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A Software for Productivity Enhancement of Horizontal Wells

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Abstract Reservoir pressure often drops due to increase in production which subsequent results in reduction in production rates of a well. Thus, the need to enhance productivity becomes inevitable. In this work, a comparative analysis on the different productivity index models was carried out for high productivity estimation. The effect of reservoir and well parameters on the productivity indices of horizontal wells were studied and several completion technologies used for well completion and proposes various reservoir conditions under which each type of completion can function most effectively were also investigated. A robust software for production enhancement in horizontal wells was also developed using Visual Basic .net application. The results of the sensitivity analysis indicated that the Productivity (PI) increased with an increase in well length for all the productivity index models. It also showed that PI increased with increase in well length and anisotropy value, and that horizontal wells are better suited for thin beds. The result of the effect of completion method on skin showed that wells that are perforated at equal interval along the wellbore experienced a little or no skin effect thereby enhancing productivity. The results can be used as a guide for the selection of the most suitable completion type for a horizontal well based on reservoir characteristics. With the use of the R-factor, it can serve as a guide when a horizontal well is due for stimulation.

Keywords Production Enhancement, Skin, Productivity Index, Horizontal Wells

1. Introduction

The application of horizontal well technology is a rapidly growing recent technology worldwide that is associated with high cost of development, especially its extension into deep and ultra-deep offshore exploration, drilling and production which comes with huge capital expenditure. It becomes necessary to optimize the use of this technology with the knowledge of effects of the various well/reservoir parameters, purposely to maximize oil recovery from reservoirs and ultimately increase company profitability. This induces the reservoir and production engineers apply methods of well stimulation, completion type efficiency evaluation and enhanced oil recovery among others. This study reviews several completion technologies used for well completion and proposes various reservoir conditions under which each type of completion can function most effectively. Sensitivity analysis was conducted on the factors that affect productivity of horizontally drilled wells. Various reservoir parameters and crude oil characteristics that will influence the choice of a completion configuration were examined to enhancing productivity. Ibelegbu (2004) in his work on the "productivity index of horizontal wells" noted that PI increases with increasing lateral length [1]. Setiawan *et al* (2016) stated that the processes and practices that enable infill drilling, reservoir management, EOR, Integrated Operations (IO) and production enhancement activities are quite complex. Setiawan further stressed that horizontal wells are more suitable for reservoirs with greater vertical permeability (KV> KH), as this increases horizontal well productivity index [2]. Economides *et al.* (1991) developed numerical techniques to facilitate the simulation of special problems in the simulation of the response of fractures (natural and induced) in regard to their contact with the well (longitudinal or transverse), conductivity, and conductivity distribution along the fracture [3].

Mukherjee *et al*. (1999) in their paper on "a parametric comparison of horizontal and vertical well performance" presented screening criteria for vertical and horizontal wells with or without induced fractures. The parametric basis of such screening makes the decision on either type of well more objective. A simple procedure to calculate the optimum number of orthogonal transverse fractures in horizontal wells and their size is also presented. The main advantages of horizontal wells include increasing the productivity per well, accessing the unconventional resources, and reducing the number of well needed and thereby reducing the cost of field development [4]. Langseth (1990) performed a numerical analysis of horizontal well performance and compared installation and operation costs of horizontal and vertical wells [5]. Economides *et al.* (1991) used a numerical reservoir simulator to examine the performance of a horizontal well. An important feature of the simulator include a flexible grid scheme that uses a finite volume technique to simulate difficult geometries and features (faults, horizontal wells, and irregular boundaries) that do not follow the standard Cartesian orthogonality of other simulators [3]. Erdal *et al.* (2011) highlighted the comparison of fractured horizontal well performance in tight sand and shale reservoirs by using a trainer flow model and showed that decreasing hydraulic-fracture spacing increases the productivity of the well, but the incremental production gain for each additional hydraulic fracture decreases [6].

Ezenweichu *et al*. (2015) observed that the severity of damage in horizontal wells is significantly increased as the ratio of vertical to horizontal permeability degrades and also to a lesser extent as formation thickness increases [7]. Danilovic *et al.* (2006) noted that well completion type affects well performance and the completion options depend on the degree of rock consolidation, on the need for water or gas shut off, the anticipated flow rate, the completion longevity, the shale reactivity and the stability, the degree of grain sorting and the lamination [8]. It was suggested that factors to be considered in selecting completion options include: Rock and Formation Type, Drilling Method Drilling Fluid/Mud Clean up, Stimulation Requirement, Production Mechanism Requirements and Work-over requirements.

2. Materials and Method

Methods of Development

Models developed from Darcy's flow equation through porous medium for development of productivity indices of horizontal wells by Joshi, Borizov, Renard-Dupuy and Giger were used in this research work. Joshi, Renard-Dupuy and Giger's models are mainly applicable to anisotropic reservoirs while Borizov's is designed for isotropic reservoirs.

2.1. Determination of Productivity Index Using Different Horizontal Well Models

a. Borisov's Model

$$J_h = \frac{qh}{P_r - P_{wf}} = \frac{0.00708\,K_h h}{\mu_o \beta_o \left[\ln\left(\frac{4r_e h}{L}\right) + \frac{h}{L}\ln\left(\frac{h}{2\pi r_w}\right)\right]} \tag{1}$$

b. Joshi's Model

$$J_h = \frac{q_o}{P_r - P_{wf}} = \frac{0.00708\,\beta K_h h}{\mu_o \beta_o \left[\ln\left(\frac{a + \sqrt{a^2 - (L/2)^2}}{\frac{L}{2}}\right) + \left(\frac{\beta h}{L}\right)\ln\left(\frac{\left(\frac{\beta h}{L}\right)^2 + \beta^2 \delta^2}{\left(\frac{\beta h r_w}{2}\right)}\right)\right]} \tag{2}$$

Where:

$$a = \left(\frac{L}{2}\right)\left[0.5 + \sqrt{0.25 + \left(\frac{2r_e h}{L}\right)^2}\right]^{0.5} \tag{3}$$

$$\beta = \sqrt{K_h / K_v} \tag{4}$$

$$\delta = \frac{h}{2} - d \tag{5}$$

c. Giger's Model

$$J_h = \frac{q_o}{P_r - P_{wf}} = \frac{0.00708\,K_h L}{\mu_o \beta_o \left[\left(\frac{L}{2}\right)\ln\left(\frac{1 + \sqrt{1 - \left(\frac{L}{2r_e h}\right)^2}}{\left(\frac{L}{2r_e h}\right)}\right) + \ln\left(\frac{h}{2\pi r_w}\right)\right]} \tag{6}$$

d. Renard and Dupuy Model

$$J_h = \frac{q_o}{P_r - P_{wf}} = \frac{0.00708\, K_h h}{\mu_o \beta_o \left[Cosh^{-1}\left(\frac{2a}{L}\right) + \left(\frac{h}{L}\right) \ln\left(\frac{h}{2\pi r_w}\right) \right]} \quad (7)$$

3. Effects of various parameters on PI and Productivity

3.1. Effect of Drainage Area on Productivity Index

Using the well parameters, and different drainage area (20 ft, 40 ft, 60 ft and 80 ft) and

$$r_e = \sqrt{\frac{A \times 43560}{\pi}}$$

(For circular drainage area) is used to calculate the PI's for different values of K_v/K_h (0.1, 0.5, 1.0) and for drainage areas.

3.2. Effect of Well Completion on Productivity Index

When a well undergoes completion, three types of skin occur - skin due to perforation (SP), skin due to penetration (SA), skin due to crush zone permeability (SC). Considering the case of skin due to penetration, some wells are fully penetrated along the interval of interest. In this case, S_a tend to zero (0); other wells are partially penetrated along the interval of interest, this results in pseudo skin due to partial completion. This kind of completion restricts fluid entry into the wellbore. However, the analysis on effect of completion on productivity will only be considered for a partially completed well.

For horizontal well h = L i.e. lateral length which might be greater than h i.e. L > h

$$G(b') = 2.948 - 7.363b' + 11.45(b')^2 - 4.675(b')^3 \quad (8)$$

$$S_p = \left(\frac{1}{b'} - 1\right)[\ln(h_D) - G(b')] \quad (9)$$

Where b' has already been defined as:

$$b' = \frac{h_p}{h} \quad (10)$$

$$h_D = \frac{h}{r_w}\sqrt{\frac{K_h}{K_v}} \text{ (for Case A)} \quad (11)$$

$$h_D = \frac{h}{2r_w}\sqrt{\frac{K_h}{K_v}} \text{ (for Case B)} \quad (12)$$

$$h_D = \frac{h}{3r_w}\sqrt{\frac{K_h}{K_v}} \text{ (for Case C)} \quad (13)$$

For horizontal well h = L i.e. lateral length which might be greater than h i.e. L >h.

$$G(b') = 2.948 - 7.363b' + 11.45(b')^2 - 4.675(b')^3 \quad (14)$$

Given the following well/reservoir parameters hp = 20 ft, h =100 ft, K_v/K_h =0.5, r_w =0.365 ft

4. Results and Discussion

4.1. Effect of Length and Anisotropy on Productivity Index

The following reservoir and well data are available for well A.

kh = 75 md, h = 25 ft, μo = 0.62 cp, B_O = 1.34 rb/stb, r_w = 0.365 ft, K_v/K_h = 0.1, 0.5, 1.0.A = 80 acres, H = 160ft, r_w = 0.365ft, r_{eh} = 1053 ft. This was done by varying the length (100ft, 500ft, 900ft, 1300ft and 1700ft and the permeability ratio . the horizontal productivity index is then calculated using the various horizontal well productivity models stated.

From the results (Figure. 4.4 and Table 4.2) as the well length increased, there was an increase in the productivity index. This implies that Horizontal well productivity can be seen to be affected by well length because a shorter well length will produce a lower productivity index compared to a longer well length.

However, the Giger's productivity index model overestimates the productivity index when compared to the real data for each well length with respect to other models used.

Table 4.1 & 4.2: Productivity Index of the Models at different Length

Length (ft)	Borisov's Model (PI; stb/d-psi)	Joshi's Model (PI; stb/d-psi)	Giger's Model (PI; stb/d-psi)	Renard Dupuy (PI; stb/d-psi)
500	29.0885	26.3244	29.209	29.0877
550	31.0345	28.1655	31.2015	31.0331
600	32.9477	29.9756	33.1732	32.9455
650	34.8375	31.7627	35.1355	34.8341
700	36.7117	33.5337	37.0986	36.7066
750	38.5768	35.2944	39.0718	38.5695
800	40.4386	37.0497	41.0635	40.4281
850	42.3019	38.804	43.0823	42.2874
900	44.1713	40.561	45.1366	44.1514
950	46.0508	42.3241	47.235	46.0239
1000	47.9441	44.0963	49.3865	47.9083

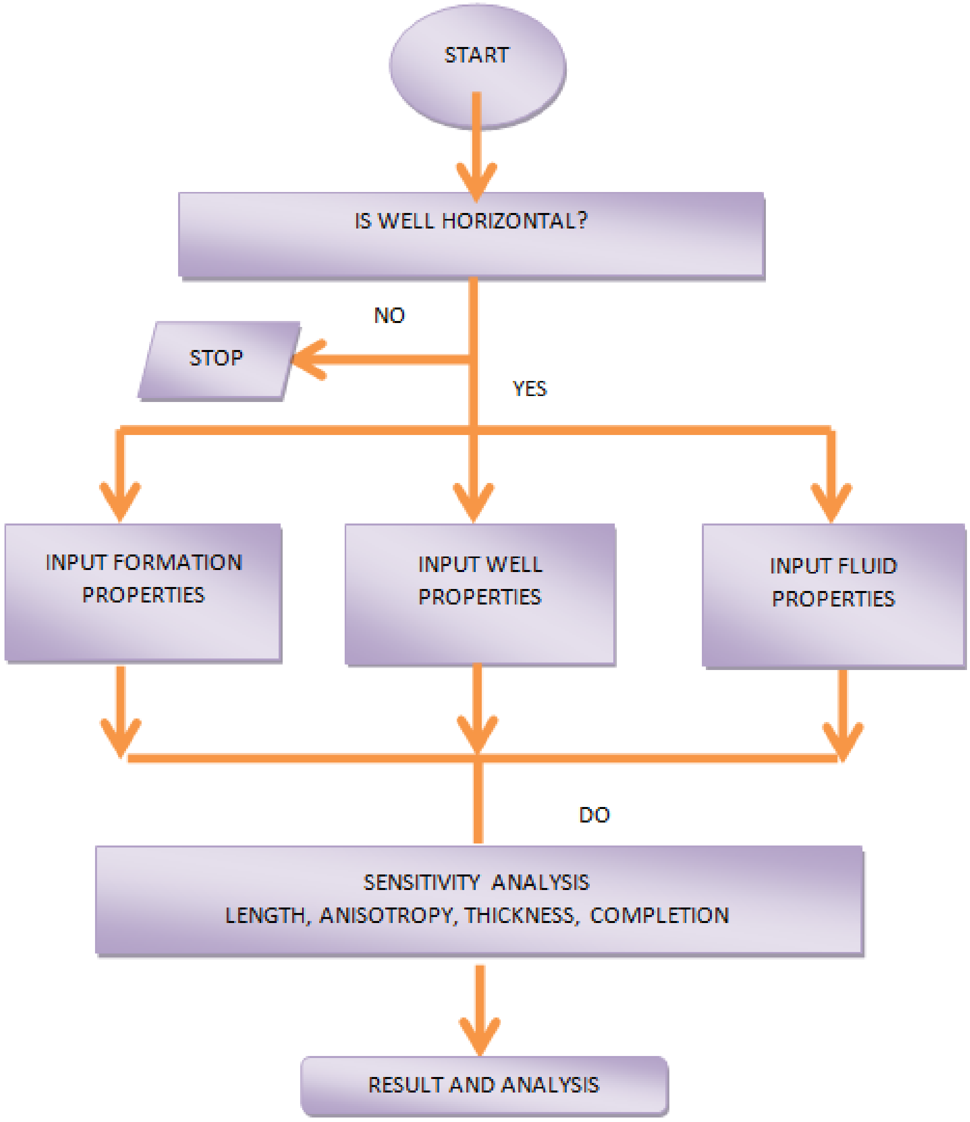

Figure 4.1: Flow chart for Software Algorithm

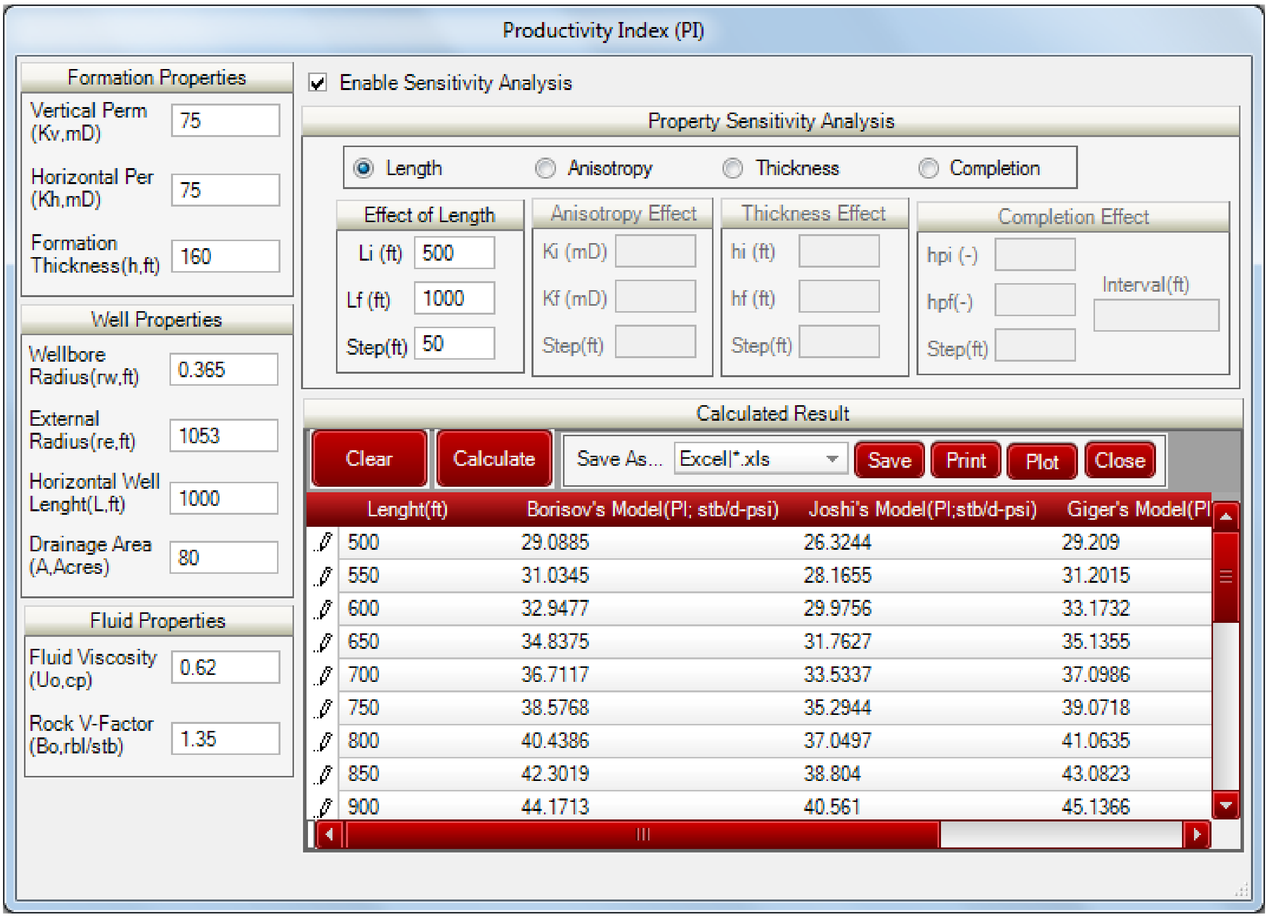

Figure 4.2: Sensitivity Analysis on Variation of Well Length vs PI

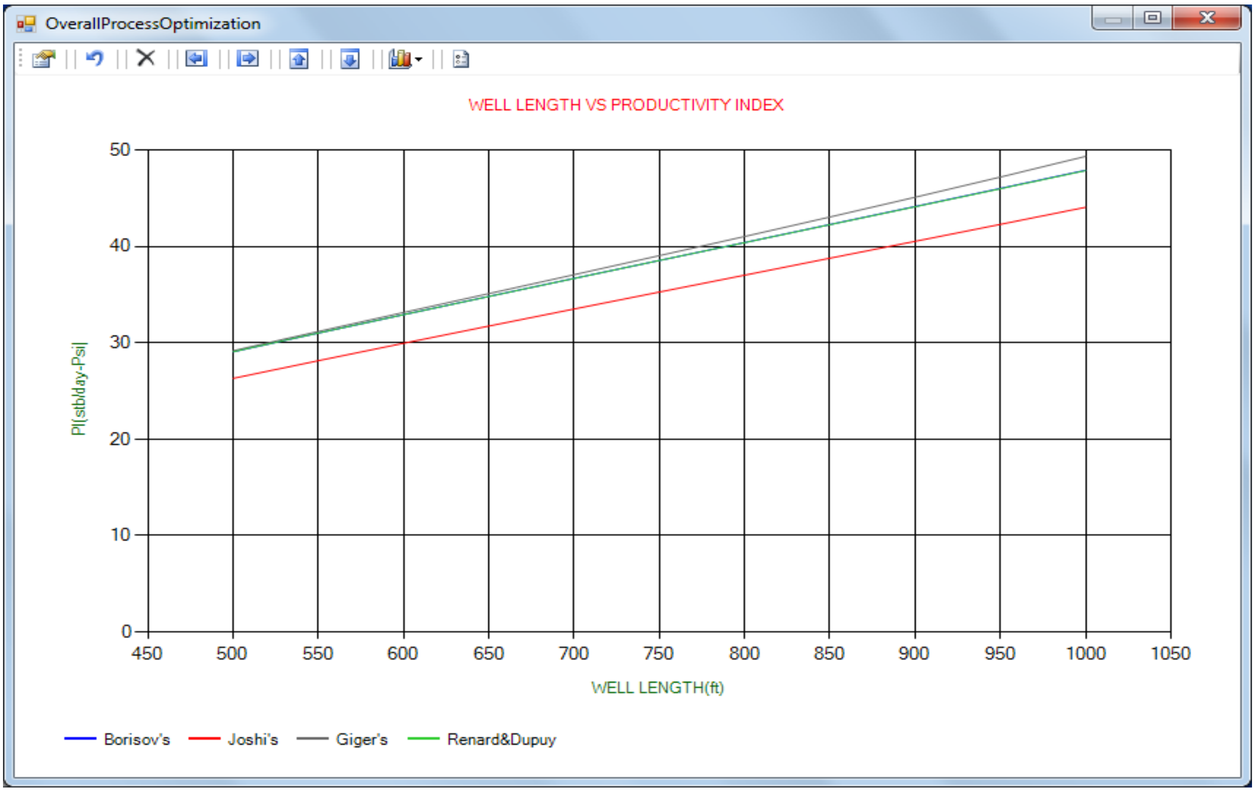

Figure 4.3: Plot of Productivity Index with Well Length Variation

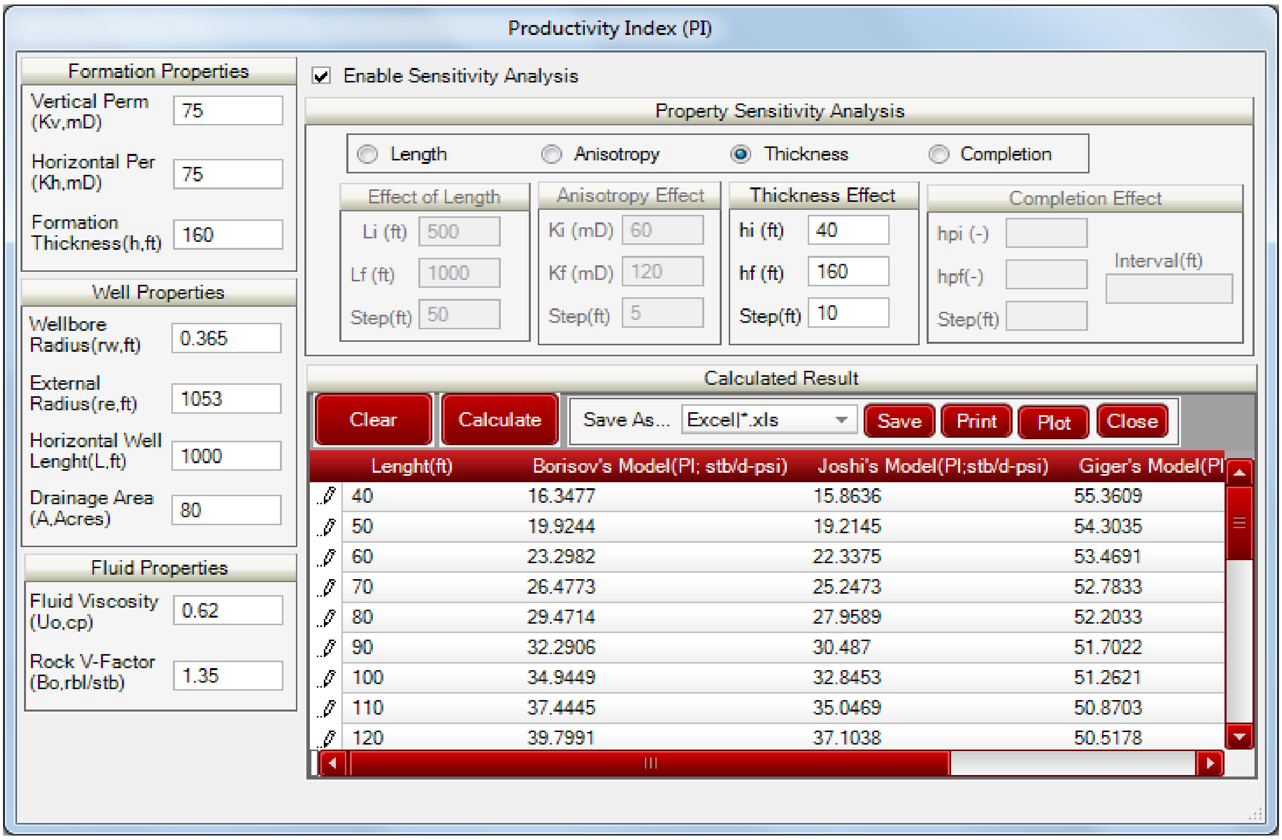

Figure 4.4: Sensitivity Analysis Well Thickness vs PI

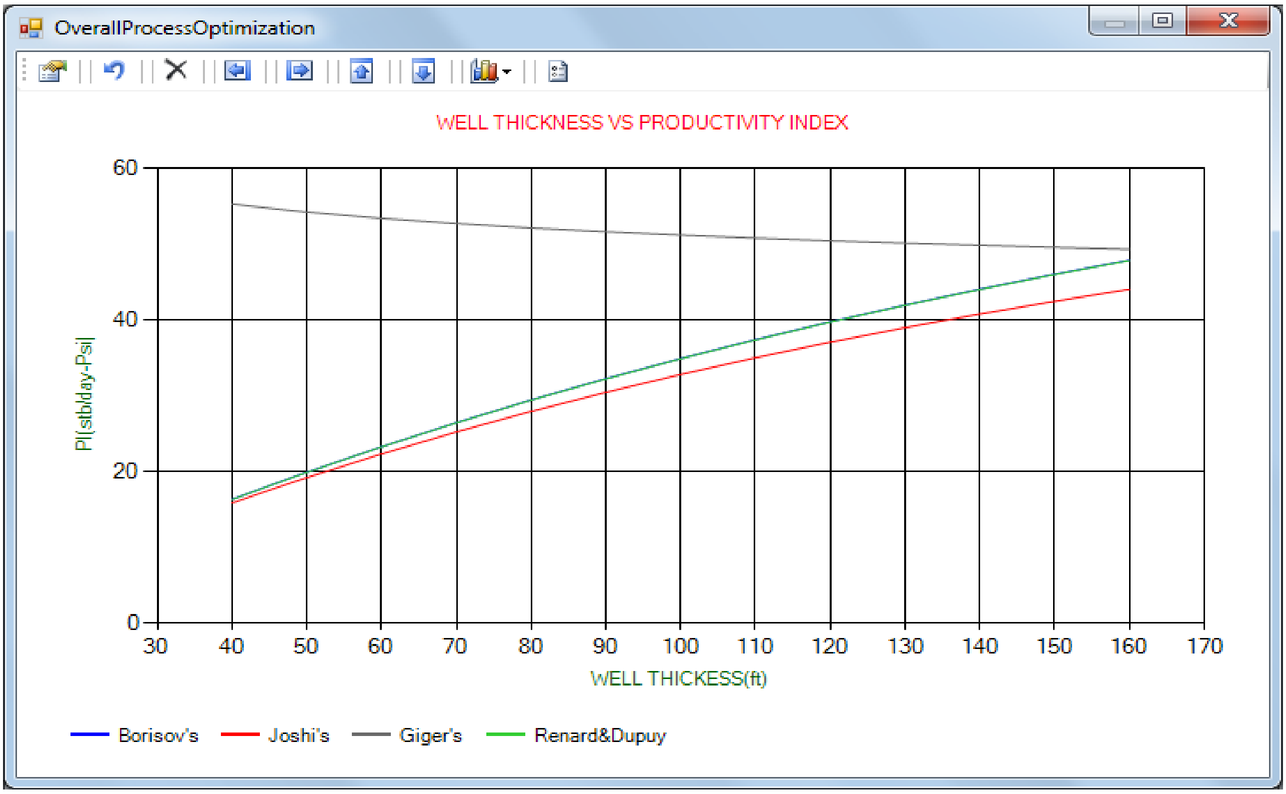

Figure 4.5: A Plot of PI with Well Thickness Variation

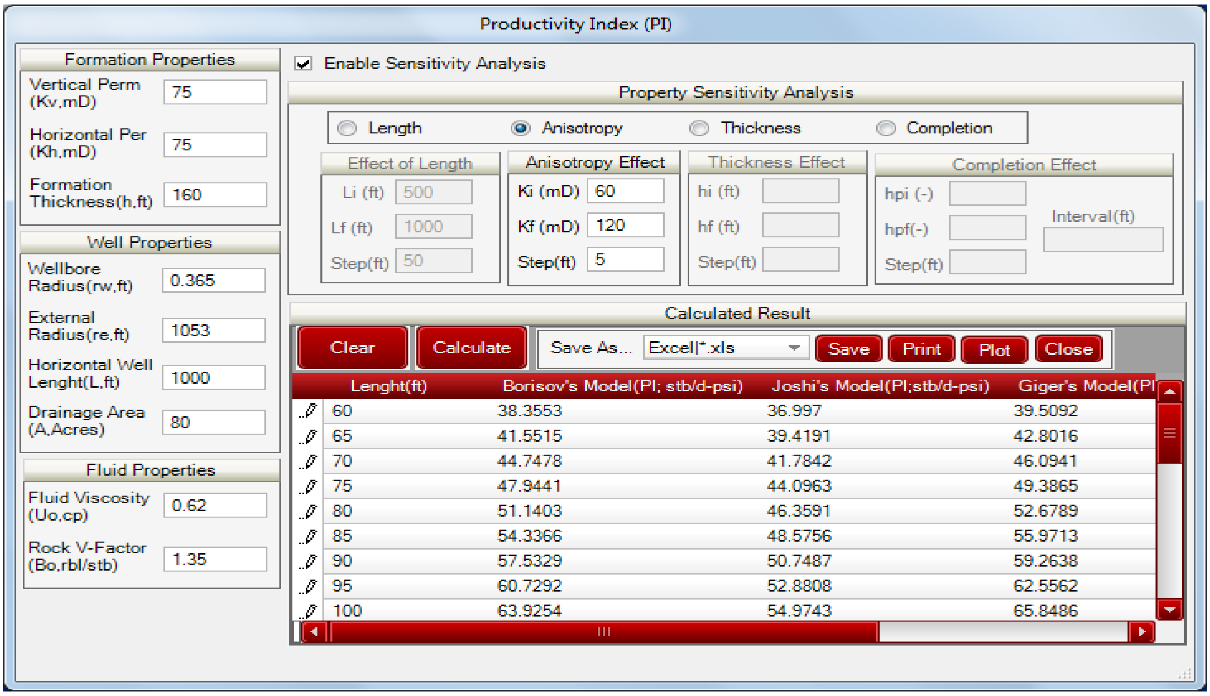

Figure 4.6: Variation of PI vs Anisotropy

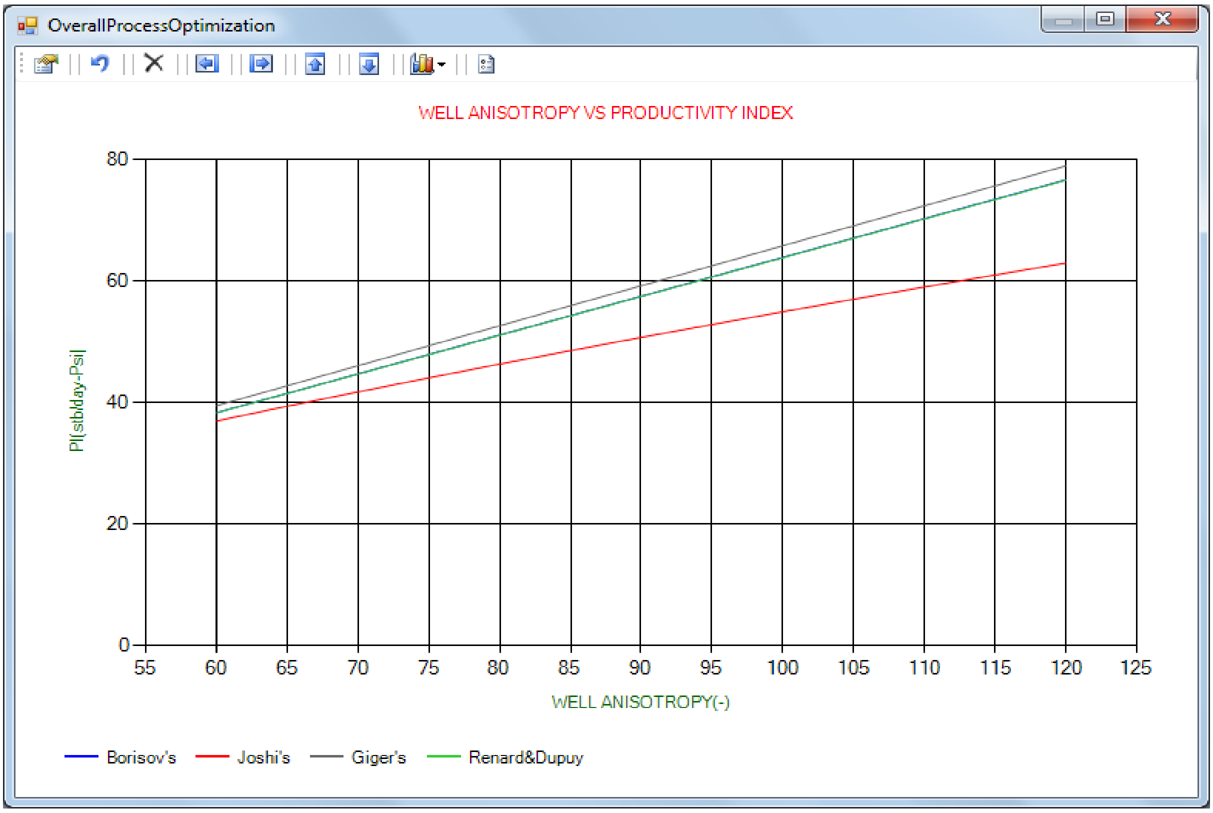

Figure 4.7: Variation of PI vs Penetration Ratio and Pseudo Skin

4.2. Effect of Pseudo-Skin Due to Partial Penetration on PI

Generally, the larger the skin, the lower the productivity index (PI) of a well. This effect is however more pronounced for the vertical well. This is due to the multiplier h/L on the horizontal well skin. h is the pay zone thickness and L is the lateral length of the horizontal well. As L increases, the effect of skin on horizontal well productivity index reduces appreciably.

Table 4.3: Effect of well thickness on PI variation with well thickness

Length (ft)	Borisov's Model (PI; stb/d-psi)	Joshi's Model (PI;stb/d-psi)	Giger's Model (PI;stb/d-psi)	Renard Dupuy (PI;stb/d-psi)
40	16.3477	15.8636	55.3609	16.331
50	19.9244	19.2145	54.3035	19.9047
60	23.2982	22.3375	53.4691	23.2757
70	26.4773	25.2473	52.7833	26.4524
80	29.4714	27.9589	52.2033	29.4444
90	32.2906	30.487	51.7022	32.2617
100	34.9449	32.8453	51.2621	34.9145
110	37.4445	35.0469	50.8703	37.4128
120	39.7991	37.1038	50.5178	39.7662
130	42.0178	39.0274	50.1979	41.984
140	44.1094	40.8278	49.9052	44.0748
150	46.0823	42.5146	49.6359	46.047
160	47.9441	44.0963	49.3865	47.9083

Table 4.4: Data showing variation of PI with anisotropy

Length (ft)	Borisov's Model (PI; stb/d-psi)	Joshi's Model (PI;stb/d-psi)	Giger's Model (PI;stb/d-psi)	Renard D upuy (PI;stb/d-psi)
60	38.3553	36.997	39.5092	38.3266
65	41.5515	39.4191	42.8016	41.5205
70	44.7478	41.7842	46.0941	44.7144
75	47.9441	44.0963	49.3865	47.9083
80	51.1403	46.3591	52.6789	51.1022
85	54.3366	48.5756	55.9713	54.2961
90	57.5329	50.7487	59.2638	57.4899
95	60.7292	52.8808	62.5562	60.6838
100	63.9254	54.9743	65.8486	63.8777
105	67.1217	57.0312	69.1411	67.0716
110	70.318	59.0533	72.4335	70.2655
115	73.5142	61.0424	75.7259	73.4594
120	76.7105	63	79.0184	76.6533

Table 4.5: Variation of Productivity Index with Penetration Ratio and Pseudo Skin for Partially Completed well (Brons and Marting Correlation)

Perforation Interval (hp: ft)	Penetration Ratio (b'; -)	CASE A, Pseudo Skin (Sp:-)	CASE A, Productivity Index (PI;stb/d-psi)	CASE B, Pseudo Skin (Sp:-)	CASE B, Productivity Index (PI;stb/d-psi)	CASE C, Pseudo Skin (Sp:-)	CASE C, Productivity Index (PI;stb/d-psi)
20	0.125	27.1994	2792.6551	22.3474	2787.8031	1.3773	2766.833
40	0.25	12.9996	2778.4553	10.9202	2776.3759	1.933	2767.3887
60	0.375	7.5542	2773.0099	6.399	2771.8547	1.4061	2766.8618
80	0.5	4.5384	2769.9941	3.8453	2769.301	0.8495	2766.3052
100	0.625	2.6434	2768.0991	2.2275	2767.6832	0.43	2765.8857
120	0.75	1.3963	2766.852	1.1653	2766.621	0.1667	2765.6224
140	0.875	0.5633	2766.019	0.4643	2765.92	0.0363	2765.492

Table 4.6: Variation of Productivity Index with Penetration Ratio and Pseudo Skin for Partially Completed well (Brons and Marting Correlation)

Perforation Interval (hp: ft)	Penetration Ratio (b')	Pseudo Skin (Sp)	Productivity Index (stb/d-psi)
Case A			
20	0.125	27.1994	2792.6551
40	0.25	12.9996	2778.4553
60	0.375	7.5542	2773.0099
80	0.5	4.5384	2769.9941
100	0.625	2.6434	2768.0991
120	0.75	1.3963	2766.852
140	0.875	0.5633	2766.019
Case B			
Perforation Interval (hp: ft)	**Penetration Ratio (b')**	**Pseudo Skin (Sp)**	**Productivity Index (stb/d-psi)**
20	0.125	22.3474	2787.8031
40	0.25	10.9202	2776.3759
60	0.375	6.399	2771.8547
80	0.5	3.8453	2769.301
100	0.625	2.2275	2767.6832
120	0.75	1.1653	2766.621
140	0.875	0.4643	2765.92
Case C			
Perforation Interval (hp: ft)	**Penetration Ratio (b')**	**Pseudo Skin (Sp:-)**	**Productivity Index (stb/d-psi)**
20	0.125	1.3773	2766.833
40	0.25	1.933	2767.3887
60	0.375	1.4061	2766.8618
80	0.5	0.8495	2766.3052
100	0.625	0.43	2765.8857
120	0.75	0.1667	2765.6224
140	0.875	0.0363	2765.492

4.3. Effect of Penetration Ratio on PI

From fig 4.4, it can be seen that productivity index shows slight decrease with increasing penetration ratio. The analysis done for the three (3) well configurations shows that the case C i.e., the well with N intervals open to production, and is the best configuration for any partial well completion. The no opened interval on the liner allows for less pressure drop and allows for easy fluid entry into the wellbore. In doing so, the problems associated with skin will be reduced. In some cases, there are cases of no skin, hence no damage around the wellbore.

4.4. Effect of Anisotropy

Fig. 4.6 shows that the productivity index (PI) will increase with increasing well anisotropy and lateral length. This increase however enhances productivity. Thus, longer horizontal well length enhances or increases productivity. This is explained by the fact that a large portion of the reservoir has been contacted and the pressure drop along the wellbore is reduced, enhancing productivity. In the case of anisotropy, it shows that horizontal wells are more suitable for reservoirs with high vertical permeability, Kv as thus will increase horizontal well productivity index.

4.5. Effect of Well Thickness

By varying well thickness (25ft, 50ft, 75ft, 100ft) 125ft with corresponding change in well length the effect was determined. Fig. 4.5 shows that the incremental gain in productivity is much higher in a thick reservoir than in a thin reservoir but when productivity ratio Jh/Jv is calculated for reservoir thickness, we will discover that a thin reservoir produces more than a thick reservoir. This is as a result of a wellbore exposure to the formation.

Therefore, we can say that horizontal wells are more productive in thin reservoir than in thick ones. In a thick reservoir, a horizontal well behaves like a vertical well because of the small exposure of the wellbore to the formation.

5. Conclusion

A comparative study of horizontal well productivity index was carried out and the factors affecting productivity of horizontal wells were incorporated. To access the performance of a well, the gross production rate and the cumulative production should be taken and studied to know the life history of the well.

The analysis done for the three (3) well configurations shows that the Case C is the best configuration for any partial well completion. The no opened interval on the liner allows for less pressure drop and allows for easy fluid entry into the wellbore. In doing so, the problems associated with skin will be reduced thus enhancing production. Thus the software is recommended for evaluating the performance of horizontal wells.

Nomenclature

a = Half major axis of drainage ellipse, ft
Bo = Oil formation volume factor, rb/stb
C = Elgaghad et al. parameter
CH = Babu and Odeh shape factor
h = Formation thickness
Jh = Horizontal well productivity index, STB/day-psi
K = Permeability, md
Kh = Horizontal permeability, md
Kv = Vertical permeability, md
L = Horizontal well length, ft
hp = perforated interval, ft
Pr = Average reservoir pressure, psia
Pwf = Flowing wellbore pressure, psi
Qo = Oil flow rate, STB/day
rc = Radius of compacted zone, ft
reh = Horizontal well drainage radius, ft
rp = radius of compacted tunnel, ft
rw = Effective wellbore radius, ft
S = Skin factor
ST = Total skin factor
Sm = Mechanical skin factor
Sp = Pseudo skin factor caused by partial
b' = Penetration ratio
β = Anisotropy (Kh/Kv), dimensionless
Sr = Babu and Odeh
Lp = Penetration tunnel length
ΔP = Pressure drop between the reservoir and wellbore, psi
δ = Eccentricity factor
X = Renard and Dupuy area
μo = Oil viscosity, cp

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