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Analysis of Pressure Data from The Horizontal Wells with Multiple Hydraulic Fractures in Shale Gas

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Abstract

In the last several years, the unconventional gas reservoirs development has grown tremendously. Most of these unconventional reservoirs have very low permeability and are not able to produce an economic flow rate without stimulation treatments. The common method to improve the production is by a horizontal well with multiple hydraulic fractures. Hydraulic fracturing is a stimulation practice to improve the permeability in order to obtain commercial production. Horizontal wells with multiple hydraulic fracture treatments have proven to be an effective method for development of unconventional reservoirs.

The objective of this paper is to investigate the interpretation of pressure transient responses from horizontal wells with single and multiple hydraulic fractures using the commercial reservoir simulator. In addition, the paper will focus on identifying the impact of the reservoir and fracture properties on the flow regimes of a horizontal well producing from the low permeability reservoirs. The different flow regimes appear during horizontal-well transient flow. However, the existence of these flow regimes is closely associated with the dimensions of the half length of the fracture, fracture permeability, drainage area, horizontal well length, etc. Hence, it is common that some flow regimes are not present.

Keywords: Induction machine, diagnostics, current spectrum, harmonics.

Nomenclature

F_{cd}	*Dimensionless Fracture Conductivity*
H	*Reservoir thickness, ft*
k	*Reservoir permeability, md*
k_f	*Fracture permeability, md*
K_x	*Reservoir permeability in X-direction, md*
K_y	*Reservoir permeability in Y-direction, md*
K_z	*Reservoir permeability in Z-direction, md*
L	*Reservoir Length, ft*
L_w	*Horizontal well length, ft*
P_{wf}	*Wellbore pressure, psia*

P_i	*Initial reservoir pressure, psia*
s	*Skin factor*
Δt	*Time, days*
W	*Reservoir width, ft*
w_f	*Fracture width, ft*
x_f	*Fracture half length, ft*
ΔP	*Pressure change, psia*
ΔP`	*Pressure derivative*

1. Introduction

Pressure transient analysis is now commonly accepted for evaluating the well performance and reservoir characteristics. In this paper, a reservoir simulation model was constructed to identify the effect of the multiple hydraulic fractures on horizontal well flow regime in unconventional reservoirs. In addition, the impact of the reservoir and hydraulic fracture properties were investigated. The flow regimes can be characterized by the slope of the plot of pressure change and its derivative versus time on diagnostic plot. In addition, these flow regimes are affected by reservoir parameters and fracture properties such as half-length of fracture, fracture permeability, drainage area, horizontal well length, etc. Hence, one or more flow regimes may not be present under certain conditions.

1- Hydraulic Fracturing of Horizontal Well

The main objective of the fractured a horizontal well is to improve the production capability of the well to achieve commercial flow rates as well as to prevent the damage around the wellbore. Hydraulic fracturing is a formation stimulation practice used to create additional permeability in a producing formation. By creating additional permeability, hydraulic fracturing facilitates the migration of fluids to the wellbore for purposes of production [1].

Hydraulic fracturing involves pumping of a fluid into a formation at a calculated, predetermined rate and pressure to generate fractures or cracks in the target formation. For shale gas development, fracture fluids are primarily water-based fluids mixed with additives which help the water to carry sand propant in the fractures. The sand propant is needed to "prop" open the fractures once the pumping of the fluids is stopped. Once the fracture has initiated, additional fluids are pumped into the wellbore to continue the development of the fracture and to carry the propant deeper into the formation. Additional fluids are needed to maintain the downhole pressure necessary to accommodate the increasing length of the opened fracture in the formation [2].

Flow Regimes for Fractured Horizontal Well

There are different flow regimes that may be present in horizontal well with single or multiple hydraulic fractures as shown in Figure 1.

1. Fracture Radial Flow
2. Radial-Linear Flow
3. Formation Linear Flow
4. Bilinear Flow
5. Pseudo-Radial Flow
6. Compound Linea Flow (Trilinear Flow)
7. Compound Pseudoradial Flow

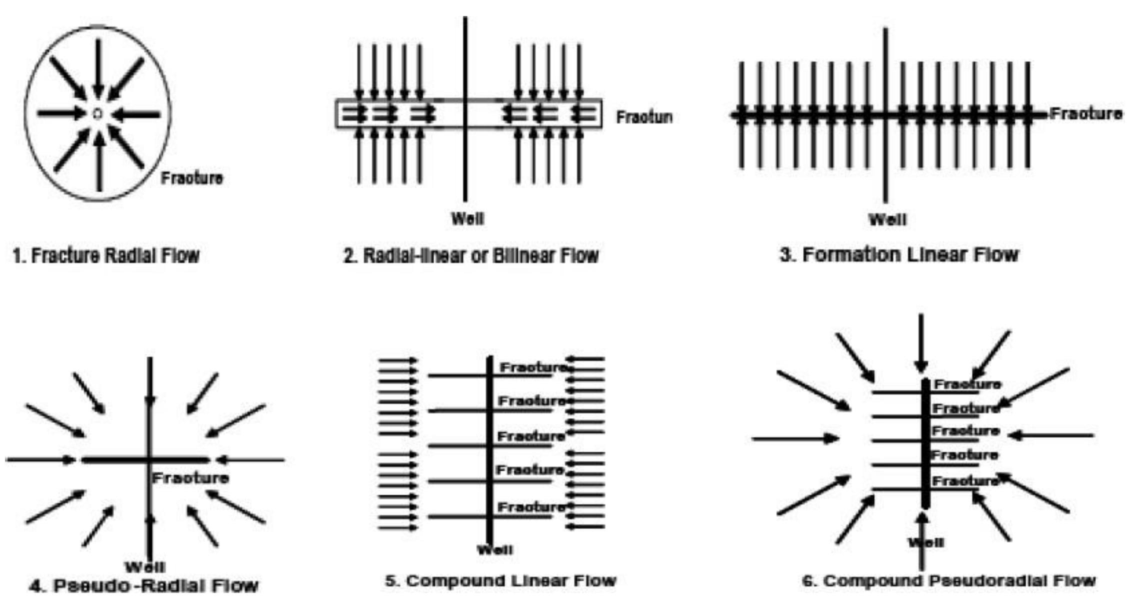


Figure 1. Flow regimes for fractured horizontal wells [6]

1. Fracture Radial Flow

Larsen and Hegre [3] found that, during this flow period, the production only is coming from the fracture. The fracture radial flow usually is masked by wellbore storage. It is characterized by a zero slope on the log-log graph. The duration of the fracture radial flow is usually very short.

2. Radial-Linear Flow

The radial-linear flow is usually encountered very early in time and it will most likely be masked by the presence of wellbore storage. The flow period is called radial-linear flow because the flow is radial towards the wellbore in the fracture and linear towards the fracture surface in the formation.

3. Bilinear Flow

The bilinear flow is present whenever most of the fluid entering the wellbore comes from the formation and fracture tip effects have not yet affected the well behavior. The bilinear flow is exhibited by finite conductivity fractures, (C_{fd}<100). This flow regime has two linear flows occurring simultaneously, one of the linear flows is in the fracture and the other linear flow is in the formation. During the bilinear flow period, (Δp) is the linear function of ($t^{1/4}$) on Cartesian coordinate paper. A log-log plot of (Δp) as a function of time exhibits a slope of one-quarter; the derivative also has a slope of one-quarter during this time period [4].

4. Formation Linear Flow

The formation linear flow occurs when horizontal linear flow in the formation is towards the fracture and incompressible flow behavior in the fracture. The formation linear flow is exhibited by high conductivity fracture (C_{fd} > 100). On Cartesian coordinate paper, (Δp) is a linear function of ($t^{1/2}$), and log-log plots of both (Δp) and pressure derivative as a function of time exhibits a slope of one-half [3,4].

5. Pseudo-Radial Flow

Pseudo-radial flow is very similar to the radial flow which commonly occurs in the reservoir. It usually takes a significant amount of time to be present. Pseudo-radial flow occurs as soon the reservoir has stabilised and behaves like a common reservoir. It is characterized by a zero slope on the log-log graph.

6. Compound Linear Flow (Trilinear Flow)

Brown [5] explained the concept of the trilinear flow for fractured horizontal wells. They indicated that the basis of the trilinear flow is the productive life for hydraulically fractured wells dominated by linear flow regimes, as shown in Figure 2. The trilinear flow couples three linear flow regions, including the outer reservoir beyond the tips of the hydraulic fractures, inner reservoir between the hydraulic fractures, and the hydraulic fracture.

7. Compound Pseudoradial Flow

The Compound Pesudoradial flow couples radial flows in two contiguous flow regions, the outer reservoir beyond the tips of the hydraulic fractures and the inner reservoir between hydraulic fractures. Due to the nature of horizontal wells, it might be very difficult to economically produce till the production flow reaches a compound pseudoradial flow.

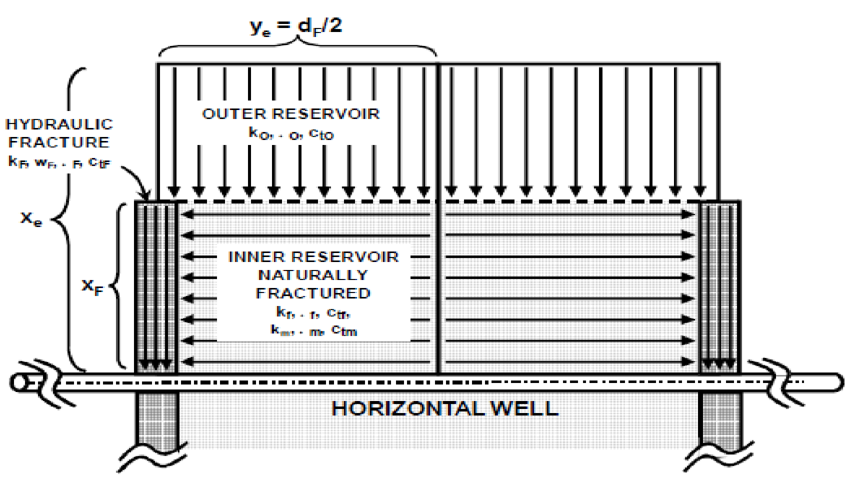


Figure 2. Trilinear flow regimes for multiple fractured horizontal well [5]

2. Objective and Methodology

The objective of this paper is to analyze the impact of the reservoir and the fracture properties of horizontal well on flow regimes. The following methodology was employed to achieve the objectives:

- A numerical reservoir model was developed to predict the pressure as a function of time.
- The impact of the number of hydraulic fractures on flow regimes was investigated.
- The impact of the fracture properties on flow regimes was investigated.
- The impact of reservoir properties on the flow regimes was investigated.

1. Numerical Models

The Eclipse was used in this study to develop the numerical reservoir model. The model was developed with a horizontal well and multiple hydraulic fractures in a very low permeability reservoir. In addition, the model consisted from five layers. The reservoir model is produced at a constant rate for one year. Table 1 shows the parameters and values in the base model and Table 2 shows the ranges of value used in the model. Figures 3 and 4 illustrate the two base models used in this study.

2. Base Model Parameters and Assumptions

In order to understand the impact of different reservoir and fracture parameters on the flow regimes, a series of cases (numerical reservoir models) were derived from the base case by changing a particular parameter while keeping the other parameters unchanged and were run using a commercial reservoir simulator. The following items are the reservoir and fracture parameters which impacts were studied:

i. Number of hydraulic fractures

The investigation assumes that the horizontal well was hydraulically fractured at the center of the well length (L/2) with one fracture. The base model parameters used are; drainage area = 4000 x 2000 ft^2, horizontal well length = 3000 ft, reservoir permeability (kx=ky) = 0.001 md and (Kz) = 0.0001 md, fracture half length (X_f) = 500 ft, the fracture width (w_f) =0.1 inch, fracture permeability (k_f) = 10,000 md and the fracture porosity is 10%. Also, more than one fracture were added to the model to see how the results may change based on the number of the fractures in the horizontal well.

ii. Reservoir permeability

To study the impact of the permeability on flow regimes, few more cases were run with lower permeability values in x, y, z directions. The reservoir permeability were 0.0001 md in x and y directions and 0.00001 md in z directions. Also, this case used for different numbers of hydraulic fractures.

iii. Fracture width

In order to investigate the impact of the fracture width on flow regimes, the lower fracture width was used, w_f = 0.01 inch. This case was run in different values of reservoir permeability, kx= 0.001 md and 0.0001 md.

iv. Drainage area and horizontal well length

The drainage area and the horizontal well length configuration are considered in this section, the drainage area was to 4000 ft in length and 1000 ft in width with the horizontal well length of 4000 ft as shown in Figure 4. This case was run with different values of the reservoir permeability. kx = 0.001 md and 0.0001 md.

v. Fracture permeability

Two different values of fracture permeability were used in this study. 10,000 md and 40,000 md..

vi. Fracture half length

To examine the impact of the fracture half-length on flow regimes, two values of fracture half-length were used – 300 ft and 500 ft.

vii. Fracture porosity

The fracture porosity was varied from 5% to 50%.

Every derived case was run for the number of hydraulic fractures of 1, 2, 3, 4, 7, and 13 except the cases where fracture permeability, fracture half length, and fracture porosity were studied. Pressure derivative vs. time plot was used for all above cases. In addition, these cases were run at base model parameters that are mentioned in Table 1.

3. Data Analysis

Five-point method was used to estimate the derivative pressure as shown in Figure 5. The following procedure used to identify the flow regimes in this study:

- Plot pressure derivative versus time on log-log plot (Diagnostic Plot). The slopes of the pressure derivative curve are mainly used to identify flow regimes.
- Identify fracture radial flow when zero slope straight line appears
- Identify bilinear flow when a quarter-slope straight line appears.
- Identify the formation linear flow when a half-slope straight line appears
- Identify the start of transitional flow at the end of first formation linear flow and the beginning of second formation linear flow.

Table 1. Parameters and values used in the base model

Reservoir Parameters	
Period of production (years)	1 year
Grid size (ft)	100x100
Model Geometry	Multilayer Reservoir (5 layers)
Shape	Rectangular
Depth, ft	7,000
Reservoir length, ft	4,000
Reservoir width, ft	2,000
Horizontal well length, ft	3,000
Thickness, ft	100
Rock Properties	
Porosity Type	Single
Reservoir porosity, fraction	0.05
X-direction Permeability (md) Y-direction Permeability (md) Z-direction Permeability (md)	0.001 0.001 0.0001

Compressibility, 1/ psia	$1x10^{-6}$
Density, lb/ft^3	150
Initial Conditions	
Reservoir pressure, psia	3,000
Water saturation, fraction	0.15
Hydraulic Fracture Properties	
Half length, ft	500
Width, inch	0.1
Top of fracture, ft	7,000
Bottom of fracture, ft	7,100
Permeability, md	10,000
Porosity, fraction	0.1
Well Production Controls	
P_{wf}, psia	300
Gas flow rate, Mscfd	100
Fluid Properties	
Standard pressure, psia	14.7
Standard temperature, °F	60
Reference Temperature, °F	120

Table 2. Ranges of values used in the model

Parameters	Ranges	Used Values
Reservoir width, ft	1,000 -2,000	1,000 &2,000
Horizontal well length, ft	3,000 - 4,000	3,000 & 4,000
Horizontal permeability, md	0.001 - 0.0001	0.001 & 0.0001
Fracture half length, ft	300-500	300 & 500
Fracture Width, inch	0.01- 0.1	0.01 & 0.1
Fracture Permeability, md	10,000- 40,000	10,000 & 40,000
Fracture Porosity, fraction	0.05 - 0.5	0.05, 0.1 & 0.5
Fracture Number	1-13	1, 2, 3, 4, 7& 13

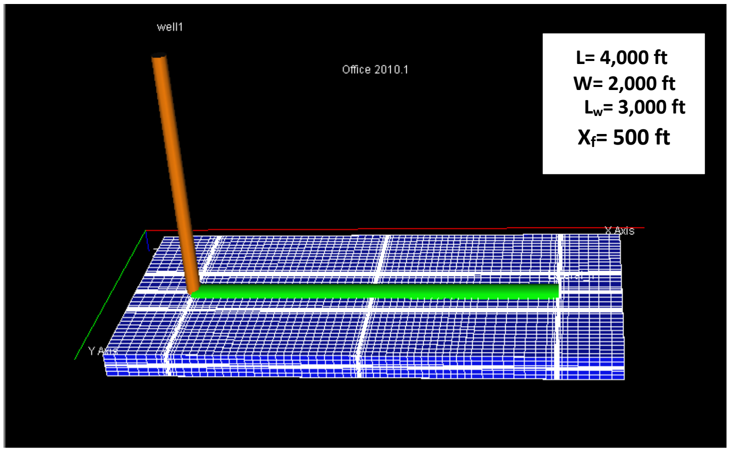


Figure 3. A horizontal well model with a 4,000 ft by 2,000 ft and well length of 3,000 ft.

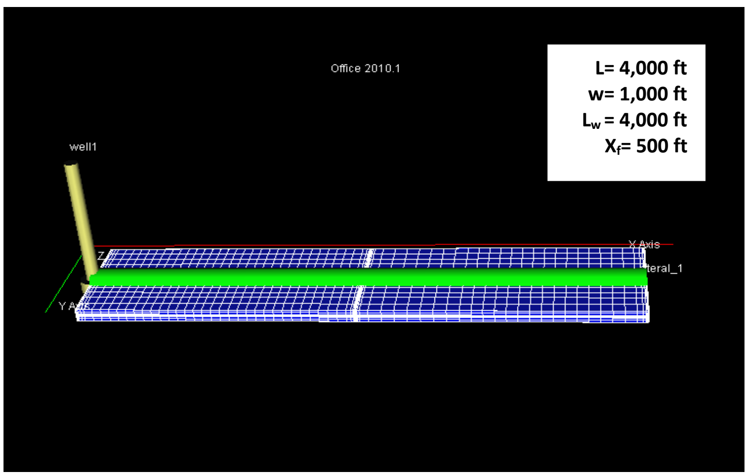


Figure 4. A horizontal well model with 4,000 ft by 1000 ft and well length of 4,000 ft

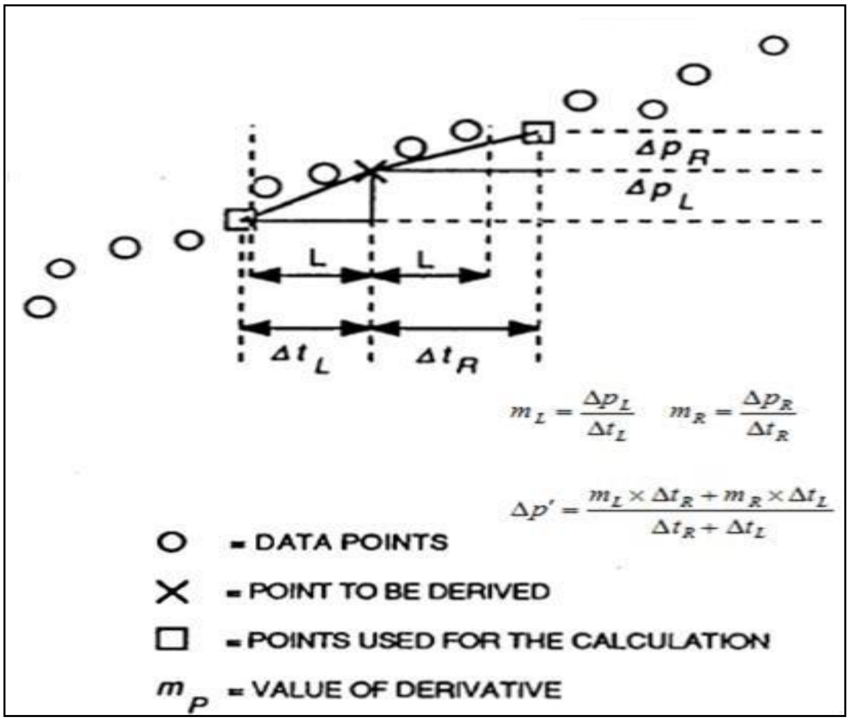


Figure 5. Five-point method for calculating the pressure derivative [4].

4. Results and Discussions

1. The Impact of the Number of Hydraulic Fractures on Flow Regimes

Figure 6 and Figure 7 show the impact of the number of hydraulic fractures on flow regime. Figure 6 is showing the plots for 1, 2, and 3 hydraulic fractures whereas Figure 7 is showing the plots for 4, 7 and 13 hydraulic fractures. All these plots are showing the presence of bi-linear flow (¼ slope) as well as two separate linear flow periods (½ slopes). The first linear flow is from the region between the fractures while the second one is from beyond the tip of the fracture and could be consider the compound linear flow (Trilinear flow). As the number of hydraulic fractures increases, the duration of bilinear flow as well as that of transitional flow decreases. Also the duration of transitional flow disappears at the higher number of hydraulic fractures and two separate linear flow periods coincide with each other and appear as one linear flow.

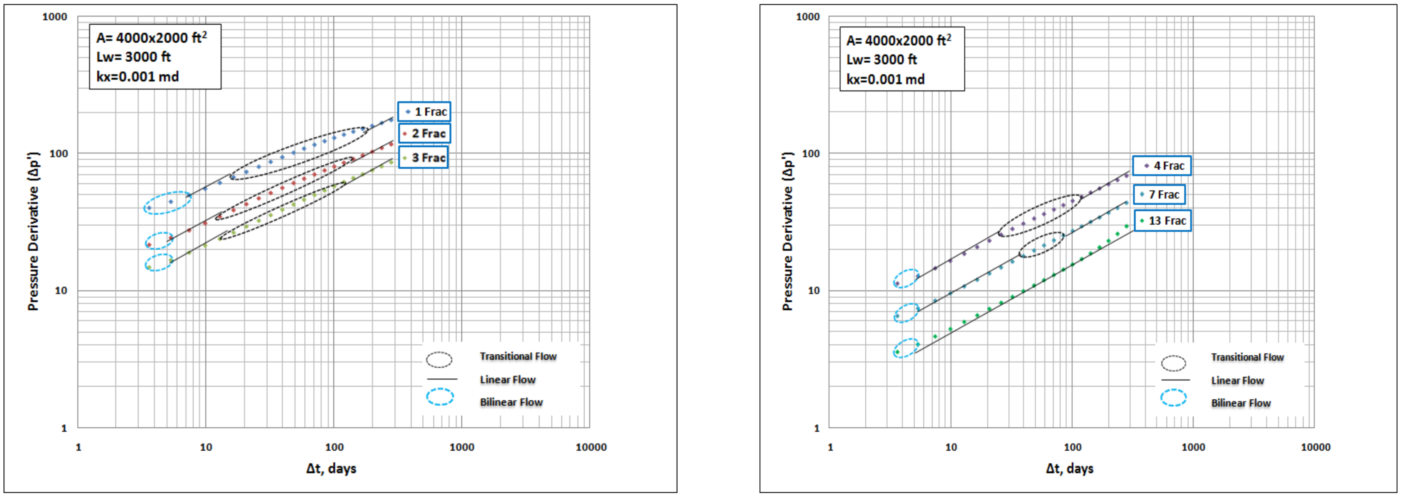


Figure 6 -7. The impact of the number of hydraulic fractures (w_f= 0.1 inch)

2. The Impact of Reservoir Permeability on Flow Regimes

Figure 8 and Figure 9 show the impact of reservoir permeability on flow regimes. For these cases, the reservoir permeability values were 0.0001 md in x and y directions and 0.00001 md in z direction. It is observed that the bi-linear flow does not appear in these cases as it did in the cases of Figure 6 and Figure 7. Thus, the decrease in the permeability diminishes the bilinear flow regimes.

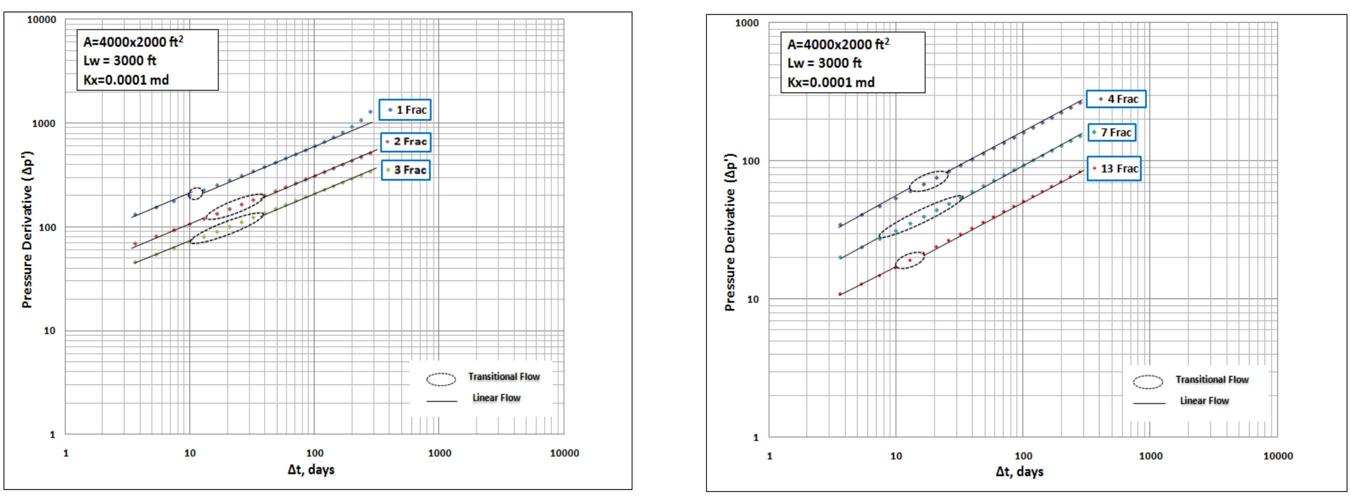


Figure 8-9. The impact of reservoir permeability (w_f= 0.1 inch)

3. The Impact of Fracture Width on Flow Regimes

The cases similar to Figure 6 through Figure 9 were run with a reduced fracture width of 0.01 inch and the results are plotted in Figure 10 through Figure 13. The fracture radial flow is observed for higher permeability cases as shown in Figure 10 and Figure 11. For the other two cases, Figure 12 and Figure 13, with lower reservoir permeabilities, no fracture radial flow is observed, but the bi-linear flow is present and it was followed by one

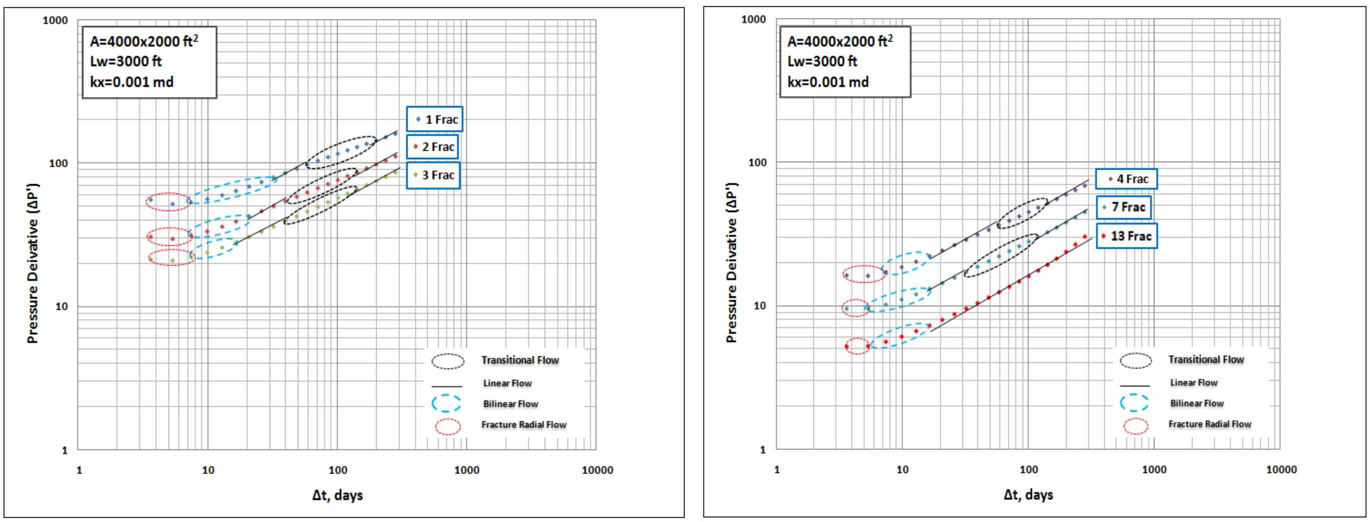


Figure 10-11. The impact of fracture width (w_f= 0.01inch)

4. The Impact of Drainage Area and Horizontal Well Length on Flow Regimes

The purpose of these runs is to investigate the second linear flow as shown in Figure 14 through Figure 17. The appearance of the second linear flow is not caused by the outer regions because the extent of the horizontal well is the same as the length of the drainage area and the extent of the fracture length is the same as the width of the drainage area. Therefore, one linear flow was perpendicular to the fracture while the other one was parallel to the fracture or perpendicular to the horizontal well. In Figure 14 through Figure 17, it is found that the second linear flows appear in the cases where the fracture numbers are less than four. When the number of fractures becomes more than four, the spacing between the fractures comes closer and only one linear flow is observed.

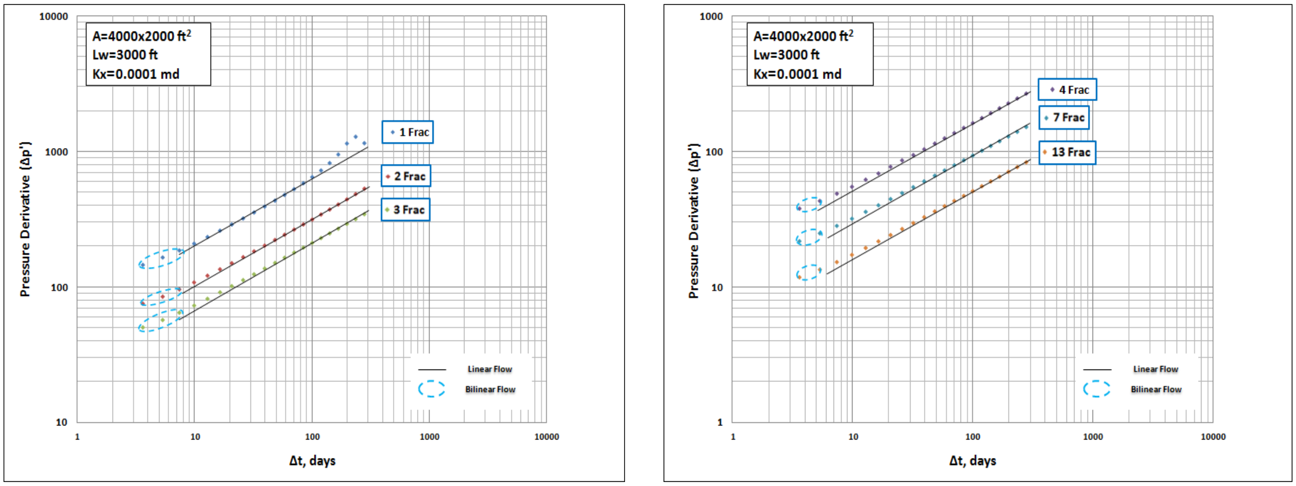


Figure 12-13. The impact of fracture width (w_f=0.01 inch)

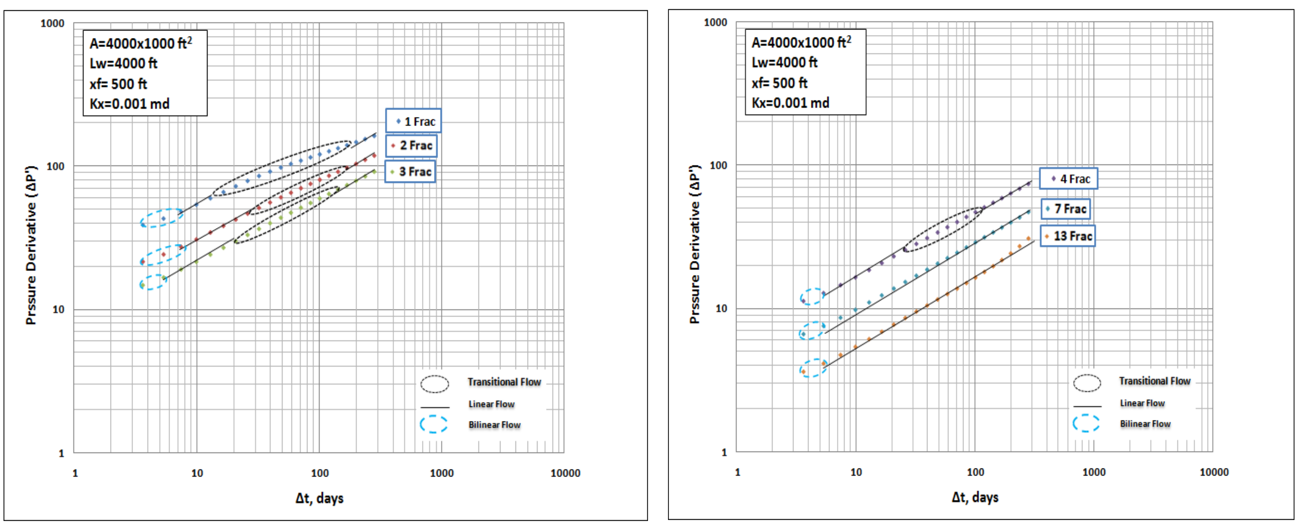


Figure 14-15. The impact of drainage area and horizontal well length (w_f=0.1 inch)

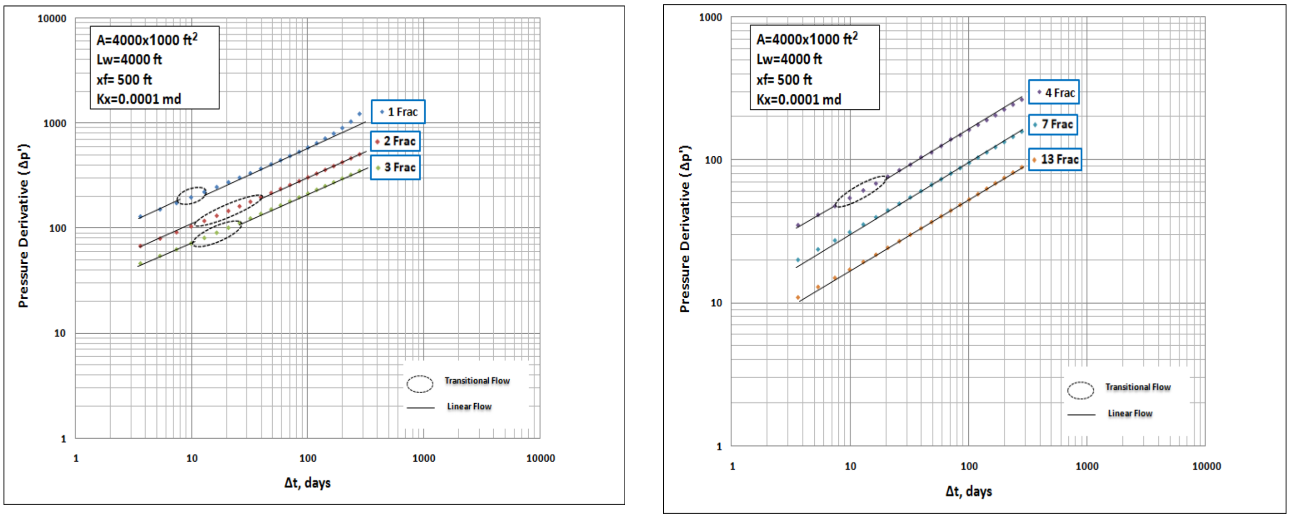


Figure 16-17. **The impact of drainage area and horizontal well length (w_f=0.1 inch)**

5. The Impact of Fracture Permeability on Flow Regimes

The fracture permeability was varied into two values – 10,000 md and 40,000 md. It was found that the fracture permeability has no impact on flow regimes. Figure 18 and Figure 19 are plotted for four and thirteen hydraulic fractures and no effect of the fracture permeability on flow regimes was observed.

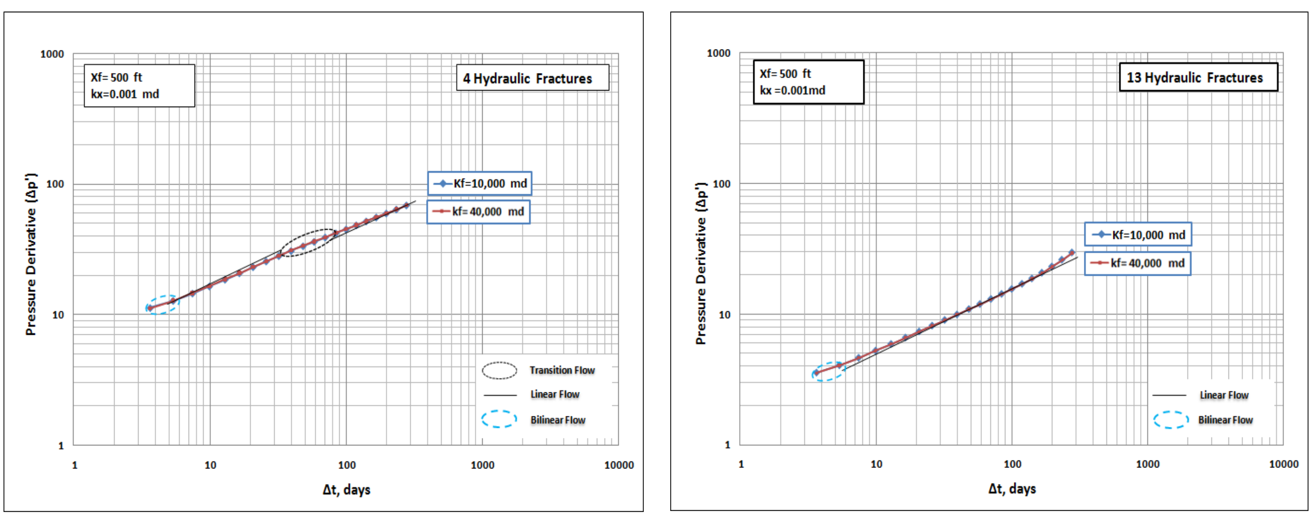


Figure 18-19. **The impact of fracture permeability on hydraulic fractures.**

6. The Impact of Fracture Half Length on Flow Regimes

Figure 20 and Figure 21 illustrate the impact of fracture half-length on flow regime; these figures explain that at a lower number (e.g. four) of hydraulic fractures, the same type of flows is observed for both fracture half lengths. However, at a higher number of fractures (e.g. thirteen), lower fracture half-length exhibits two linear flows whereas at a higher fracture half-length two linear flows overlap each other and become one linear flow.

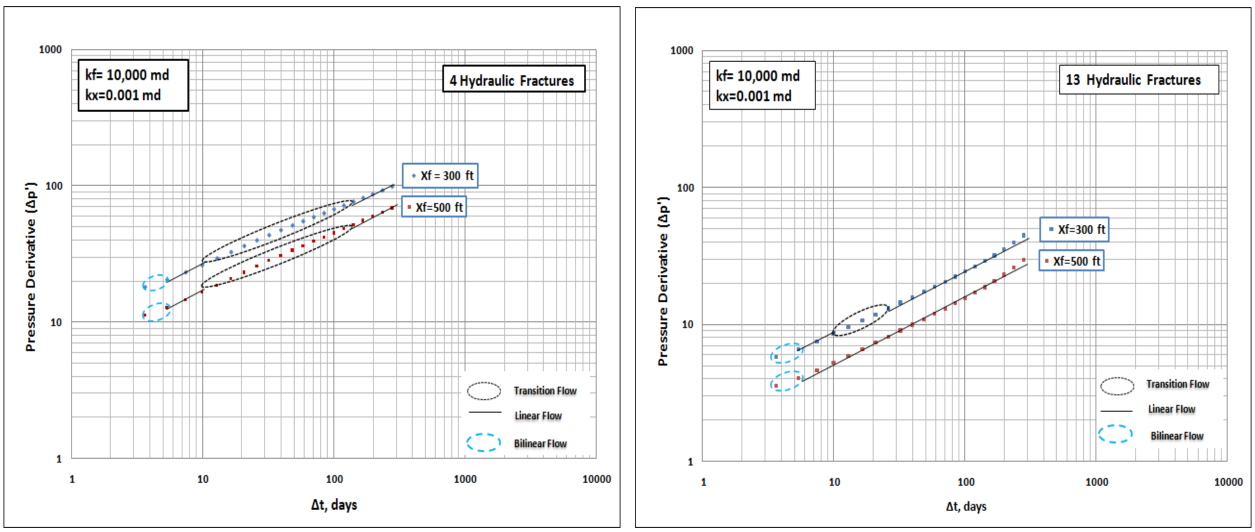
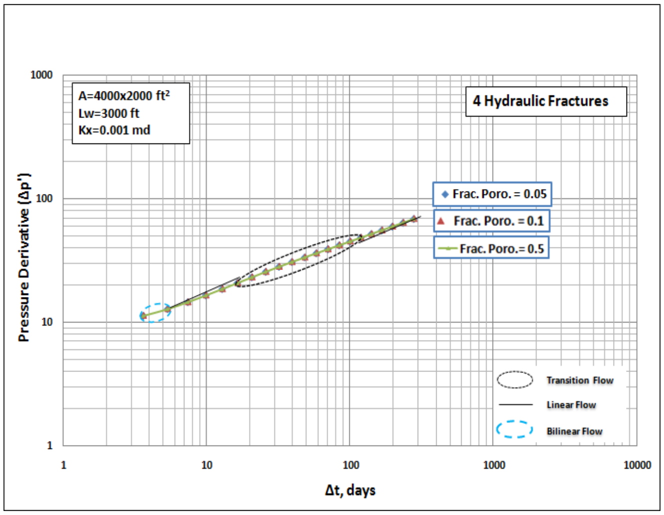


Figure 20-21. **The impact of fracture half-length on hydraulic fractures**

7. The Impact of Fracture Porosity on Flow Regimes

Figure 22 and Figure 23 show that there is no effect of fracture porosity on flow regimes with different numbers of hydraulic fractures as the curves with different fracture porosity coincide with each other. The values range used for fracture porosity is shown in Figure 22.



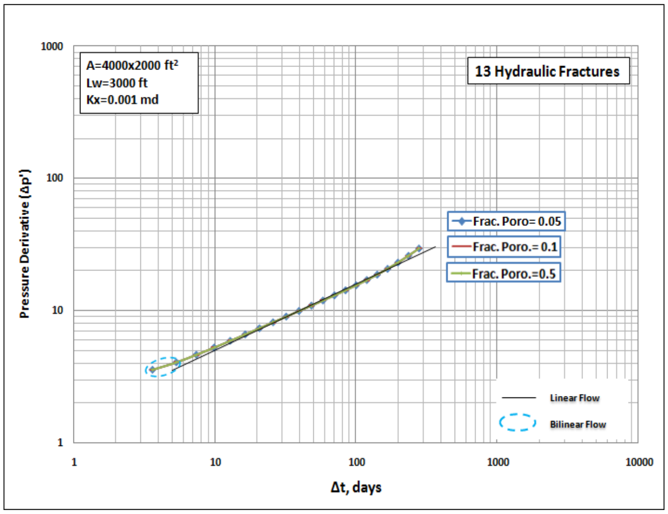


Figure *22*-23. The impact of fracture porosity on hydraulic fractures

4. Conclusion

The objective of this paper was to understand the pressure transient responses from horizontal wells with multiple hydraulic fractures. In addition, the impact of the reservoir and fracture properties in horizontally fractured wells on flow regimes in low permeability was also studied. Based on the results, the following conclusions were made:

1. Different flow regimes are observed, the fracture-radial flow, bilinear flow, linear flow and Compound linear flow.
2. The fracture radial flow appears with the decrease in fracture width.
3. The horizontal wells with a higher number of hydraulic fractures exhibit a longer linear flow period than those wells with a fewer number of hydraulic fractures.
4. Permeability and porosity of the hydraulic fracture do not have any significant impact on the flow regimes.
5. Drainage area and horizontal well length have a significant effect on flow regimes with a higher number of hydraulic fractures. When the extent of the horizontal well is equal

to the length of the drainage area and the extent of the fractures is equal to the width of the drainage area, two linear flows become one linear flow at a higher number of hydraulic fractures.

6. The increase in the number of hydraulic fractures results in the two linear flow to become one linear flow.
7. With the decrease in the permeability of the reservoir, bilinear flow tends to disappear, because of the increase in the fracture conductivity

5. References

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