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PRODUCTIVITY INDEX OF MULTILATERAL WELLS

Upendar Naik Nunsavathu

**Thesis Submitted to the
College of Engineering and Mineral Resources
At West Virginia University
In partial fulfillments of the requirements
For the degree of**

**Master of Science
In
Petroleum and Natural Gas Engineering**

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Prof. Samuel Ameri
Dr. Daniel E. Della-Giustina**

**Department of Petroleum and Natural Gas Engineering
Morgantown, West Virginia
2006**

**Keywords: Petroleum & Natural Gas Engineering, Multilateral wells,
Productivity index, Dimensionless time, Dimensionless pressure.**

Abstract

Productivity Index of Multilateral wells

Uponder Naik Nunsavathu

In the history of petroleum science there are a vast variety of productivity solutions for different well types, well configurations and flow regimes. The main well types that were considered for calculating the productivity indexes were vertical wells and horizontal wells. The configurations considered were multilayer perforations, dual lateral wells with laterals at same depths, stacked wells etc. There are few solutions to estimate the well productivity for complex configurations like multilateral wells.

The main objective of this work is to identify a numerical solution method for calculating productivity indexes for different well configurations like single vertical well, single horizontal well, dual lateral well with laterals at same depth, dual laterals with laterals at different depths and four laterals well. A three-phase, three-dimensional black oil reservoir simulator (ECLIPSE) is used in this thesis. Apart from comparing the productivity indexes of different well configurations, dimensionless pressure derivatives with respect to dimensionless time is also compared for all the above well configurations.

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CHAPTER I. INTRODUCTION

1.1 Overview

1.1.1 Background

Deliverability of wells is the main focus of petroleum industry anywhere in the world. Advances in science and technology applied to drilling and production engineering resulted in a modern well design, ability to drill and complete a well with complicated trajectory in order to reach a certain part of the reservoir. As most of the oil and gas reserves are much more extensive in their horizontal dimensions than in their vertical (thickness) dimensions, the concept of horizontal drilling technology came into existence. Advances in computer hardware and software development triggered a new approach to the reservoir enabling a more detailed and better quality analysis and selection of the drainage strategy and field development concept. Multilateral wells are the part of advanced horizontal drilling technology. The first multilateral well was drilled in Russia in 1950's (Figure 1.1)¹. Europe's first multi-lateral wells were completed by Elf Aquitaine in 1984 in the Paris Basin, France. Norsk Hydro completed successfully the first ever Level 5 multilateral well in the Oseburg Field, North Sea during 1996. In USA, Shell successfully completed its first Level 6 multilateral well during 1998.

Figure 1.1- Russia's first Multilateral well¹.

1.1.2 General Definition

A multilateral well as defined by TAML¹ group (Technical Advancements of Multilaterals) is one in which there will be more than one horizontal or near horizontal lateral well drilled from a single side (mother-bore) and connected back to a single bore.

1.1.3 Geometry of Multi-Lateral and Multi-branched wells

Well geometry of multi-lateral wells named according to their configuration and number of laterals. e.g. Stacked Tri-lateral, Radial Quadrilateral etc.

Different well configurations are shown in Figure 1.2¹

Figure 1.2 - Different Well Configurations

1.1.4 Classification System (TAML)

There are two tiers of TAML classifications:

- Complexity ranking.
- Functional classification.

▪ Complexity ranking

A number between 1 and 6 defines multilateral junction complexity. Table 1.1 illustrates the complexity ratings.

▪ Functionality classification

This provides more technical detail on the major Multilateral/Multi-branched well attributes. This is divided into two sections:

1. Well description.
2. Junction description.

Table 1.1- Complexity ranking of multilateral wells¹.

Level	Illustration	Description
1	(or)	Open/ Unsupported Junction Barefoot mother-bore & lateral or slotted liner hung-off in either bore
2	(or)	Mother-bore Cased and Cemented Lateral Open Lateral either barefoot or with slotted liner hung-off in open hole
3	(or)	Mother-bore Cased and Cemented Lateral Cased but not Cemented Lateral liner 'anchored' to mother-bore with liner 'hanger' but not cemented
4	(or)	Mother-bore and Lateral Cased and Cemented Both bores cemented at the junction
5		Pressure Integrity at the Junction Straddle packers or (integral) mechanical casing seal. (Cement is not acceptable)
6		Pressure Integrity at the Junction Achieved with the casing (Cement is NOT acceptable)
6S		Downhole Splitter Large main well bore with 2 (smaller) lateral wellbores of equal size

1.1.5 Advantages² of Multilateral wells

The advantages of multilateral wells are:

- Higher productivity indexes.
- Relatively thin layer drainage can be accomplished.
- Decreased water and gas conning.
- Exposure to natural fractures will be high.
- In secondary and EOR applications, long horizontal injection wells provide higher injectivity rates.
- Better vertical and areal sweep (particularly for irregular or odd-shaped drainages).
- These are alternative to infill drilling operations because existing surface installations can be utilized.
- In heterogeneous reservoirs, more oil and gas pockets can be exploited and an increased number of fissures can be intersected.

1.1.6 Disadvantages² of Multilateral wells

The disadvantages of multilateral wells are:

- Higher costs.
- Highly sensitive to heterogeneities and anisotropies (both stress and permeability).
- Very complicated drilling, completion and production technologies are used.
- Complicated and expensive stimulation techniques are used.
- Selection of appropriate candidates is difficult.
- Interference of well branches may occur (Cross flow may take place).

CHAPTER II. THEORY

In general the production data in the form of flow rate and flowing pressure are available in an oil and gas producing field. Additionally, testing of a well yields reservoir pressure and other formation properties such as permeability, skin, and drainage area. One practical approach is to use productivity index (PI) to characterize the performance of a well and also compare it with similar wells. The productivity index is also denoted by letter 'J' and mathematically expressed for an oil well as:

$$J = \frac{q}{\Delta p} = \frac{q}{(p - p_w)}$$

In general, units used are bbl/day/psi or m³/day/kPa.

Productivity index is also considered as the measure of the capacity of the well. In this form PI represents a steady state flow condition.

During the operational life, the hydrocarbon producing well passes through various stages. These stages mainly depend on the pressure drop and the boundary conditions. There are four different flow scenarios, which occur during the operational life of the well. They are:

- Unsteady state.
- Pseudo – steady state.
- Steady state.
- Late Transient.

2.1. Unsteady state:

This is the condition of the well when the pressure disturbance caused by the flow has not reached any of the reservoir boundaries. This is also known as Infinite – acting or Transient state (Figure 2.1).

Figure 2.1. – Representation of Infinite – acting (or) Transient state.

Mathematically, unsteady state is defined as:

$$\frac{\partial P}{\partial t} = f(r, t)$$

2.2. Pseudo – steady State:

This is the condition of the well in a bounded reservoir when the pressure disturbance caused by the flow has reached all of the reservoir boundaries. During this flow regime the reservoir behaves like a tank. The pressure throughout the reservoir decreases at the same constant rate. (Figure 2.2)

Figure 2.2. - Representation of Pseudo – steady state.

Mathematically, pseudo-steady state is given as:

$$\frac{\partial P}{\partial t} = \text{constant}$$

2.3. Steady state:

This condition occurs during the late time region when a constant pressure boundary exists. Constant pressure boundaries arise when the reservoir has aquifer support or gas cap expansion support.

Mathematically, steady state is given as:

$$\frac{\partial P}{\partial t} = 0$$

2.4. Late Transient State:

This is the state between unsteady state and pseudo – steady state. During this regime the pressure distribution reaches some of the boundaries but not all of it. (Figure 2.4)

Figure 2.4. - Representation of Late Transient state.

CHAPTER III. PREDICTION OF PRODUCTIVITY METHODS

There are different methods for predicting Productivity Index (PI) of both types of wells (Vertical wells and Horizontal wells). In this study, multilateral wells are considered as horizontal wells.

3.1 Steady State PI

There are different methods³ for predicting the PI for Steady state Horizontal wells. They are:

- Borisov's method.
- The Giger – Reiss – Jourdan method.
- Joshi's method.
- The Renard – Dupuy method.

3.1.1 Borisov's method

Borisov proposed the following expression for predicting the productivity index of a horizontal well in an isotropic reservoir, i.e., $k_v = k_h$.

$$J_h = \frac{0.00708hk_h}{\mu_o B_o \left[\ln\left(\frac{4r_{eh}}{L}\right) + \left(\frac{L}{h}\right) \ln\left(\frac{h}{2\pi r_w}\right) \right]}$$

3.1.2 The Giger – Reiss – Jourdan method

Giger – Reiss – Jourdan proposed the following expression for predicting the productivity index of a horizontal well in an isotropic reservoir, i.e., $k_v = k_h$.

$$J_h = \frac{0.00708Lk_h}{\mu_o B_o \left[\left(\frac{L}{h}\right) \ln(X) + \ln\left(\frac{h}{2r_w}\right) \right]}$$

$$X = \frac{1 + \sqrt{1 + \left(\frac{L}{2r_{eh}}\right)^2}}{L / (2r_{eh})}$$

For reservoir anisotropy, he proposed the following relationships:

$$J_h = \frac{0.00708k_h}{\mu_o B_o \left[\left(\frac{1}{h}\right) \ln(X) + \left(\frac{B^2}{L}\right) \ln\left(\frac{h}{2r_w}\right) \right]}$$

$$B = \sqrt{\frac{k_h}{k_v}}$$

3.1.3 Joshi's method

Joshi proposed the following expression for estimating the productivity index of a horizontal well in an isotropic reservoir:

$$J_h = \frac{0.00708hk_h}{\mu_o B_o \left[\ln(R) + \left(\frac{h}{L}\right) \ln\left(\frac{h}{2r_w}\right) \right]}$$

$$R = \frac{a + \sqrt{a^2 - (L/2)^2}}{(L/2)}$$

Here 'a' is half the major axis of the drainage ellipse and is given by:

$$a = (L/2) \left[0.5 + \sqrt{0.25 + (2r_{eh}/L)^4} \right]^{0.5}$$

For the reservoir anisotropy, he proposed following relationships with vertical permeability, k_v :

$$J_h = \frac{0.00708hk_h}{\mu_o B_o \left[\ln(R) + \left(\frac{B^2 h}{L} \right) \ln \left(\frac{h}{2r_w} \right) \right]}$$

$$B = \sqrt{\frac{k_h}{k_v}}$$

$$R = \frac{a + \sqrt{a^2 - (L/2)^2}}{(L/2)}$$

Here 'a' is half the major axis of the drainage ellipse and is given by:

$$a = (L/2) \left[0.5 + \sqrt{0.25 + (2r_{eh}/L)^4} \right]^{0.5}$$

3.1.4 The Renard – Dupuy method

For an isotropic reservoir, Renard and Dupuy proposed the following expression:

$$J_h = \frac{0.00708hk_h}{\mu_o B_o \left[\cosh^{-1} \left(\frac{2a}{L} \right) + \left(\frac{h}{L} \right) \ln \left(\frac{h}{2\pi r_w} \right) \right]}$$

Here 'a' is half the major axis of the drainage ellipse and is given by:

$$a = (L/2) \left[0.5 + \sqrt{0.25 + (2r_{eh}/L)^4} \right]^{0.5}$$

For anisotropic reservoirs, these authors proposed the following relationship:

$$J_h = \frac{0.00708hk_h}{\mu_o B_o \left[\cosh^{-1} \left(\frac{2a}{L} \right) + \left(\frac{Bh}{L} \right) \ln \left(\frac{h}{2\pi r'_w} \right) \right]}$$

where

$$r'_w = \frac{(1+B)r_w}{2B}, \quad B = \sqrt{\frac{k_h}{k_v}}$$

3.2 Pseudo-Steady State PI

There are different methods for predicting the PI for pseudo – steady state horizontal wells. Three methods are discussed below:

- Babu – Odeh method.
- Kuchuk method.
- Economides method.

3.2.1 Babu – Odeh method⁴

Babu & Odeh presented the following equation for pseudo-steady state conditions:

$$J_h = \frac{0.00708 L_y \sqrt{k_x k_y}}{\mu B \left[\ln\left(\frac{\sqrt{L_x h}}{r_w}\right) + \ln(C_h) - 0.75 + S_R + S_d \right]}$$

where,

$$\ln(C_h) = 6.28 L_x / h \sqrt{k_z / k_x} \left[\frac{1}{3} - \frac{x_o}{L_x} + \left(\frac{x_o}{L_x}\right)^2 \right] - \ln(\sin 180^\circ z_o h) - 0.5 \ln\left[\left(\frac{L_x}{h}\right) \sqrt{k_z / k_x}\right] - 1.088$$

here x_o and z_o are the coordinates measuring the centre of the well in the vertical plane, L_x and L_y are the dimensions of the drainage area, orthogonal and parallel respectively to the horizontal well. S_R and S_d are the skin factors under different conditions.

3.2.2 Kuchuk method⁴

Productivity equation suggested by Kuchuk used an approximate infinite-conductivity solution. It is expressed as:

$$J_h = \frac{k_h h / (70.6 \mu_o)}{F + (h / 0.5 L) \sqrt{k_h / k_v} S_x}$$

where F is a dimensionless function and depends upon $y_w/(2y_e)$, $x_w/(2x_e)$, $L/(4x_e)$ and (y_e/x_e)

$\sqrt{k_x / k_y}$. The value of s_x is calculated using the following equation:

$$s_x = \ln \left[\left(\frac{\pi r_w}{h} \right) \left(1 + \sqrt{\frac{k_v}{k_h}} \right) \sin \left(\frac{\pi z_w}{h} \right) \right] - \sqrt{\frac{k_h}{k_v}} \left(\frac{2h}{L} \right) \left[\frac{1}{3} - \left(\frac{z_w}{h} \right) + \left(\frac{z_w}{h} \right)^2 \right]$$

3.2.3 Economides Method⁵

Economides suggested the following equation for calculating the PI:

$$J = \frac{q_o}{(p - p_{wf})} = \frac{\bar{k} x_e}{887.22 B \mu (p_D + \frac{x_e}{2\pi L} \sum s)}$$

where,

$$p_D = \frac{x_e C_H}{4\pi h} + \frac{x_e}{2\pi L} s_x$$

$\sum s$ - is the summation of all damage and pseudo-skin factors.

Skin effect s_x is:

$$s_x = \ln \left(\frac{h}{2\pi r_w} \right) - \frac{h}{6L} + s_e$$

where,

$$s_e = \frac{h}{L} \left[\frac{2z_w}{h} - \frac{1}{2} \left(\frac{2z_w}{h} \right)^2 - \frac{1}{2} \right] - \ln \left[\sin \left(\frac{\pi z_w}{h} \right) \right]$$

3.3 Literature Review

3.3.1 Analytical Solutions

There are two main categories under which any oil or gas well is classified according to their design as a vertical well or a horizontal well. An unstimulated horizontal well can generate production rates of two to five times to that of an unstimulated vertical well at a similar pressure drawdown. Apart from this main advantage there are also few disadvantages of horizontal wells. Some of the disadvantages of horizontal wells are the less effectiveness in thicker reservoirs (>500 ft), reservoirs with low vertical permeability (relative to horizontal permeability) and in stratified reservoirs with impermeable shale barriers. Improvement of well completion and stimulation technology can overcome these disadvantages. The use of hydraulic fractures to enhance horizontal well productivity is explained by Giger et al⁶ and Giger⁷.

There have been several attempts to describe and estimate horizontal well productivity and/or injectivity indexes and several models have been used for this purpose. A widely used approximation for the well drainage is a parallelepiped model with no-flow or constant-pressure boundaries at the top or bottom, and either no-flow or infinite-acting boundaries at the sides.

One of the earliest models was introduced first by Borisov⁸, which assumed a constant pressure drainage ellipse whose dimensions depend on the well length. Using this configuration Joshi⁹ came up with an equation, which accounted for vertical-to-horizontal permeability anisotropy. Then Economides et al.,¹⁰ modified it for a wellbore in elliptical coordinates. This model does not account for either early-time or late-time phenomena nor, more importantly, actual well and reservoir configurations.

Babu & Odeh¹¹ used an expression, which was complicated and cumbersome to calculate, for the pressure drop at any point by integrating appropriate point source (Green's) functions in space and time. Their work assumes that the well is parallel to the y-axis of the parallelepiped model. Goode and Thambynayagam¹² solved a model for horizontal well pressure transient response in Laplace space and inverted solution using a numerical inverter. Kuchuk et

al.¹³ extended the Goode and Thambynayagam¹² approach by including constant pressure (at the top and/or bottom) boundaries.

In general it is believed that the productivity of a horizontal well is proportional to the well length. But as the length increases, drilling and well control becomes more difficult. Apart from this, transportation of large volumes of liquid along a long horizontal borehole results in considerable pressure losses in the wellbore. Wellbore pressure loss yields a decrease in well productivity. Multilateral wells provide an alternative to drilling long single horizontal wells. There are many publications, which have discussed the flow into multilaterals. These can be grouped into three categories: productivity models^{14 - 17}, transient flow models¹⁷⁻²⁵ and field applications^{26 - 30}.

CHAPTER IV. APPROACH USING RESERVOIR SIMULATION

4.1 Numerical Simulation Models for Multilateral wells

To evaluate the productivity index of multilateral wells, reservoir simulation software, ECLIPSE from Schlumberger, is used in this thesis. The ECLIPSE simulator is used to generate different models in this thesis with version 2005A for black oil (ECLIPSE 100). ECLIPSE 100 is a fully implicit, three-phase, three-dimensional black oil simulator. The black oil model considers the reservoir fluids consisting of reservoir oil, solvent gas and water. The reservoir oil and solvent gas components are assumed to be miscible in all proportions.

In this study, five different horizontal completions were considered. Namely:

1. Single Lateral.
2. Dual Lateral (with laterals at same depth).
3. Dual Lateral (with laterals at different depths).
4. Four Laterals (with laterals perpendicular to each other).
5. Single Vertical Well.

Additionally, four different lengths of 500 ft., 1000 ft., 1500 ft., and 2000 ft. were considered for all lateral completions.

In all cases, the following wellbore configurations were used:

Main borehole diameter	:	12 in.
Casing Inner diameter	:	8.4 in.
Casing Outer diameter	:	9 in.
Casing Roughness	:	0.001 in.
Tubing Inner diameter	:	2.0 in.
Tubing Outer diameter	:	2.441 in.
Tubing Inner roughness	:	0.012 in.
Tubing Outer roughness	:	0.012 in.
Packer set at a vertical depth	:	4950 ft.

GRID STRUCTURE:

Direction	Minimum cell size	Maximum cell size	Growth factor
X – direction	1 ft.	500 ft.	2
Y – direction	1 ft.	500 ft.	2
Z – direction	1 ft.	500 ft.	2

All of the above-mentioned configurations, which were generated using ECLIPSE, are described below. All runs were conducted for 30 years.

Single Lateral:

Figure 4.1 is the schematic of a 500 ft Single Lateral Well. Figure 4.2 shows grid structure used for the 500 ft Single Lateral Well.

Figure 4.1: 500 ft. Single Lateral Well.

Figure 4.2: Grid structure of 500 ft. Single Lateral Well.

Figure 4.3 is the schematic of a 1000 ft Single Lateral Well. Figure 4.4 shows grid structure used for the 1000 ft Single Lateral Well.

Figure 4.3: 1000 ft. Single Lateral Well.

Figure 4.4: Grid structure of 1000 ft. Single Lateral Well.

Figure 4.5 is the schematic of a 1500 ft Single Lateral Well. Figure 4.6 shows grid structure used for the 1500 ft Single Lateral Well.

Figure 4.5: 1500 ft. Single Lateral Well.

Figure 4.6: Grid structure of 1500 ft. Single Lateral Well.

Figure 4.7 is the schematic of a 2000 ft Single Lateral Well. Figure 4.8 shows grid structure used for the 2000 ft Single Lateral Well.

Figure 4.7: 2000 ft. Single Lateral Well.

Figure 4.8: Grid structure of 2000 ft. Single Lateral Well.

Dual Lateral:

Figure 4.9 is the schematic of a 500 ft Dual Lateral Well and Figure 4.10 shows grid structure used for the 500 ft Dual Lateral well.

Figure 4.9: 500 ft. Dual Lateral Well.

Figure 4.10: Grid structure of 500 ft. Dual Lateral Well.

Figure 4.11 is the schematic of a 1000 ft Dual Lateral Well and Figure 4.12 shows grid structure used for the 1000 ft Dual Lateral well.

Figure 4.11: 1000 ft. Dual Lateral Well.

Figure 4.12: Grid structure for the 1000 ft. Dual Lateral Well.

Figure 4.13 is the schematic of a 1500 ft Dual Lateral Well and Figure 4.14 shows grid structure used for the 1500 ft Dual Lateral well.

Figure 4.13: 1500 ft. Dual Lateral Well.

Figure 4.14: Grid structure for the 1500 ft. Dual Lateral Well.

Figure 4.15 is the schematic of a 2000 ft Dual Lateral Well and Figure 4.16 shows grid structure used for the 2000 ft Dual Lateral well.

Figure 4.15: 2000 ft. Dual Lateral Well.

Figure 4.16: Grid structure for the 2000 ft. Dual Lateral Well.

Dual Lateral well with laterals at different depths:

Figure 4.17 is the schematic of a 500 ft Dual Lateral Well with laterals at different depths and

Figure 4.18 shows grid structure used for this 500 ft Dual Lateral well.

Figure 4.17: 500 ft. Dual Lateral Well with laterals at different depths.

Figure 4.18: Grid structure for the 500 ft. Dual Lateral Well with laterals at different depths.

Figure 4.19 is the schematic of a 1000 ft Dual Lateral Well with laterals at different depths and Figure 4.20 shows grid structure used for this 1000 ft Dual Lateral well.

Figure 4.19: 1000 ft. Dual Lateral Well with laterals at different depths.

Figure 4.20: Grid structure for the 1000 ft. Dual Lateral Well with laterals at different depths.

Figure 4.21 is the schematic of a 1500 ft Dual Lateral Well with laterals at different depths and Figure 4.22 shows grid structure used for this 1500 ft Dual Lateral well.

Figure 4.21: 1500 ft. Dual Lateral Well with laterals at different depths.

Figure 4.22: Grid structure for the 1500 ft. Dual Lateral Well with laterals at different depths.

Figure 4.23 is the schematic of a 2000 ft dual lateral well with laterals at different depths and Figure 4.24 shows grid structure used for this 2000 ft Dual Lateral well.

Figure 4.23: 2000 ft. Dual Lateral Well with laterals at different depths.

Figure 4.24: Grid structure for the 2000 ft. Dual Lateral Well with laterals at different depths.

Four Laterals:

Figure 4.25 is the schematic of a 500 ft four lateral well with laterals at same depths and Figure 4.26 shows grid structure used for this 500 ft Four Lateral well.

Figure 4.25: 500 ft. 4-Laterals Well.

Figure 4.26: Grid structure for the 500 ft. 4-Laterals Well.

Figure 4.27 is the schematic of a 1000 ft four lateral well with laterals at same depths and Figure 4.28 shows grid structure used for this 1000 ft Four Lateral well.

Figure 4.27: 1000 ft. 4-Laterals Well.

Figure 4.28: Grid structure for the 1000 ft. 4-Laterals Well.

Figure 4.29 is the schematic of a 1500 ft four lateral well with laterals at same depths and Figure 4.30 shows grid structure used for this 1500 ft Four Lateral well.

Figure 4.29: 1500 ft. 4-Laterals Well.

Figure 4.30: Grid structure for the 1500 ft. 4-Laterals Well.

Figure 4.31 is the schematic of a 2000 ft four lateral well with laterals at same depths and Figure 4.32 shows grid structure used for this 2000 ft Four Lateral well.

Figure 4.31: 2000 ft. 4-Laterals Well.

Figure 4.32: Grid structure for the 2000 ft. 4-Laterals Well.

Vertical Well:

Figure 4.33 is the schematic of a Vertical well. Figure 4.34 shows grid structure used for this Vertical well.

Figure 4.33: Single Vertical well.

Figure 4.34: Grid structure for the Vertical Well.

CHAPTER V: RESULTS AND DISCUSSION

For all the configurations that were described in the previous chapter had the following:

Reservoir description:

Length of the reservoir	:	10000 ft.
Width of the reservoir	:	10000 ft.
Thickness	:	100 ft.
Porosity	:	0.25
Permeability:		
X- Direction	:	10 mD.
Y- Direction	:	10 mD.
Z- Direction	:	1 mD.
Compressibility	:	1E-6 /psi.
Initial reservoir pressure	:	3500 psia.
Datum Depth (TVDSS)	:	5180 ft.

Fluid Properties:

Oil density at surface	:	49.9 lb/ft ³ .
Oil formation volume factor	:	1.25 rb/stb.
Oil compressibility	:	3E-6 /psi.
Oil Viscosity	:	1 cp.
Total GOR	:	0.00697224 Mscf/stb.
Bubble point pressure	:	50 psia.
Gas Gravity	:	0.7
Skin	:	2

Runs were conducted using the above data with the configurations given in Chapter IV (with different lateral lengths), field pressure rates, field oil production rates, well bottom hole pressure and field pressure variations are tabulated. Using these values, Productivity Index, J for each configuration (for different lateral lengths) is calculated with the following equation:

$$J = \frac{q}{\Delta p} = \frac{q}{(p_{field} - p_{WBHP})}$$

The basic equation that governs single-phase flow of a slightly compressible fluid in a porous medium is given by:

$$\left[\frac{\partial^2 p_D}{\partial x_D^2} + \frac{\partial^2 p_D}{\partial y_D^2} + \frac{\partial^2 p_D}{\partial z_D^2} = \frac{\partial p_D}{\partial t_D} \right] \text{ (in dimensionless variables).}$$

To convert the space coordinates or lengths to their dimensionless equivalent, they are scaled by the reservoir length in the x-direction, x_e and the following forms were used:

$$x_D = x / x_e,$$

$$y_D = y / x_e,$$

$$z_D = z / x_e.$$

The following dimensionless time is used:

$$t_D = \frac{2.637 \times 10^{-4} \times k \times t}{\phi \times C_t \times \mu \times x_e^2},$$

where 2.637×10^{-4} is the conversion factor for time measured in hours, and field units for k , x_e , μ , and C_t .

The dimensionless variables p_D , t_D are tabulated for each configuration. Dimensionless well-bore pressure is calculated with,

$$p_D = \frac{k \times h}{141.2 \times q_t \times \mu \times B_o} [p_{field} - p_{WBHP}]$$

After calculating the dimensionless pressure and time differences, dimensionless pressure derivative values are calculated and tabulated for all the configurations. The pressure derivative is given by:

$$(dp_D/dt_D)t_D$$

Using above values, different plots are generated to check the variation of productivity index with respect to time and dimensionless pressure derivative with respect to dimensionless time. The plots are prepared for the following configurations:

1. Single lateral well.
2. Dual lateral well.
3. Dual Lateral well with laterals at different depths.
4. Four lateral well.
5. Single Vertical Well.

Lateral lengths of 500 ft, 1000 ft, 1500 ft, 2000 ft are considered for all these configurations.

Single Lateral Well:

The results for the 500 ft. single lateral well for productivity index values are presented in Figure 5.1. As shown in Figure 5.1 the productivity index value shows a linear trend for 10 years 9 months. Compared to a vertical well completed in the same reservoir the productivity values are 57% greater indicating a larger production.

Figure 5.1: Variation of Productivity Index with time for a Single lateral well with 500 ft lateral length.

Figure 5.2 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 500 ft lateral length.

Figure 5.2: Variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 500 ft lateral length.

The results for the 1000 ft. single lateral well for productivity index values are presented in Figure 5.3. As shown in Figure 5.3 the productivity index value shows a linear trend for 5 years 5 months. Compared to a vertical well completed in the same reservoir the productivity values are 50% greater indicating a larger production.

Figure 5.3 Variation of Productivity Index with time for a Single lateral well with 1000 ft lateral length.

Figure 5.4 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 1000 ft lateral length.

Figure 5.4: Variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 1000 ft lateral length.

The results for the 1500 ft. single lateral well for productivity index values are presented in Figure 5.5. As shown in Figure 5.5 the productivity index value shows a linear trend for 2 years 7 months. Compared to a vertical well completed in the same reservoir the productivity values are 50% greater indicating a larger production.

Figure 5.5 Variation of Productivity Index with time for a Single lateral well with 1500 ft lateral length.

Figure 5.6 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 1500 ft lateral length.

Figure 5.6: Variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 1500 ft lateral length.

The results for the 2000 ft. single lateral well for productivity index values are presented in Figure 5.7. As shown in Figure 5.7 the productivity index value shows a linear trend for 1 year 9 months. Compared to a vertical well completed in the same reservoir the productivity values are 46% greater indicating a larger production.

Figure 5.7: Variation of Productivity Index with time for a Single lateral well with 2000 ft lateral length.

Figure 5.8 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 2000 ft lateral length.

Figure 5.8: Variation of dimensionless pressure and its derivative with dimensionless time for a Single lateral well with 2000 ft lateral length.

Dual Lateral Well with Laterals at same height:

The results for the 500 ft. Dual Lateral (laterals at same depth) well for productivity index values are presented in Figure 5.9. As shown in Figure 5.9 the productivity index value shows a linear trend for 4 years 1 month. Compared to a vertical well completed in the same reservoir the productivity values are 49% greater indicating a larger production.

Figure 5.9: Variation of Productivity Index with time for a Dual Lateral well with 500 ft lateral lengths, which are at the same depth.

Figure 5.10 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 500 ft lateral length, which are at same depth.

Figure 5.10: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 500 ft lateral lengths, which are at the same depth.

The results for the 1000 ft. Dual Lateral (laterals at same depth) well for productivity index values are presented in Figure 5.11. As shown in Figure 5.11 the productivity index value shows a linear trend for 2 years 7 month. Compared to a vertical well completed in the same reservoir the productivity values are 46% greater indicating a larger production.

Figure 5.11 Variation of Productivity Index with time for a Dual Lateral well with 1000 ft lateral lengths, which are at the same depth.

Figure 5.12 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1000 ft lateral length, which are at same depth.

Figure 5.12: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1000 ft lateral lengths, which are at the same depth.

The results for the 1500 ft. Dual Lateral (laterals at same depth) well for productivity index values are presented in Figure 5.13. As shown in Figure 5.13 the productivity index value shows a linear trend for 1 year 9 months and decreases to zero at the end of a dimensionless time of 11000 days. Compared to a vertical well completed in the same reservoir the productivity values are 43% greater indicating a larger production.

Figure 5.13: Variation of Productivity Index with time for a Dual Lateral well with 1500 ft lateral lengths, which are at the same depth.

Figure 5.14 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1500 ft lateral length, which are at same depth.

Figure 5.14: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1500 ft lateral lengths, which are at the same depth.

The results for the 2000 ft. Dual Lateral (laterals at same depth) well for productivity index values are presented in Figure 5.15. As shown in Figure 5.15 the productivity index value shows a linear trend for 1 year 6 months and decreases to zero at the end of a dimensionless time of 9500 days. Compared to a vertical well completed in the same reservoir the productivity values are 34% greater indicating a larger production.

Figure 5.15: Variation of Productivity Index with time for a Dual Lateral well with 2000 ft lateral lengths, which are at the same depth.

Figure 5.16 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 2000 ft lateral length, which are at same depth.

Figure 5.16: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 2000 ft lateral lengths, which are at the same depth.

Dual Lateral Well with Laterals at different height:

The results for the 500 ft. Dual Lateral (laterals at different depths separated by 50 ft) well for productivity index values are presented in Figure 5.17. As shown in Figure 5.17 the productivity index value shows a linear trend for 2 years 7 months Compared to a vertical well completed in the same reservoir the productivity values are 49% greater indicating a larger production.

Figure 5.17: Variation of Productivity Index with time for a Dual Lateral well with 500 ft lateral lengths, which are at different depths.

Figure 5.18 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 500 ft lateral length, which are at different depths.

Figure 5.18: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 500 ft lateral lengths, which are at different depths.

The results for the 1000 ft. Dual Lateral (laterals at different depths separated by 50 ft) well for productivity index values are presented in Figure 5.19. As shown in Figure 5.19 the productivity index value shows a linear trend for 1 year 5 months Compared to a vertical well completed in the same reservoir the productivity values are 48% greater indicating a larger production.

Figure 5.19: Variation of Productivity Index with time for a Dual Lateral well with 1000 ft lateral lengths, which are at different depths.

Figure 5.20 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1000 ft lateral length, which are at different depths.

Figure 5.20: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1000 ft lateral lengths, which are at different depths.

The results for the 1500 ft. Dual Lateral (laterals at different depths separated by 50 ft) well for productivity index values are presented in Figure 5.21. As shown in Figure 5.21 the productivity index value shows a linear trend for 1 year 3 months and decreases to zero at the end of a dimensionless time of 11000 days. Compared to a vertical well completed in the same reservoir the productivity values are 43% greater indicating a larger production.

Figure 5.21: Variation of Productivity Index with time for a Dual Lateral well with 1500 ft lateral lengths, which are at different depths.

Figure 5.22 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1500 ft lateral length, which are at different depths.

Figure 5.22: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 1500 ft lateral lengths, which are at different depths.

The results for the 2000 ft. Dual Lateral (laterals at different depths separated by 50 ft) well for productivity index values are presented in Figure 5.23. As shown in Figure 5.23 the productivity index value shows a linear trend for 1 years 6 months and decreases to zero at the end of a dimensionless time of 9500 days. Compared to a vertical well completed in the same reservoir the productivity values are 34% greater indicating a larger production.

Figure 5.23: Variation of Productivity Index with time for a Dual Lateral well with 2000 ft lateral lengths, which are at different depths.

Figure 5.24 shows the variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 2000 ft lateral length, which are at different depths.

Figure 5.24: Variation of dimensionless pressure and its derivative with dimensionless time for a Dual Lateral well with 2000 ft lateral lengths, which are at different depths.

Four Laterals well:

The results for the 500 ft. Four Laterals (laterals at same depth) well for productivity index values are presented in Figure 5.25. As shown in Figure 5.25 the productivity index value shows a linear trend for 1 year 3 months. Compared to a vertical well completed in the same reservoir the productivity values are 47% greater indicating a larger production.

Figure 5.25: Variation of Productivity Index with time for a 4-lateral well with 500 ft lateral lengths, which are at the same depth.

Figure 5.26 shows the variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 500 ft lateral length, which are at same depth.

Figure 5.26: Variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 500 ft lateral lengths, which are at the same depth.

The results for the 1000 ft. Four Laterals (laterals at same depth) well for productivity index values are presented in Figure 5.27. As shown in Figure 5.27 the productivity index value shows a linear trend for 1 year 3 months and decreases to zero at the end of a dimensionless time of 11000 days. Compared to a vertical well completed in the same reservoir the productivity values are 35% greater indicating a larger production.

Figure 5.27: Variation of Productivity Index with time for a 4-lateral well with 1000 ft lateral lengths, which are at the same depth.

Figure 5.28 shows the variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 1000 ft lateral length, which are at same depth.

Figure 5.28: Variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 1000 ft lateral lengths, which are at the same depth.

The results for the 1500 ft. Four Laterals (laterals at same depth) well for productivity index values are presented in Figure 5.29. As shown in Figure 5.29 the productivity index value shows a linear trend for 1 year and decreases to zero at the end of a dimensionless time of 7500 days. Compared to a vertical well completed in the same reservoir the productivity values are 32% greater indicating a larger production.

Figure 5.29: Variation of Productivity Index with time for a 4-lateral well with 1500 ft lateral lengths, which are at the same depth.

Figure 5.30 shows the variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 1500 ft lateral length, which are at same depth.

Figure 5.30: Variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 1500 ft lateral lengths, which are at the same depth.

The results for the 2000 ft. Four Laterals (laterals at same depths) well for productivity index values are presented in Figure 5.31. As shown in Figure 5.31 the productivity index value shows a linear trend for 8 months and decreases to zero at the end of a dimensionless time of 6500 days. Compared to a vertical well completed in the same reservoir the productivity values are 29% greater indicating a larger production.

Figure 5.31: Variation of Productivity Index with time for a 4-lateral well with 2000 ft lateral lengths, which are at the same depth.

Figure 5.32 shows the variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 2000 ft lateral length, which are at same depth.

Figure 5.32: Variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 2000 ft lateral lengths, which are at the same depth.

The results for the single Vertical well for productivity index values are presented in Figure 5.33.

As shown in Figure 5.33 the productivity index value shows a linear trend for 6 years.

Figure 5.33 Variation of Productivity Index with time for a single Vertical Well.

Figure 5.34 shows the variation of dimensionless pressure and its derivative with dimensionless time for a single Vertical Well.

Figure 5.34: Variation of dimensionless pressure and its derivative with dimensionless time for a single Vertical Well.

Figure 5.35 shows the variation of Productivity Index with time for a single lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths.

Figure 5.35: Variation of Productivity Index with time for a single lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths.

Figure 5.36 shows the variation of Productivity Index with time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the same depth.

Figure 5.36: Variation of Productivity Index with time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the same depth.

Figure 5.37 shows the variation of Productivity Index with time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the different depth.

Figure 5.37: Variation of Productivity Index with time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the different depth.

Figure 5.38 shows the variation of Productivity Index with time for a 4-lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the same depth.

Figure 5.38: Variation of Productivity Index with time for a 4-lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the same depth.

Figure 5.39 shows the variation of dimensionless pressure and its derivative with dimensionless time for a single lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths.

Figure 5.39: Variation of dimensionless pressure and its derivative with dimensionless time for a single lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths.

Figure 5.40 shows the variation of dimensionless pressure and its derivative with dimensionless time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at same depths.

Figure 5.40: Variation of dimensionless pressure and its derivative with dimensionless time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the same depth.

Figure 5.41 shows the variation of dimensionless pressure and its derivative with dimensionless time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at different depths.

Figure 5.41: Variation of dimensionless pressure and its derivative with dimensionless time for a dual lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at different depths.

Figure 5.42 shows the variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at same depths.

Figure 5.42: Variation of dimensionless pressure and its derivative with dimensionless time for a 4-lateral well with 500 ft, 1000 ft, 1500 ft and 2000 ft lateral lengths, which are at the same depth.

PI, Dimensionless Pressure and Dimensionless Pressure Derivative Curve trends:

The productivity index values curve show a linear trend initially for all the configurations (single lateral, dual laterals (laterals at same and different depths), 4-laterals) that were considered and start declining at a later stage. The dimensionless pressure values show a linear trend initially for all the configurations (single lateral, dual laterals (laterals at same and different depths), 4-laterals) that were considered and start increasing at the later stage. The dimensionless pressure derivative values show a declining trend initially for all the configurations (single lateral, dual laterals (laterals at same and different depths), 4-laterals) that were considered and increase at the later stage.

The productivity index value shows a linear trend for 10 years 9 months for a 500 ft single lateral well and the productivity values are 57% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 4 years 1 month for a 500 ft dual lateral well with laterals at same depth and the productivity values are 49% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 2 years 7 months for a 500 ft dual lateral well with laterals at different depth and the productivity values are 49% greater similar to the Dual Laterals at the same depth. However, the boundary effects are observed earlier at the Dual Laterals with laterals at different depths when compared to Dual Laterals well with laterals at same depths. The productivity index value shows a linear trend for 1 year 3 months for a 500 ft 4-lateral well with laterals at same depth and the productivity values are 47% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 5 years 5 months for a 1000 ft single lateral well and the productivity values are 50% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 2 years 7 months for a 1000 ft dual lateral well with laterals at same depth and the productivity values are 46% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 1 year 5 months for a 1000 ft dual lateral well with laterals at different depth and the productivity values are 48% greater almost similar to the

Dual Laterals at the same depth. However, the boundary effects are observed earlier at the Dual Laterals with laterals at different depths when compared to Dual Laterals well with laterals at same depths. The productivity index value shows a linear trend for 1 year 3 months for a 1000 ft 4-lateral well with laterals at same depth and the productivity values are 35% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 2 years 7 months for a 1500 ft single lateral well and the productivity values are 50% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 1 year 9 months for a 1500 ft dual lateral well with laterals at same depth and the productivity values are 43% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 1 year 3 months for a 1500 ft dual lateral well with laterals at different depth and the productivity values are 43% greater similar to the Dual Laterals at the same depth. However, the boundary effects are observed earlier at the Dual Laterals with laterals at different depths when compared to Dual Laterals well with laterals at same depths. The productivity index value shows a linear trend for 1 year for a 1500 ft 4-lateral well with laterals at same depth and the productivity values are 32% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 1 year 9 months for a 2000 ft single lateral well and the productivity values are 46% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 1 year 6 months for a 2000 ft dual lateral well with laterals at same depth and the productivity values are 34% greater when compared to a vertical well completed in the same reservoir. The productivity index value shows a linear trend for 1 year 6 months for a 2000 ft dual lateral well with laterals at different depth and the productivity values are 34% greater similar to the Dual Laterals at the same depth. However, the boundary effects are observed earlier at the Dual Laterals with laterals at different depths when compared to Dual Laterals well with laterals at same depths. The productivity index value shows a linear trend for 8 months for a 2000 ft 4-lateral well with laterals at same depth and the productivity values are 29% greater when compared to a vertical well completed in the same

reservoir.

CHAPTER VI: CONCLUSION AND FUTURE WORK

The main focus of this work is to calculate the productivity indexes for different types of configurations using a numerical solution method and examine the variation of dimensionless pressure with respect to dimensionless time for all these configurations. To achieve the above mentioned objective five different types of configurations were considered. They were single vertical well, single horizontal well (for lateral length of 500 ft, 1000 ft, 1500 ft, 2000 ft), dual lateral well with laterals at same depth (for lateral lengths of 500 ft, 1000 ft, 1500 ft, 2000 ft), dual lateral well with laterals at different depths (for lateral lengths of 500 ft, 1000 ft, 1500 ft, 2000 ft), 4-lateral well with laterals at same depth (for lateral lengths of 500 ft, 1000 ft, 1500 ft, 2000 ft). Using a three-phase black oil simulator (ECLIPSE) configurations were created and runs were conducted for a period of 30 years. Results of these runs were tabulated and productivity indexes for these configurations were calculated and plotted. Along with this dimensionless pressure, dimensionless time and derivative of dimensionless pressure are also calculated and plotted. Based on results, the following conclusions were drawn from this research:

1. Productivity Indexes show a linear trend until the boundary effects are felt. This linear trend sections are shorter for longer laterals as a result of oil recoveries in a shorter time.
2. All lateral configurations show increase in PI values when compared to the PI value obtained from a vertical well completed in the same reservoir.
3. PI values show a decreasing trend with increase in time while the dimensionless PI values show decreasing trend with increase in dimensionless time.
4. The derivative curves for the dimensionless PI values show a minimum value. And the dimensionless times corresponding to the minimum point exhibit similar values for all configurations considered in this study.
5. In the case of wells with two lateral configurations where one considers both laterals at same depths and the second one considers laterals extending from vertical at different depths, PI values are similar. Thus, the location of deviation points for laterals do not affect the PI values for the two configurations used in the runs.

FUTURE WORK:

Future work can include the following:

- More configurations (like 4 or more lateral well with laterals at different depths, 4-lateral well with laterals placed at some angle etc.) should be considered and productivity index should be calculated for all the configurations.
- For all configurations, runs should be made with different skin factors and permeabilities.
- Runs should be conducted to show the effect of well completion effects such as hole size and completion intervals.

Appendix

Nomenclature

h = formation thickness, ft.

k_h = horizontal permeability, md

k_v = vertical permeability, md

L = length of the horizontal well, ft.

r_{eh} = drainage radius of the horizontal well, ft.

r_w = wellbore radius, ft.

J_h = productivity index, STB/day/psi.

q = flow rate, STB/day.

μ = Viscosity, cp.

B_o = Formation Volume factor, bbls/STB.

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