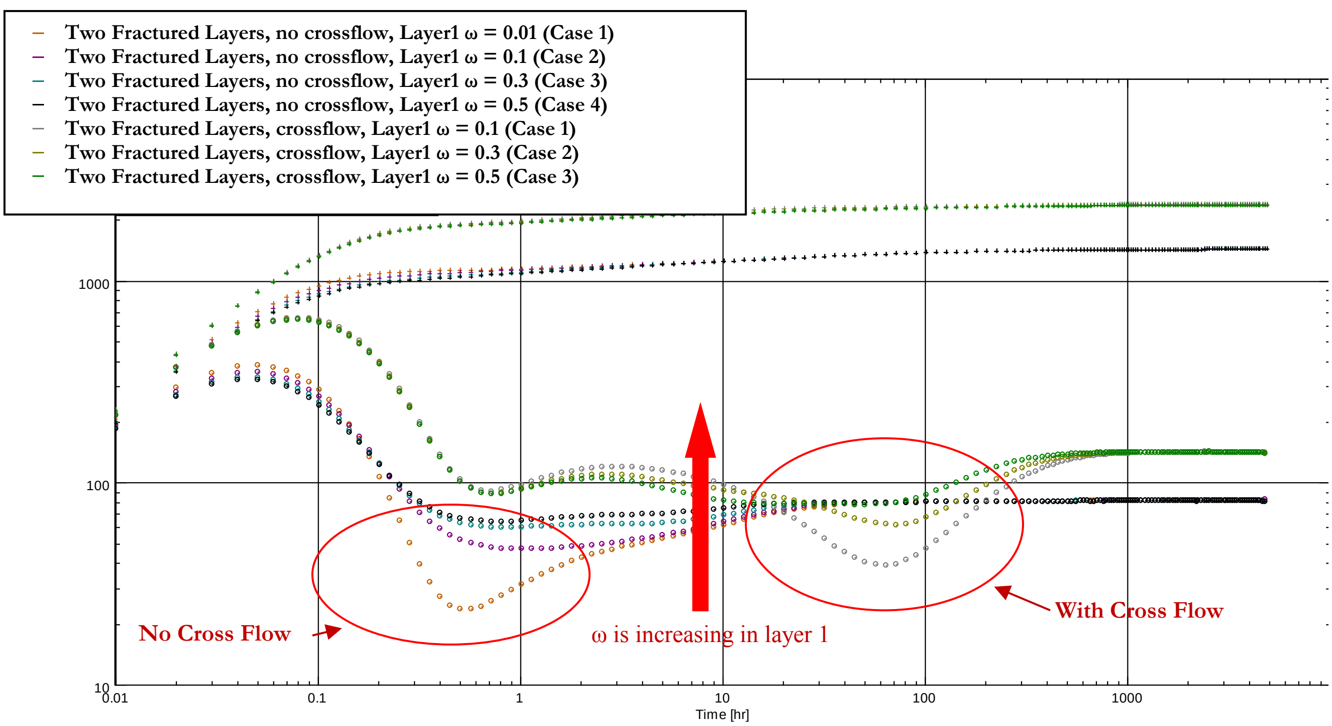

Figure 6.25: Two fractured layers (**ω** variation) Comparing Cross flow with no Cross Flow

6.4.2 Two fractured layers (λ variation) with and without cross flow

Figure 6.26 shows all the models with and without cross flow, with variation of λ in the low permeability fractured layer. As mentioned earlier, lowering λ in the low permeability fractured layer will cause a delay in the second layer response and will shift the second dip to the right due to the low fluid exchange between the matrix and the fractures. As the models show, the cross flow affects the contribution of the low permeable fractured layer since it flows to the wellbore and to the high permeability fractured layer too, causing the low permeability fractured layer transition period to be longer. In other words, the communication between the fractures and matrix is lower when there is cross flow since the matrix is exchanging flow with the fractures, and at the same time with the other layer. This causes the second dip in the pressure derivative to be shallower in the case of cross flow compared to the no cross flow case.

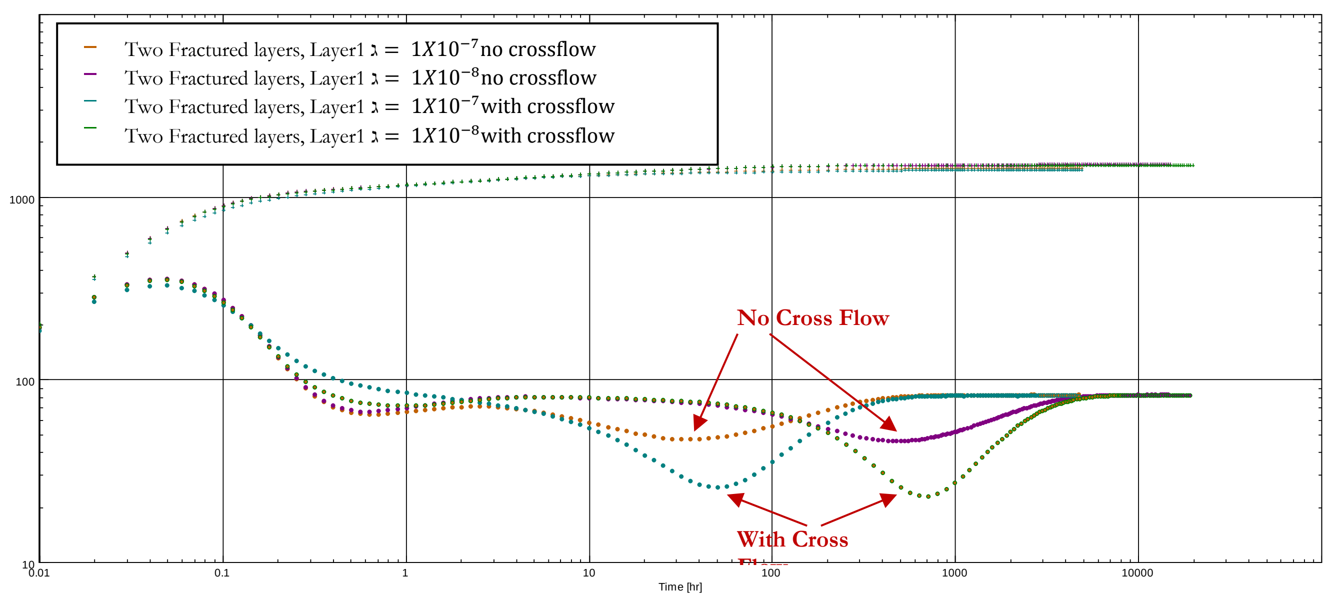

Figure 6.26: Two fractured layers (λ variation) Comparing Cross flow with no Cross Flow

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

Several numerical models have been constructed using Saphir software to simulate the different cases of a multilayer system. Those models have been used to investigate the effect of reservoir parameter variation on the transient pressure behavior including variation of permeability in homogeneous layer, and the variation of ω and λ in the fractured layer. The following are some conclusions drawn from this work:

1. In a two layered reservoir where one of the layers is homogeneous and the other one is fractured, and where there is no cross flow between layers, the following conclusions can be drawn:
    a. When the permeability of the homogeneous layer is low, the system behaves as if it is single fractured layer.
    b. When the permeability of the homogeneous layer is high, the system behaves as a single homogeneous layer.

2. In a two layered reservoir where one of the layers is homogeneous and the other one is fractured, and where there is cross flow between layers, the following conclusions can be drawn:
    a. When the permeability of the homogeneous layer is low, the pressure derivative response shows two dips. The first dip represents the transition period of the high permeability fractured layer where the matrix of the high permeability

layer starts flowing into the fractures. The second dip represents the response of the low permeability homogeneous layer flowing into the high permeability fractured layer and to the wellbore.

b. When the permeableability homogeneous layer is high, the pressure response behaves similar to the single fractured layer with high ω.

3. In a two layered reservoir where both layers are fractured and there is no cross flow between layers, the fractures in both layers flow simultaneously to the wellbore at early time. For each layer, its matrix flows to the layer's fractures only since there is no crossflow between the layers. Due to that, the two layers' pressure response is similar to that one of a single fractured layer for low values of ω (0.01) in the low permeability fractured layer. When ω increases in the low permeability fractured layer, the fractures flow to the wellbore for longer time since the fractures have more storage. Due to that, the dip tends to flatten compared to the sharp dip of the one-layer fractured system. Therefore, as ω increases in the low permeability fractured layer, the dip tends to flatten more and more which results in less transition period.

4. In a two layered reservoir where both layers are fractured and there is cross flow between layers, two dips are observed on the pressure derivative where the first one reflects the transition period of the high permeability fractured layer and the second one reflects the transition period of the low permeability fractured layer. Lower ω in the low permeability fractured layer causes the second dip to be sharper (longer transition period due to low ω) with no effect on the pressure derivative response of the high permeability fractured layer. Increasing ω causes the dip to be shallower

(shorter transition period due to high ω) with no effect on the pressure derivative response of the high permeability fractured layer.

5. In a two layered reservoir where both layers are fractured and there is no cross flow between layers, the pressure response shows that both layers are contributing at the same time when λ is the same in both layers ($\lambda = 1X10^{-6}$). Because λ is the same, only one dip is seen. With lower λ, the pressure derivative shows two dips where the first dip reflects the transition period of the high permeability fractured layer and the second dip reflects the transition period of the low permeability fractured layer. When λ decreases in one of the layers, this causes the transition period to be longer and it delays the response of the low permeable fractured layer.

6. In a two layered reservoir where both layers are fractured and there is cross flow between layers, the pressure derivative of both fractured layers acts like one single fractured layer when λ is the same in both layers. When λ is decreased in the low permeability fractured layer, this causes a delay of the low permeability fractured layer contribution. This delay shifts the second dip (which reflects the low permeability fractured layer transition period) to the right. This is due to the lower fluid exchange between the matrix and the fractures of that layer which resulted in taking longer time to observe the response of that layer.

7. The design of the well test in 2-layer systems is very important. If the well is not flowed for enough time or the test and data gathering for the shut-in period is stopped earlier than needed, this may lead to wrong test results and wrong estimates of the layers properties especially the estimation of **ω.**

7.2 Recommendations

To completely understand the effect of natural fractures on the pressure transient behavior of layered reservoirs, it is recommended to further investigate the following:

1. Investigate the effect of partial penetration on the pressure transient behavior of fractured multi-layer system with variation of ω and λ of the layers. Investigate the effect of the leakage factor between the layers.
2. Investigate the effect of fractured multi-layer system for the case of horizontal well with variation of ω and λ of the layers on the pressure transient behavior of horizontal well. Investigate the effect of the leakage factor between the layers.

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APPENDIX

Table A.1: Fluid properties and general parameters

Property	Value
Oil compressibility c_o, psi^{-1}	$3X10^{-6}$
Oil viscosity μ, cp	1
Oil formation volume factor B_o, RB/STB	1.29
Initial reservoir pressure, psi	5000
Producing time (hours)	100
Shut-in time (hours)	5000
Total oil rate (bbl/d)	5000
Skin	0
Wellbore storage	Constant

Table A.2: Parameters for ω calculation

ω	φ_f	c_f (psi^{-1})	φ_m	c_m (psi^{-1})
0.01	0.02	$1.25X10^{-7}$	0.08	$3X10^{-6}$
0.1	0.02	$1.3X10^{-6}$	0.08	$3X10^{-6}$
0.3	0.02	$5.11X10^{-6}$	0.08	$3X10^{-6}$
0.5	0.02	$1.2X10^{-5}$	0.08	$3X10^{-6}$

Table A.3: Parameters for λ calculation

λ	r_w (ft)	k_m (md)	k_f (md)
$1X10^{-6}$	0.3	2.35	25000
$1X10^{-7}$	0.3	0.33	35000
$1X10^{-8}$	0.3	0.047	50000

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