Graduate Theses, Dissertations, and Problem Reports

2021

Productivity Index for Unconventional Gas Wells

Yousef Khajah
yfkhajah@mix.wvu.edu

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Part of the [Other Engineering Commons](#)

Recommended Citation

Khajah, Yousef, "Productivity Index for Unconventional Gas Wells" (2021). *Graduate Theses, Dissertations, and Problem Reports*. 7997.

<https://researchrepository.wvu.edu/etd/7997>

This Problem/Project Report is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Problem/Project Report in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Problem/Project Report has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

2021

Productivity Index for Unconventional Gas Wells

Yousef Khajah

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Part of the [Other Engineering Commons](#)

Productivity Index for Unconventional Gas Wells

Yousef F. Khajah

Report Submitted to
Benjamin M. Statler College of Engineering and Mineral Resources at West
Virginia University

In Partial fulfillment of requirements for the degree of

Master of Science

In

Petroleum and Natural Gas Engineering

Kashy Aminian, Ph.D., Chair

Samuel Ameri, Ph.D.

Ilkin H. Bilgesu, Ph.D.

Department of Petroleum and Natural Gas Engineering

Morgantown, West Virginia

2021

Keywords: Productivity Index, Unconventional Reservoirs, Horizontal Well,
Hydraulic Fracturing

Copyright 2021 Yousef F. Khajah

Abstract

Productivity Index for Unconventional Gas

Wells Yousef F. Khajah

Productivity Index reflects the ability of a well to produce hydrocarbons and is often used to analyze the well's performance. Productivity Index is the ratio of the flow rate to the drawdown pressure under pseudo-steady state flow conditions. The unconventional gas formation such as shale are the main target of the gas exploration and production. The application of horizontal drilling and hydraulic fracturing technologies have been instrumental in development of shale gas resources. The evaluation of the productivity index for unconventional gas wells is however challenging because the production mainly occurs under the transient conditions.

This research aims to evaluate the transient productivity index for a horizontal well with multiple hydraulic transverse fractures drilled in an ultra-low permeability gas formation. Additionally, the impacts of different hydraulic fractures configurations are investigated. The approach taken to conduct this research study was to build a reservoir model using CMG simulation software, identify the production periods for different flow regimes, estimate the average productivity index for the infinite-acting period, and finally perform a sensitivity analysis and compare different well configurations.

The results of the study indicate that the fracture half-length and to a lesser extent the fracture spacing impact both the duration of transient flow and the productivity index of the horizontal well. The fracture conductivity was however found to only have minor impacts on transient flow duration and the productivity index.

ACKNOWLEDGMENT

I would like to thank my research advisor Dr. Kashy Aminian for supporting me and giving me this invaluable experience. I would like to thank and acknowledge Mohamed El Sgher for his help and guidance. I would like to thank Dr. Ilkin Bilgesu for his kind help and support.

I would like to thank Dr. Samuel Ameri for his continuous support, encouragement, and for all the opportunities I was given.

I would like to express my gratitude to my parents and family. Without their support, it would be impossible for me to complete my study.

Table of contents

CHAPTER 1: INTRODUCTION	1
CHAPTER 2: LITERATURE REVIEW	2
2.1. Productivity Index	2
2.2. Pseudo-pressure.....	4
2.3. Flow Regimes.....	4
.....	5
2.5 Flow Regimes in Unconventional Reservoir.....	6
2.6. CMG Software	10
CHAPTER 3: METHODOLOGY	11
CHAPTER 4: RESULTS AND DISCUSSION	14
4.1. Base Model Results	14
4.2. Parametric Study Results	16
4.2.1. Impact of Fracture half-length.....	16
4.4 Fracture conductivity.....	23
CHAPTER 5: CONCLUSION AND RECOMMENDATION	26
References:.....	44

List of Figures

Figure 1: Productivity Index	2
Figure 2: Pressure Disturbance	5
Figure 3: Psuedo-Pressure Derivative Responses for a Horizontal well in a Homogenous Reservoir (<i>After Medeiros et al.2008</i>)	8
Figure 4: United States Shale Basins	9
Figure 5 : Marcellus and Utica Shale Formation Map	10
Figure 6: Adjusted Pressure Derivative Responses	14
Figure 7: Productivity Index	15
Figure 8: Derivative Responses for different fracture half-lengths	16
Figure 9: Productivity Index Plot for Different Fracture half-Length	17
Figure 10: Derivative Responses.....	19
Figure 11: Productivity Index Plot	20
Figure 12: Derivative Responses.....	23
Figure 13: Productivity Index Plot	24

List of Tables

Table 1: Reservoir Properties	12
Table 2 : Hydraulic Fracture Properties	13
Table 3: Parametric Studies.....	13
Table 4: Base Model Flow Periods and Productivity Index	15
Table 5: Duration of the Flow Periods	17
Table 6: Productivity Index for Different Fracture Half-Lengths	17
Table 7: PERCENT CHANGE RELATIVE TO THE BASE MODEL.....	18
Table 8: Duration of the flow periods	21
Table 9: Productivity Index For Different Fracture Spacing.....	21
Table 10: Percent change relative to Base Model	22
Table 11: Duration of the flow periods	24
Table 12: Productivity Index.....	25
Table 13: Percent change relative to Base Model	25

Nomenclature

$\overline{P_{a,R}}$	Adjusted average reservoir pressure, psi
$P_{a,wf}$	Adjusted wellbore flowing pressure, psi
P_e	External boundary radius pressure. Field units psi.
c_t	Formation compressibility, psi^{-1}
q_{sc}	Production rate at standard condition, Mscf/D
$\emptyset$	Reservoir porosity
Δ	Difference operator
A	Drainage area, ft^2
h	Reservoir thickness
T	Reservoir temperature, °F
Z	Gas-compressibility factor
G	Initial gas in place, Mscf
J	Gas productivity index, $\frac{(\frac{\text{MMcf}}{\text{day}})}{\text{psi}}$
P_a	Adjusted reservoir pressure, psi
$m(p)$	Gas pseudopressure, psi
q	Total surface flow rate at standard conditions, $\frac{\text{MMcf}}{\text{day}}$
μ	Gas viscosity, cp
t_a	Adjusted time, hours
P_a	Adjusted pressure, psi

t_{ap} Pseudo time, $\frac{hr}{cp} psi^{-1}$

P_p Pseudo pressure, $\frac{psi^2}{cp}$

CHAPTER 1: INTRODUCTION

Productivity Index, defined as the ratio of the flow rate to pressure-drawdown, is commonly used to analyze the performance of the well and predict the production rates under different conditions. It is challenging to determine the productivity index for a well completed in an unconventional reservoir because of the unsteady-state flow conditions.

The unconventional gas formations such Marcellus Shale are characterized by ultra-low permeability. One way to improve gas productivity is to drill a horizontal well. Horizontal wells allow for more contact with the formation and consequently increase the total gas production from low permeability formations. However, it is challenging to drain the ultra-low permeability reservoirs in a reasonable time frame with horizontal wells. An effective way to increase the productivity of horizontal well completed in ultra-low permeability reservoir is multi-stage hydraulic fracturing. During hydraulic fracturing water, sand, and other ingredients are injected under high-pressure to form fractures in the rock. These hydraulic fractures provide high permeability pathways for the gas to flow to the well. If these high permeability flow paths intercept the natural fractures in the formation, commercial natural gas production can be achieved from the shale (Navarro 2011).

This research aims to evaluate the impact of hydraulic fracture properties on the transient productivity index for a horizontal well with multiple hydraulic transverse fractures drilled in an ultra-low permeability gas formation. Additionally, the impacts of different hydraulic fractures configurations are investigated.

CHAPTER 2: LITERATURE REVIEW

2.1. Productivity Index

The productivity index is one of the common measurements used to evaluate a well's ability to produce hydrocarbons. It is the volume of fluid delivered per psi of drawdown at the sandface. Productivity index is the ratio of the production rate (q) at the surface to the pressure drawdown (pressure drop) at the midpoint of the producing interval, $(P_r - P_{wf})$, where P_{wf} is the flowing pressure at the wellbore, and P_e is the pressure at the external boundary (formation pressure).

Figure 1: Productivity Index

During the steady-state condition, the outer boundary pressure remains constant $P_e = P_{a,R}$ and therefore, the productivity index remains constant.

$$J = \frac{q}{(P_{a,R} - P_{a,wf})} \quad (2.1.1)$$

During pseudo-steady-state, the outer boundary pressure, P_e , decreases at the same rate as the average reservoir pressure. $\overline{P_{a,R}}$. The bottom-hole flowing pressure, $P_{a,wf}$, also decrease at the same rate as the average reservoir pressure; thus, the term in the denominator of the productivity index remains constant. As a result, The productivity index remains constant.

$$J = \frac{q}{(\overline{P_{a,R}} - P_{a,wf})} \quad (2.1.2)$$

During the unsteady-state , the productivity index is not constant.

Transient productivity index is a convenient means of discussing the productivities of Horizontal wells in tight formations (Medeiros, Ozkan, and Kazemi 2008). The cumulative productivity index can is a measure of cumulative production per average drawdown.

$$J = \frac{q}{(\overline{P_{a,R}} - P_{a,wf})} \quad (2.1.3)$$

The transient productivity index could also be evaluated using the reservoir properties as a function of gas pseudo-pressure, $m(p)$ (Medeiros, Ozkan, and Kazemi 2008). This definition is applicable to both transient and boundary-dominated flow. The average reservoir pressure can be obtained from an estimated gas in place:

$$J = \frac{q_{sc}(t)}{\Delta m(p) - \Delta m(\bar{p})} = \frac{q_{sc}(t)}{\Delta m(p) - \frac{2.356Tq_{sc}t_a}{\phi(\mu c_t)_i Ah}} \quad (2.1.4)$$

Where:

$$\Delta m(\bar{p}) = m(p_i) - m(\bar{p})$$

$$ta = \frac{(\mu c_t)_i Z_i G}{q_{sc}(t) 2p_i} [m(\bar{p}) - m(p_{wf})]$$

t_a = material balance time

2.2. Pseudo-pressure

Pseudo-pressure, P_p , accounts for the changes in gas compressibility and viscosity as a function of pressure. Adjusted pressure is used to convert the units of pseudo pressure $\frac{psi^2}{cp}$ to *psi*.

Pseudo time, t_{ap} , accounts for the changes in gas compressibility, gas viscosity, and formation porosity as a function of pressure and time. Adjusted time is used to convert the units of pseudo time $\frac{hr}{cp} psi^{-1}$ to *hours*.

The spreadsheet takes the reservoir temperature and gas gravity as inputs. For every pressure step, starting from $p' = 1 \text{ psi}$ till the specified reservoir pressure $p' = p$, it calculates the term $\frac{2p'}{\mu z}$. The summation of the area under the curve of $\frac{2p'}{\mu z}$ vs. p is the pseudo pressure, P_p . The same concept can be used to calculate the adjusted time.

2.3. Flow Regimes

The productivity index depends on the flow period of the producing well. When the well starts to produce, hydrocarbons flow into the wellbore, the pressure at the wellbore, P_{wf} , drops instantaneously, causing a pressure disturbance to form and move away from the wellbore,

towards the reservoir boundaries. If the reservoir boundary does not allow fluid to flow, it is called "No Flow Boundary". The pressure disturbance results from movement of hydrocarbon molecules from areas of high pressure to areas of low pressure. The speed at which the pressure disturbance travels depends on the properties of the reservoir rock (permeability, porosity, and compressibility) and the the reservoir fluid properties (viscosity and compressibility). Diffusivity, which the combination of the rack and fluid properties, is used ro define the pressure disturbance propagation behavior.

Figure 2: Pressure Disturbance

2.4. Reservoir Boundaries

In the analytical solution to the diffusivity equation, the external boundary condition is selected to be either infinite-acting (case a) or boundary dominated (cases b,c).

- a) The pressure at the outer boundary at ($r = \infty$) of the reservoir remains at the initial reservoir pressure (P_i). Referred to as Infinite-acting condition.
- b) There is no-flow at the outer boundary and the pressure gradient at the boundary ($\frac{dP}{dr}$) is zero. Referred to as Pseudo-steady-state condition.
- c) Constant Pressure Outer Boundary: The pressure at the boundary remains constant. Referred to as Steady-state condition.

2.5 Flow Regimes in Unconventional Reservoir

In the ultra-lowpermeability unconventional gas reservoirs, the infinite-acting period can last for most of the well's lifetime (Stewart, 2011).

The graph of $\log p_D$ versus t_D can be used to display the solution to the diffusivity equation. A plot of the actual pressure difference $\Delta p = p_i - p_{wf}$ versus real time t on a log-log scale will have exactly the same shape as the dimensionless theoretical solution provided the data correspond to the model. The term "derivative" refers to the local slope of the appropriate semilog plot and is given the symbol p' . For a constant drawdown $p' = dp_{wf} / d(\ln t)$. A derivative log-log diagnostic plot is presentation of p' versus t on log-log scales. Extraction of the logarithmic derivative p' magnifies the fine detail of the basic semilog graph and enhances interpretation particularly in connection with reservoir heterogeneity.

The diagnostic plot is divided into three main regions ((“[Http://Www.Fekete.Com/San/Webhelp/Welltest/Webhelp/Content/Html_files/Reference_materials/Flow_regimes.Htm](http://www.fekete.com/San/Webhelp/Welltest/Webhelp/Content/Html_files/Reference_materials/Flow_regimes.Htm),” n.d.):

- Early time region: Wellbore and near-wellbore

In multi-fractured horizontal wells, the observed flow regimes in this region include wellbore storage, vertical radial flow within the fractures, linear flow within the fractures, and bilinear flow.

- Middle time region: Infinite-acting

In multi-fractured horizontal wells, the observed flow regimes are early linear (toward fractures), early radial flow (around each fracture before interference between fracs), linear flow within the fractures, and bilinear flow.

- Late time region: Boundary dominated

In multi-fractured horizontal wells, pseudo-steady state flow occurs.

Identifying the flow regimes from the log-log derivative plot:

- The wellbore dominated period is detected from the unit-slope line on log-log ΔP_a vs Δt_a and log-log $\Delta P'_{a,ln}$ vs Δt_a
- Infinite-acting period is identified by having a slope, m' , equal to zero on the log-log $\Delta P'_{a,ln}$ vs Δt_a
- Boundary dominated period occurs after the infinite-acting period and is detected by any deviation from $m' = 0$.

Figure 3 illustrates the typical pseudo-pressure derivative responses for a horizontal well in a homogenous, tight formation and Figure 4 illustrates the typical pressure derivative responses for a horizontal well with two hydraulic fractures.

Figure 3: Psuedo-Pressure Derivative Responses for a Horizontal well in a Homogenous Reservoir (After Medeiros et al.2008)

Figure 4. Psuedo-Pressure Derivative Responses for a Horizontal well with Two Transverse Hydraulic Fractures (After Medeiros et al.2008)

2.5. Unconventional Shale Reservoir

Shale rock contains significant amounts of natural gas. Natural gas primarily consists of methane(CH_4), burns cleanly and emits the lowest quantity of carbon dioxide per calorie of any fossil fuel. Shale gas production is one of the most rapidly expanding trends in onshore domestic oil and gas exploration and production. The percent contribution of natural gas to the U.S. energy supply is expected to remain constant for the following years to come. Some of the natural gas uses include industrial, commercial, electrical generation sectors, and residential heating. (Nash, 2010). Each of the shale basins is different, and each has a unique set of exploration criteria and operational challenges.

Figure 4: United States Shale Basins
(Nash, 2010)

Unconventional reservoirs have changed the united states' industry; it allowed gas export. Unconventional reservoirs are far from being well understood due to their complexities in the flow system and heterogeneity. Unlike conventional reservoirs, the gas in shale reservoirs does not flow naturally to the surface due to the low permeability of the formation. The shale reservoir needs to be hydraulically fractured, creating pathways and increasing the permeability, allowing the gas to produce. Shale reservoirs are heterogeneous where the vertical and horizontal permeabilities are not the same.

Figure 5 : Marcellus and Utica Shale Formation Map
(“<https://Marcelluscoalition.Org/Pa-Map/>,” n.d.)

2.6. CMG Software

The CMG software package is used to build a reservoir model for an oil or a gas reservoir. The CMG model simulate the behavior of the reservoir based on the input that is provided such as reservoir rock properties, fluid types, initial reservoir parameters, hydraulic fractures properties, and Adsorption characteristics (Langmuir constants) for unconventional reservoir . A reservoir

model was developed using CMG-GEM to simulate the base case for the horizontal well with hydraulic fractures in this study. A logarithmically-spaced, locally refined, dual-porosity (LS-LR-DK) reservoir model was adopted to effectively simulate hydraulic fracture and natural fracture behavior. The dual permeability model was selected to incorporate the naturally fractured nature of shales, and the logarithmic refinement was required to capture the transient effects around the hydraulic fracture. Logarithmically-spaced gridding would allow for the fine gridding required around the fracture, but it would not create unnecessary grid refinement far away from the fracture. The dual-permeability model accounts for the flow that can occur in the natural fractures, in the matrix, and in transition from the matrix to natural fracture.

CHAPTER 3: METHODOLOGY

The objective of the study is to evaluate the transient productivity index for a horizontal well with multiple hydraulic transverse fractures drilled in an ultra-low permeability gas formation. Additionally, the impacts of different hydraulic fractures configurations are investigated. The general methodology that was employed to achieve this objective is as follows:

- 1) The numerical reservoir simulator (CMG-GEM, 2019) was utilized to build the base case model, and obtain the production times, reservoir pressures, and gas flow rates. Table 1 summarizes the reservoir properties, and Table 2 shows the fracture properties for the base model (El Sgher, Aminian, and Ameri 2018).
- 2) The reservoir pressures, obtained from the model, were converted to adjusted pressures, and the production times were converted to adjusted times:

$$P_a = \left(\frac{\bar{\mu}z}{2\bar{p}} \right) * Pseudopressure \quad (3.1)$$

$$t_a = (\overline{\mu c_g}) * t_{ap} \quad (3.2)$$

Where,

$$Pseudopressure = \int_0^p \frac{2p'}{\mu z} dp'$$

$$t_{ap} = \int_0^t \frac{dt'}{\mu c_g} dp'$$

- 3) The flow regimes were identified from the log-log derivative plot.
- 4) The productivity index was calculated for the infinite-acting period.

$$J = \frac{q}{(\overline{P}_{a,R} - P_{a,wf})} \quad (3.3)$$

5) Parametric Studies

The parametric studies, using the base model, were conducted to investigate the impact of fracture half-length, fracture conductivity, and fracture spacing on the duration of transient flow and the productivity index. Table 3 shows parameters and their values used for parametric studies.

Table 1: Reservoir Properties

Reservoir Parameters	Values	Units
Model Dimensions (L× W × H)	4000×1000×90	ft.
Initial Reservoir Pressure	4700	psia
Fissure Porosity	0.0001	Fraction
Matrix Porosity	0.045	Fraction
Fissure Permeability i, j, k	0.001,0.001,0.0001	md
Matrix Permeability i, j, k	0.0004,0.0004,0.00004	md
Water Saturation	0.15	Fraction
Rock Density	120	lb/ft ³
Wellbore Pressure	500	Psia
Langmuir Pressure	240	psi
Langmuir Volume	0.032	gmol/lb

Table 2 : Hydraulic Fracture Properties

Parameter	Value	Unit
Fracture Half-length	120	ft.
Fracture Conductivity	25	md-ft
Number of Hydraulic Fractures	8	dimensionless
Stage Spacing	300	ft.

Table 3: Parametric Studies

Parameters	Base Case	Range	
Fracture Half-length, X_f	120	50 - 400	ft.
Fracture Conductivity $K_f \cdot w_f$	25	5 -25	md-ft.
Fracture Stage Spacing with Increasing and Decreasing the number of stages	300 (8 stages)	80 (30 Stages), 200 (14 Stages), and 400 (6 Stages)	ft.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Base Model Results

Figure 7 is a plot of the adjusted pressure derivative responses for the base model. The plot was used to identify the flow periods. The boundary-dominated period starts when the derivative curve, in orange, deviates from the infinite-acting period (slope = 0). Table 4 presents the results obtained from Figure 7. Figure 8 shows the the average productivity index for the base model.

Figure 6: Adjusted Pressure Derivative Responses

Figure 7: Productivity Index

Table 4: Base Model Flow Periods and Productivity Index

Flow Period	Range (days)	Duration (years)	Average Productivity Index (Mscf/day)/(psi)
Early-time period (Transient)	0-1,840	5.04	0.249
Middle-time period (Late Transient)	1,840-3,800	5.37	0.201
Late-time period (Boundary-Dominated)	3,800-9,000	14.25	0.177

4.2. Parametric Study Results

4.2.1. Impact of Fracture half-length

Figure 9 is a plot of the adjusted pressure derivative responses for different fracture half-lengths. The flow period durations are given in Table 5. As the fracture half-length increases, the early-time period ends earlier, the middle-time period starts and ends earlier, and the late-time period starts earlier. Figure 10 shows the average productivity index for different fracture half-lengths. The Productivity Index values for different flow periods are presented in Table 6. Table 6 shows that as the fracture half-length increases, the productivity index is improved significantly in the early-time period, middle-time period, and the late-time period.

Figure 8: Derivative Responses for different fracture half-lengths

Figure 9: Productivity Index Plot for Different Fracture half-Length

Table 5: Duration of the Flow Periods

Xf, ft.	50	120*	200	300	400
EARLY PERIOD, YEARS	7.12	5.04	3.15	1.78	1.26
MIDDLE PERIOD, YEARS	8.36	5.37	2.33	1.51	1.48
LATE PERIOD, YEARS	9.18	14.25	19.18	21.37	21.92

*Base Case

Table 6: Productivity Index for Different Fracture Half-Lengths

Flow Periods	Early Period	Middle Period	Late Period
Xf = 50 ft.	0.152	0.136	0.127
Xf=120 ft.*	0.249	0.201	0.177
Xf = 200 ft.	0.391	0.318	0.236
Xf = 300 ft.	0.586	0.564	0.318
Xf = 400 ft.	0.761	0.836	0.376

*Base Case

Table 7 shows the percent change, relative to the base model, in the Productivity Index values and the production duration for different flow periods. From Table 7, as the fracture half-length increases, there is a significant percent increase in the productivity index during the early-time period, middle-time period, and the late-time period. The opposite effect is observed when the fracture half-length is shortened, e.g. $x_f=50$ ft. Additionally,

the fracture half-length significantly impact the production duration in each of the flow periods.

Table 7: PERCENT CHANGE RELATIVE TO THE BASE MODEL

	Flow Periods	% change in Average J	% change in period duration
Xf = 50 ft.	Early	-39%	41%
	Middle	-32%	56%
	Late	-28%	-36%
Xf = 200 ft.	Early	57%	-38%
	Middle	58%	-57%
	Late	34%	35%
Xf = 300 ft.	Early	135%	-65%
	Middle	181%	-72%
	Late	80%	50%
Xf = 400 ft.	Early	206%	-75%
	Middle	317%	-72%
	Late	113%	54%

4.2.2 Impact of the Fracture Spacing

Figure 11 is a plot of the pressure derivative responses. The curves were used to identify the flow periods.

Figure 10: Derivative Responses

Fig. 12 shows the effect of the fracture spacing on the average productivity index.

Figure 11: Productivity Index Plot

Table 8 shows the total production time for the selected fracture spacing values in different flow periods. As the fracture spacing is improved, e.g. shorter fracture spacing, the early-time period ends earlier, the middle-time period starts and ends earlier, and the late-time period starts earlier. The opposite effect is observed for when the fracture spacing is longer, e.g. spacing=400ft.

Table 8: Duration of the flow periods

Spacing, ft.	80	200	300*	400
EARLY PERIOD, YEARS	3.84	4.38	5.04	7.67
MIDDLE PERIOD, YEARS	4.79	4.52	5.37	6.58
LATE PERIOD, YEARS	16.03	15.75	14.25	10.41

*Base Case

Table 9: Productivity Index For Different Fracture Spacing

Flow Periods	Early Period	Middle Period	Late Period
Spacing = 80 ft.	0.5387	0.2334	0.1872
Spacing=200 ft.*	0.3469	0.2240	0.1863
Spacing= 300 ft.	0.2487	0.2007	0.1765
Spacing= 400 ft.	0.1833	0.1403	0.1246

*Base Case

The Productivity Index values for different flow periods are presented in Table 9. As the fracture spacing is improved, e.g. shorter fracture spacing, the productivity index is improved in the early-time period, middle-time period, and the late-time period. The opposite effect is observed for the longer fracture spacing, e.g. $x_f=400\text{ft}$.

Table 10 shows the percent change, relative to the base model, in the Productivity Index values and the production duration for different flow periods. As the fracture spacing is improved, e.g. shorter fracture half-length, there is a percent increase in the productivity index in the early-time period, middle-time period, and the late-time period. The opposite effect is observed for the longer fracture spacing, e.g. $x_f=400\text{ft}$. Additionally, fracture spacing impact the production duration in each of the flow periods.

Table 10: Percent change relative to Base Model

	Flow Periods	% Increase in Average J	% increase in the period duration
spacing = 80ft	Early	117%	-24%
	Middle	16%	-11%
	Late	6%	13%
spacing =200ft	Early	39%	-13%
	Middle	12%	-16%
	Late	6%	11%
spacing=400ft	Early	-26%	52%
	Middle	-30%	22%
	Middle	-29%	-27%

4.4 Fracture conductivity

Figure 13 is a plot of the pressure derivative responses. The curves were used to identify the flow periods.

Figure 12: Derivative Responses

Fig. 14 shows the effect of the fracture conductivity on the average productivity index.

Figure 13: Productivity Index Plot

Table 11 shows the total production time for the selected fracture conductivity values in different flow periods. The fracture conductivity appears to have insignificant impact on the flow periods.

Table 11: Duration of the flow periods

Conductivity, md*ft.	2.5	25*	50
EARLY PERIOD, YEARS	5.34	5.04	4.66
MIDDLE PERIOD, YEARS	6.03	5.37	5.21
LATE PERIOD, YEARS	13.29	14.25	14.79

*Base Case

Table 12: Productivity Index

Flow Periods	Early Period	Middle Period	Late Period
Conductivity= 2.5md*ft.	0.2320	0.1857	0.1662
Conductivity=25 md*ft.*	0.2487	0.2007	0.1765
Conductivity= 50 md*ft.	0.2677	0.2041	0.1779

*Base Case

The Productivity Index values for different flow periods are presented in Table 12. The fracture conductivity appears to have insignificant impact on the productivity index.

Table 13 shows the percent change, relative to the base case, in the Productivity Index values and the production duration for different flow periods. The fracture conductivity has little and insignificant impact on both the percent change in the productivity index and the percent change in the production duration in each of the flow periods.

Table 13: Percent change relative to Base Model

	Flow Periods	% Increase in Average J	% increase in the period duration
conductivity = 2.5md*ft	Early	-7%	6%
	Middle	-8%	12%
	Late	-6%	-7%
conductivity = 50md*ft	Early	8%	-8%
	Middle	2%	-3%
	Late	1%	4%

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Conclusions:

- In an unconventional tight shale gas reservoir, the majority of the well's lifetime is spent in the early and middle time periods.
- The productivity index for a hydraulically fractured horizontal well completed in the unconventional shale gas reservoir depends on the flow regime and the hydraulic fracture properties.
- The hydraulic fracture half-length, spacing, and conductivity impact both the duration of the flow regimes and the productivity index.
- The Productivity Index is a function of, but not limited to, the fracture-half length, fracture spacing, and fracture conductivity.
- Fracture half-length has significant impact on the production.
- Fracture spacing impacts the production.
- Fracture conductivity does not have a significant impact on the production.
- The fracture half-length affects the productivity index more than fracture spacing and fracture conductivity. Meanwhile, the fracture spacing affects the productivity index more than the fracture conductivity.

Relationship strength with the Productivity Index:

$$\text{fracture half length} > \text{fracture Spacing} > \text{fracture conductivity}$$

- The flow regime periods are a function of, but not limited to, the fracture-half length, fracture spacing, and fracture conductivity.

- When the fracture half-length is increased, the middle period (infinite-acting period) occurs earlier and lasts for a shorter period. Fracture half-length significantly affect the start, end, and duration of the flow time periods.
- When the fracture spacing is decreased, the middle period (infinite-acting period) occurs earlier and lasts for a shorter period. Fracture spacing does not significantly contribute to the start, end, and duration of the flow time periods.
- When the fracture conductivity is increased, the middle period (infinite-acting period) occurs earlier and lasts for a shorter period. Fracture spacing does not significantly contribute to the start, end, and duration of the flow time periods.
- The fracture half-length affects the flow time regimes and duration more than fracture spacing and fracture conductivity. Meanwhile, the fracture spacing affect is stronger than the fracture conductivity.

Relationship strength with the flow regime :

$$fracture\ half\ length > fracture\ Spacing > fracture\ conductivity$$

Recommendations:

- Perform sensitivity analysis studies to understand the effect of the other parameters to ultimately improve the well's productivity through the Productivity Index.
- Attempt to find a correlation, to predict the Productivity Index, for a gas well with multiple hydraulic fractures.

References

gher, Mohamed, Kashy Aminian, and Samuel Ameri. 2018. "Geomechanical Impact on Gas Recovery from Marcellus Shale." In *Day 4 Wed, April 25, 2018*, D041S009R002. Garden Grove, California, USA: SPE. <https://doi.org/10.2118/190054-MS>.

"<https://Marcelluscoalition.Org/Pa-Map/>." n.d.

"http://www.fekete.com/San/Webhelp/Welltest/Webhelp/Content/html_files/Reference_materials/F_low_regimes.htm." n.d.

Medeiros, F, E Ozkan, and H Kazemi. 2008. "Productivity and Drainage Area of Fractured Horizontal Wells in Tight Gas Reservoirs," 10.

Nash, Katelyn M., ed. 2010. *Shale Gas Development*. Energy Science, Engineering and Technology. New York: Nova Science Publishers.

Navarro, Gabriel L., ed. 2011. *Marcellus Shale and Shale Gas: Facts and Considerations*. Earth Sciences in the 21st Century. New York: NOVA, Nova Science Publishers, Inc.

Stewart, George. 2011. *Well Test Design & Analysis*. Tulsa, Okla: PennWell.