An Empirical Correlation for Two-Phase Inflow Performance Relationship in Horizontal Oil Wells

Ramadan Emara [1, 2]

[1](Home) Mining and Petroleum Engineering Department, Faculty of Engineering, Al Azhar University
[2](Secondment) Petroleum and Natural Gas Technology Department, Faculty of Engineering, The British University in Egypt

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Abstract - *The appropriate method to increase the well productivity in low permeability and naturally fractured reservoirs is the horizontal well because of its large reservoir contact area. Several investigators have utilized reservoir simulation to evaluate the horizontal well performance in solution gas drive reservoirs. This research scrutinizes the performance of a two phase inflow for a horizontal oil well producing through the boundary dominated flow regime. A 430 data points were collected from simulation of 43 data sets of fluid property, relative permeability and reservoir geometry. All data sets were investigated from initial pressure to minimum bottom-hole pressure. Linear regression analysis was used to develop an empirical inflow performance relationship (IPR) based on the simulator outcomes. Statistical analyses were used to evaluate the performance of the developed correlation. The obtained outcomes include an average relative error (ARE) of 0.78, an average absolute error (AARE) of 2.37 and coefficient of regression (R^2) of 0.995. The presented IPR relationship was compared to other horizontal inflow performance relationships available in literature. The proposed correlation exhibited suitable approximations of well performance over a wide range of operating circumstances.*

Key Words: Two-phase IPR; Solution gas drive reservoir; Horizontal oil well IPR.

1. INTRODUCTION

The main task of a petroleum engineer is to enhance the well productivity. The horizontal well is the suitable solution for this purpose because of its reservoir contact area. The horizontal well accomplishes higher ultimate recovery than a vertical well in certain reservoir condition. In low permeability and naturally fractured reservoirs, the horizontal well represents the economic solution. The horizontal well represents an appropriate method for both production and injection in several enhanced oil recovery applications. Many researchers have used reservoir simulation to study the horizontal oil well behavior. These researches have led to present empirical correlations of IPR to estimate the performance of a horizontal oil well. In 1968, Vogel[1] investigated the performance of a vertical well in a solution gas drive reservoir. He developed an empirical IPR based on the investigation of simulation outcomes, and it was simple to apply and gain rapid approval by industry. In 1973, Fetkovich[2] scrutinized data of multi-rate tests accomplished in 40 boundary- dominated flow oil wells of 6 different oil reservoirs. He displayed that, once the gas saturation of oil wells becomes larger than the critical gas saturation, the typical inflow performance relationship (IPR) of gas wells can also be applied for oil wells. The presented IPRs were for vertical oil wells and could not be suitable for horizontal oil wells. In 1987, Plahn et al.[3] utilized a reservoir simulator to study the effect of different reservoir rock and fluid properties on the behavior of multiphase flow of horizontal oil wells in a solution gas drive reservoir. They presented a set of type curves to predict the production from horizontal oil wells. In 1989, Bendakhlia and Aziz [4] investigated the horizontal oil wells performance in a solution gas drive reservoir using a commercial reservoir simulator. The authors concluded that, the reservoir fluid and rock properties did not affect significantly on the IPRs. They presented an IPR function of the stage of reservoir depletion. In 1990, Cheng[5] investigated the performance of slanted and horizontal oil wells using a vertical/horizontal/slanted well simulator (Boast VHS). The author observed that, the IPRs for horizontal and slanted wells proceed like to the Vogel's IPR parabolic shape. He developed separate empirical IPRs corresponding with various angles. In 1998, Retnanto and Economides[6] scrutinized the horizontal and multibranched oil well performance in a solution gas drive reservoir using reservoir simulation. Based on nonlinear regression the authors developed an empirical IPR using simulation results. In 2005, Wiggins[7] investigated the performance of a horizontal oil well in a solution gas drive reservoir. The well was fully penetrating the reservoir producing through the boundary dominated flow regime. He presented two IPRs base on simulator results linear regression analysis. In 2013, based on linear regression analysis, Jabbar and AlNuaim[8] introduced an equation of IPR for a horizontal oil well producing from a solution gas drive reservoir using simulation results. The authors regressed the coefficients of the Harrison exponential equation to produce their equation. In 2013, Mohammadreza et al.[9] presented a Vogel-type IPR relationship based on regression analysis. They concluded that, the coefficients of their equation is a function of vertical and horizontal permeability ratio. In 2015. Ali Musa and Enamul[10] developed correlations of IPR based on regression analysis of actual data. The data was 62 set of downhole production data for 18 horizontal wells. They classified the data based on productivity index to produce their equations. In this research, a reservoir simulator was utilized to investigate the rate-pressure behavior of a horizontal oil well in a solution gas drive reservoir. The present paper suggests an empirical IPR based on linear regression analysis of the performance data produced through the simulation study. The developed IPR is compared to literature IPRs and shows suitable accuracy with those relationships.

2. Methodology

Eclipse Black oil reservoir simulator was used to generate rate-pressure data for a horizontal oil well in a solution gas drive reservoir. The simulation outcomes were created under the following assumptions: The horizontal well is completely penetrating the reservoir as shown in Fig 1, the production starts at the bubblepoint pressure, saturation of water phase is immobile, capillary pressure is negligible and boundary-dominated flow condition prevails. Forty-three various cases of reservoir circumstances were simulated to produce the rate-pressure behavior data. These cases cover a wide range of reservoir fluid, rock and geometry data. Table 1 illustrates the ranges of the simulated parameters. These parameters are initial pressure, temperature, oil gravity, gas gravity, residual oil saturation, critical gas saturation, connate water saturation, rock compressibility, horizontal well length, drainage width, horizontal and vertical permeabilities and pay zone thickness. A base case was installed to start the parameters sensitivity analysis. Afterwards, each parameter was varied from the lower value to the upper value of its range in each simulation run. In Table 1, the base case variable values are shown in the top line. For the rest of the cases reported, the reservoir variables are varied independently over the range presented in the table while preserving the values of the remainder of the variables in the base case. A blank space in the Table 1 displays that the base case value is carried forward. For each simulation case, the performance data of a horizontal oil well was obtained at constant bottomhole pressure. The maximum oil production rate was obtained from the simulator results at a minimum flowing bottomhole pressure of 14.7 psia.

For all Forty-three reservoir cases, the inflow performance curves were developed from the generated data. Fig. 2 shows the pressure-production behavior for the base case developed in this paper. The curve is convex as observed by Vogel in his research of vertical oil wells. Based on Vogel observation, he presented a robust normalization procedure which led to the development of his IPR. Fig. 3 illustrates the normalized presentation of the information offered in Fig.2. The results of all simulation cases were normalized in this manner. Linear regression analysis was implemented on these outcomes. Generally the resulting equation can be written as follows:

$$\frac{q_o}{q_{om}} = \frac{1+P1\left(\frac{p_{wf}}{p_r}\right)+P2\left(\frac{p_{wf}}{p_r}\right)^2}{1+P3\left(\frac{p_{wf}}{p_r}\right)+P4\left(\frac{p_{wf}}{p_r}\right)^2} \tag{1}$$

Where:
P1= -1.875898
P2= 0.875071
P3=-1.536952
P4= 0.558035

3. Correlation Validation

In order to validate the accuracy of the derived correlation, statistical analysis has been used to evaluate its performance. Statistical indicators are presented in the appendix. The obtained outcomes include an average relative error (ARE) of 0.78, an average absolute error (AARE) of 2.37 and coefficient of regression (R^2) of 0.995 for horizontal oil well IPR.

4. Results and Discussion

For verifying the proposed two-phase inflow performance relationship of a horizontal oil well, the presented correlation was compared to the IPR methods of Cheng, Retnanto and Economides, Wiggins, Ali Musa and Enamul, Mohammad reza et al, Harrison and Jabbar and AlNuaim to estimate their suitability for use. Table 2 illustrates five simulated drawdowns test data. Table 3 illustrates a comparison of eight IPRs approaches to the simulated data that are shown in Table 2. This case compares how well each correlation estimates the maximum oil production rate from given test data. It is observed for this case that the proposed IPR provides the best estimates of the maximum oil production rate. However, percent differences for the IPR Presented in this study is less than 1% for test 1, 2, 3 and 4 and less than 5% for test 5, while the IPRs of the other methods estimate the simulated data of percent differences greater than 40% for test 5.

5. Conclusion

- Numerical reservoir simulator was used to generate data of inflow performance for a horizontal oil well in a solution gas drive reservoir.
- Based on the simulator outcomes, an empirical inflow performance relationship has been presented for horizontal oil wells producing from solution gas drive reservoirs that are suitable for use over a wide range of reservoir properties
- The presented correlation is Vogel-type IPR that demand single point estimates of bottomhole flowing pressure, average reservoir pressure and oil production rate.

Nomenclature

API	Oil gravity
C	Rock compressibility, psi^{-1}
h	Oil formation thickness, ft
L	Horizontal well length, ft
k_h	horizontal permeability, md
K_v	vertical permeability, md
q_o	Oil production rate, STB/d
q_{om}	Maximum oil production rate, STB/d
P_1-P_4	Correlation coefficients
P_i	Initial reservoir pressure, psi
P_{wf}	Bottomhole flowing pressure, psi
S_{wi}	initial water saturation, fraction
S_{or}	residual oil saturation, fraction
S_{gc}	Critical gas saturation, fraction
T	Reservoir temperature, ^oF
X_a	drainage width, ft
ϕ	porosity, fraction
Υ_g	gas gravity

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APPENDIX

Statistical Error Analysis

The following three statistical parameters were used in this study to evaluate the accuracy of the correlations.

1- Average percent relative error (ARE)

$$E_r = \frac{1}{n_d}\sum_{1}^{n_d} E_i$$

Where

$$E_i = \left(\frac{x_{measured} - x_{estimated}}{x_{measured}}\right)_i * 100\,(i = 1,2,\ldots n_d)$$

2- Average absolute percent relative error (AARE)

$$E_a = \frac{1}{n_d}\sum_{1}^{n_d} E_i$$

3- Coefficient of correlation

$$r^2 = 1 - \sum_{1}^{n_d}(x_{measured} - x_{estimated})^2 / \sum_{1}^{n_d}(x_{measured} - x_{average})^2$$

The lower the value of E_r the more equally distributed are the errors between positive and negative values. The lower value of E_a the better the correlation.

The correlation coefficient describes the range of connection between two variables namely experimental and estimated values obtained from the correlation.

The value of r^2 varies from -1 to +1. As the value of correlation coefficient approaches +1, it means there is a strong positive relationship between these two variables.

Table 1: Simulation cases

Case	Pi	T	API	ϕ	Yg	S_{or}	S_{gc}	S_{wi}	C	L	Xa	Kh	Kv	h
Base Case	3500	180	45	0.2	0.65	0.3	0.05	0.25	0.00004	1500	1500	100	15	80
1	1500													
2	2500													
3	5000													
4		150												
5		165												
6		220												
7			20											
8			35											
9			60											
10				0.12										
11				0.16										
12				0.24										
13					0.55									
14					0.6									
15					0.7									
16						0.2								
17						0.25								
18						0.4								
19							0.02							
20							0.04							
21							0.1							
22								0.15						
23								0.2						
24								0.35						
25									0.000002					
26									0.000004					
27									0.00006					
28										500				
29										1000				
30										2000				
31											750			
32											1250			
33											3000			

Table 1: Continued

34												30		
35												70		
36												150		
37													5	
38													10	
39													20	
40														50
41														65
42														100

Table 2: Draw down Test Data

Item	Test 1	Test 2	Test 3	Test 4	Test 5
Reservoir Pressure, psi	5000	5000	3500	3500	1500
Bottom-hole Flowing Pressure, psi	2250	1250	2275	1925	1425
Oil Flow Rate, STB/d	10024	11423	4911.24	6184.7	455.62
Maximum oil Flow Rate, STB/d	12693.5	12693.5	7751.75	8541.6	2724.5

Table 3: Comparison of IPR Methods in Estimating the Maximum Oil Flow Rate

Method	Test 1 Error %	Test 2 Error %	Test 3 Error %	Test 4 Error %	Test 5 Error %
Cheng	6.173798	6.837288	1.734292	2.68301	42.74946
Retnanto and Economides	2.404854	2.45846	14.4138	8.41684	146.7242
Wiggins	15.23254	5.566786	33.55806	23.70714	120.1337
Ali Musa and Enamul	5.46944	7.140656	3.927128	1.330583	61.50319
Mohammad reza et al	22.40743	9.474616	44.83109	32.82265	144.9958
Harrison[8]	5.008297	1.465582	13.35043	9.027321	63.02585
Jabbar and AlNuaim	23.36134	33.37452	6.68926	15.6851	92.43212
This Study	0.08701	0.028333	0.257106	0.539955	4.840017

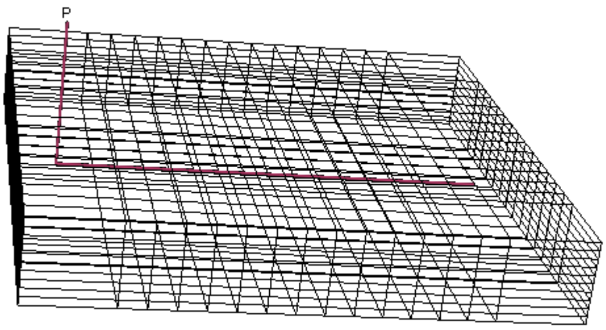

Fig. 1: The horizontal model for simulation data

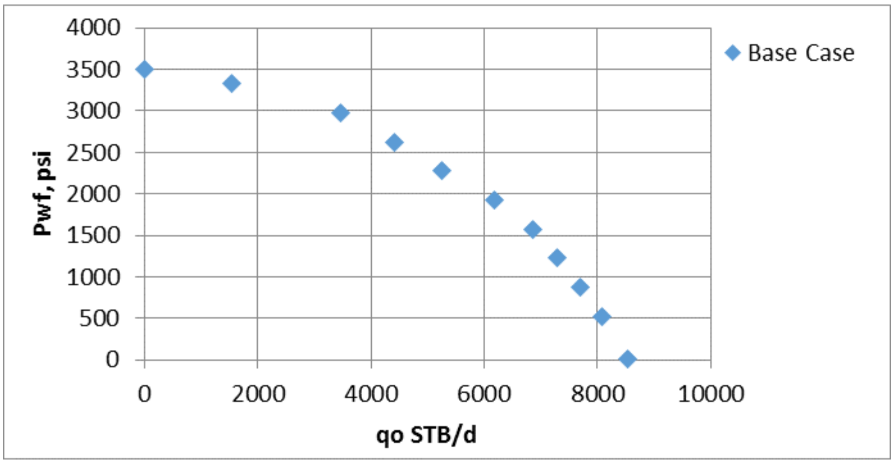

Fig. 2: Inflow performance data for the Base case

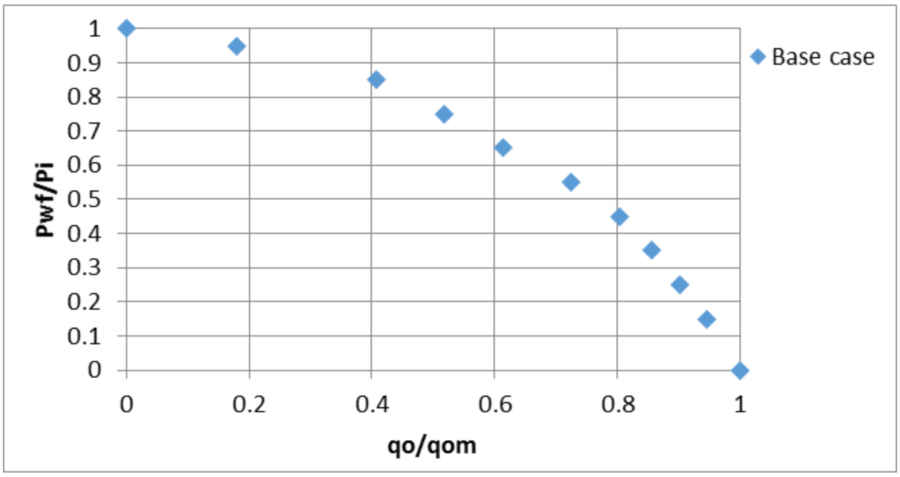

Fig. 3: Dimensionless performance data for the Base case