PREDICTION OF OILWELL PERFORMANCE IN BOUNDED RESERVOIRS

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ABSTRACT

The petroleum engineer is often required to estimate the pressure-production performance of an oil well in order to determine its productive capacity. This paper discusses various methods that have been proposed in the literature for describing individual well performance in solution-gas drive reservoirs. The forms of the oilwell deliverability equations will be presented as well as methods for predicting future performance. An example will be used to illustrate and identify data requirements for each method.

INTRODUCTION

When considering the performance of oil wells, it is often assumed that production rates are proportional to pressure drawdown. Based on this assumption, a well's behavior can be estimated by its productivity index (PI). This straight-line relationship can be derived from Darcy's[1] law for the steady-state flow of a single, incompressible fluid.

Evinger and Muskat[2] were some of the earliest investigators to look at oilwell performance. They pointed out that a straight-line relationship should not be expected when two phases are flowing in the reservoir. They presented evidence based on the multiphase flow equations that a curved relationship existed between flow rate and pressure. Their method for predicting performance did not gain wide acceptance by petroleum engineers as it required knowledge of reservoir rock and fluid properties.

In 1966, Vogel[3] presented an empirical inflow performance relationship (IPR) for solution-gas drive reservoirs based on computer simulation results. Vogel's method gained almost immediate acceptance due to its simplicity and the fact that it gave fairly reliable results. Fetkovich[4] would later present an empirical relationship based on field data that has also gained wide acceptance. Others[5,6] have also proposed methods for predicting performance.

Standing[7] proposed a method for predicting future performance based on Vogel's equation. He related the current reservoir pressure and maximum flow rate to the future reservoir pressure to determine the maximum flow rate at the new pressure. Fetkovich developed a similar method for his relationship. Other researchers[8-10] have proposed methods to predict future performance based on test data, some requiring information at two different reservoir pressures.

In this paper, we will discuss several of the commonly used inflow performance methods and identify their data requirements. We will also present several methods for predicting future performance. The methods will be illustrated through an example. The proper use of these methods can assist the petroleum engineer in predicting the performance of oil wells and determining their productive capacity.

DELIVERABILITY EQUATIONS

In this section we will briefly describe several of the commonly used methods for predicting the pressure-production performance of oil wells in solution-gas drive reservoirs. The methods that we will discuss were proposed by Vogel,[3] Fetkovich,[4] Jones, Blount and Glaze[5] and Klins and Majcher.[6]

Vogel was the first to present an easy to use method for predicting performance of oil wells. His empirical IPR is based on computer simulation results. His relationship is

$$\frac{q_o}{q_{o,max}} = 1 - 0.2\left(\frac{p_{wf}}{\bar{p}_r}\right) - 0.8\left(\frac{p_{wf}}{\bar{p}_r}\right)^2 \quad \text{.......... (1)}$$

To use this relationship, the engineer needs to determine the oil production rate and flowing wellbore pressure from a production test. He also needs an estimate of the current reservoir pressure which is best obtained from a transient well test.

Fetkovich proposed the isochronal testing of oil wells to estimate their productivity in 1974. His deliverability equation is based on the empirical gas well deliverability equation proposed by Rawlins and Schellhardt.[11] His equation is

$$q_o = C\left(\bar{p}_r^2 - p_{wf}^2\right)^n \quad \text{.......... (2)}$$

and requires a multiple rate test (at least three) to determine C and n. To use this method one needs the flowing wellbore pressures at the multiple production rates and an estimate of the reservoir pressure. A log-log plot of the pressure squared difference versus flow rate is used to determine n. The data is expected to plot as a straight line with n being the inverse of the slope of the curve. In terms of the maximum flow rate, Fetkovich's IPR equation is

$$\frac{q_o}{q_{o,max}} = \left[1 - \left(\frac{p_{wf}}{\bar{p}_r}\right)^2\right]^n \quad \text{.......... (3)}$$

Jones, Blount and Glaze also proposed a multiple rate test method. In their method they have tried to develop a way to estimate non-Darcy flow effects. The basic equation to describe the flow of oil is

$$\frac{\bar{p}_r - p_{wf}}{q_o} = C + D\,q_o \quad \text{.......... (4)}$$

where C represents their laminar flow coefficient and D is the turbulence coefficient. To use this method, one must obtain multiple rate test information similar to Fetkovich's method. Jones, Blount and Glaze stated at least two points were required. A plot of the pressure difference divided by the flow rate (the left hand side of Eq. 4) versus the flow rate is prepared. The data points are expected to plot as a straight line with the slope being the turbulence coefficient D. The laminar flow coefficient C is the intercept of this plot. Once C and D have been determined, the flow rate at any other flowing wellbore pressure can be obtained by solving Eq. 4. This relation is

$$q_o = \frac{-C + \sqrt{C^2 + 4\,D\,(\bar{p}_r - p_{wf})}}{2\,D} \quad \text{.......... (5)}$$

The maximum flow rate is obtained from Eq. 5 by letting the flowing wellbore pressure equal zero.

Recently, Klins and Majcher have proposed a Vogel-type IPR based on regression analysis of simulator results. Their IPR requires an estimate of the bubble point pressure of the produced oil. This single rate method also requires the production rate, flowing wellbore pressure and reservoir pressure. The IPR is

$$\frac{q_o}{q_{o,max}} = 1 - 0.295\left(\frac{p_{wf}}{\bar{p}_r}\right) - 0.705\left(\frac{p_{wf}}{\bar{p}_r}\right)^d \quad \text{.......... (6)}$$

where

$$d = \left(0.28 + \frac{0.72\,\bar{p}_r}{p_b}\right)(1.24 + 0.001\,p_b) \quad \text{.......... (7)}$$

FUTURE PERFORMANCE METHODS

Once the engineer has determined the current productive capacity of a well, he often desires to predict future performance for planning purposes. In this section, we present several methods for predicting future performance.

The methods proposed by Standing,[7] Fetkovich,[4] Uhri and Blount,[8] Kelkar and Cox[9] and Klins and Clark[10] will be discussed.

Standing was one of the first to address the prediction of future well performance from IPR's. He used Vogel's relationship and the PI to propose the relation

$$\frac{J^*_f}{J^*_p} = \frac{\left(\frac{k_{ro}}{\mu_o B_o}\right)_f}{\left(\frac{k_{ro}}{\mu_o B_o}\right)_p} \qquad (8)$$

where J* is a modified productivity index. The difficulty in using this method is that J* must be estimated. Standing developed the relation

$$J^*_p = \frac{1.8\, q_o}{\overline{p}_r\left[1.0 - 0.2\left(\frac{p_{wf}}{\overline{p}_r}\right) - 0.8\left(\frac{p_{wf}}{\overline{p}_r}\right)^2\right]} \qquad (9)$$

to estimate the current J*; however, J* at future conditions must be determined from Eq. 8. This requires that we know relative permeability and fluid property information. This requirement makes Standing's method difficult to use since we must estimate saturations, relative permeabilities and fluid properties at a future reservoir pressure. Though Standing offered his recommendations on estimating these values, his method is seldom used in practice.

Fetkovich, based on experience, suggested that the J* ratio proposed by Standing could be estimated by a linear relationship in the reservoir pressure ratios. He applied this idea to his proposed deliverability equation. This allows the future maximum production rate to be determined from

$$\frac{q_{o,max,f}}{q_{o,max,p}} = \frac{\overline{p}_{r,f}}{\overline{p}_{r,p}}\left(\frac{\overline{p}^2_{r,f}}{\overline{p}^2_{r,p}}\right)^n \qquad (10)$$

This method requires no more information than what was required for the deliverability equation. It is important to note that this method assumes the n and C coefficients in Eq. 2 do not change between the present and future reservoir conditions.

Uhri and Blount proposed a 'pivot point' method to estimate future performance that requires information at two different reservoir pressures. Their method requires the determination of two constants:

$$A = \frac{\overline{p}_{r,1} - \overline{p}_{r,2}}{\dfrac{\overline{p}_{r,1}^2}{q_{o,max,1}} - \dfrac{\overline{p}_{r,2}^2}{q_{o,max,2}}} \qquad (11)$$

$$n = \overline{p}_{r,1}\left(\frac{A\,\overline{p}_{r,1}}{q_{o,max,1}} - 1\right) \qquad (12)$$

Once A and n have been determined, the maximum production rate at any future reservoir is determined from

$$q_{o,max,f} = \frac{A\,\overline{p}_{r,f}^2}{\overline{p}_{r,f} + n} \qquad (13)$$

The maximum flow rates required in Eqs. 11 and 12 are to be determined from Vogel's IPR using the test information at the two different reservoir pressures.

Kelkar and Cox also proposed a two point method for predicting future performance. To use their method one must determine the maximum flow rate at two different reservoir pressures using any method that one desires. To determine the maximum flow rate at some future pressure, J* at the two test reservoir pressures must be calculated from

$$J^* = \frac{q_{o,max}}{\overline{p}_r} \qquad (14)$$

Once J* has been determined for the two test points, A' and B' are calculated by

$$A' = \frac{J^*_1 - J^*_2}{\overline{p}_{r,1}^2 - \overline{p}_{r,2}^2} \qquad (15)$$

and

$$B' = \frac{\dfrac{J^*_1}{\overline{p}_{r,1}^2} - \dfrac{J^*_2}{\overline{p}_{r,2}^2}}{\dfrac{1}{\overline{p}_{r,1}^2} - \dfrac{1}{\overline{p}_{r,2}^2}} \qquad (16)$$

The future maximum flow is determined from

$$q_{o,max,f} = A' \overline{p}_{r,f}^3 + B' \overline{p}_{r,f} \quad \text{.......... (17)}$$

Klins and Clark have recently proposed a method to predict future performance based on regression analysis of simulator results. Their method utilizes an IPR (they recommend Klins and Majcher) and Fetkovich's deliverability equation. To use this method, one determines the current maximum production rate from Eq. 6 or other method if desired. Using the test data and the calculated maximum production rate, one determines n and C for Fetkovich's equation, Eq. 2. (If Fetkovich's equation was used to estimate the maximum production rate, one will have already determined these values.) Next, one must determine

$$\frac{n}{n_{p_b}} = 1.0 + 0.0577\left(1 - \frac{\overline{p}_r}{p_b}\right) - 0.2459\left(1 - \frac{\overline{p}_r}{p_b}\right)^2 + 0.5030\left(1 - \frac{\overline{p}_r}{p_b}\right)^3 \quad \text{.......... (18)}$$

and

$$\frac{C}{C_{p_b}} = 1.0 - 3.5718\left(1 - \frac{\overline{p}_r}{p_b}\right) + 4.7981\left(1 - \frac{\overline{p}_r}{p_b}\right)^2 - 2.3066\left(1 - \frac{\overline{p}_r}{p_b}\right)^3 \quad \text{.......... (19)}$$

at the reservoir pressure of the test. One then calculates n and C at the bubble point pressure by using

$$n_{p_b} = n \Big/ \left(\frac{n}{n_{p_b}}\right) \quad \text{.......... (20)}$$

and

$$C_{p_b} = C \Big/ \left(\frac{C}{C_{p_b}}\right) \quad \text{.......... (21)}$$

Using the calculated values of n and C at the bubble point, one can estimate these values at a future reservoir pressure by using Eqs. 18 and 19. That is, calculate new n and C ratios at the future reservoir pressure and then calculate

$$n_f = n_{p_b}\left(\frac{n}{n_{p_b}}\right)_f \quad \text{.......... (22)}$$

and

$$C_f = C_{p_b}\left(\frac{C}{C_{p_b}}\right)_f \quad \text{.......... (23)}$$

The maximum future production rate is then calculated by using Fetkovich's relation

$$q_{o,max,f} = C_f\left(\bar{p}^2_{r,f}\right)^{n_f} \quad \text{.......... (24)}$$

In all the methods presented, once the future maximum production rate is determined, inflow performance curves at the new reservoir pressure can be developed using the IPR of one's choosing.

EXAMPLE APPLICATION

In this section we will demonstrate how to apply each IPR and future performance method by using an example. Table 1 contains well test information that will be used in applying the IPR methods. Table 2 contains information that will be used in predicting future performance by each method.

IPR Methods

Vogel Method. In order to use Vogel's method, one must have well test information that includes oil production rate, flowing wellbore pressure and an estimate of the average reservoir pressure. Using the information from Table 1 for 150 BOPD, $q_{o,max}$ can be calculated from Eq. 1. Eq. 1 must be rearranged to make this calculation as follows.

$$q_{o,max} = \frac{q_o}{\left[1 - 0.2\left(\frac{p_{wf}}{\bar{p}_r}\right) - 0.8\left(\frac{p_{wf}}{\bar{p}_r}\right)^2\right]}$$

$$q_{o,max} = \frac{150.0}{1 - 0.2\left(\frac{2023}{2883}\right) - 0.8\left(\frac{2023}{2883}\right)^2} = 322 \text{ BOPD}$$

After $q_{o,max}$ is determined, Eq. 1 can be used to estimate production rates at other values of flowing wellbore pressures to develop an inflow performance curve. As before, Eq. 1 must be rearranged to estimate the production rate at a flowing wellbore pressure of 930 psi.

$$q_o = q_{o,max}\left[1 - 0.2\left(\frac{p_{wf}}{\bar{p}_r}\right) - 0.8\left(\frac{p_{wf}}{\bar{p}_r}\right)^2\right]$$

$$q_o = 322\left[1 - 0.2\left(\frac{930}{2883}\right) - 0.8\left(\frac{930}{2883}\right)^2\right] = 274 \text{ BOPD}$$

Fetkovich Method. One must have multiple flow rate information at the same reservoir pressure to use Fetkovich's method. This is required in order to determine n and C. If this information is not available, one could assume that n is equal to unity and proceed with the calculations.

Using the multiple rate test data found in Table 1, one would prepare the data for plotting by generating a table similar to the one that follows.

q_o, BOPD	p_{wf}, psi	$(p_r^2 - p_{wf}^2) \times 10^3$, psi^2
25.0	2755	721.7
150.0	2023	4219.2
250.0	1339	6518.8

The data in the above table is plotted on a log-log graph to determine the n and C values required in Fetkovich's equation. Fig. 1 presents this graph. The exponent n is the inverse of the slope of this graph which for this example is 1.0377. Eq.3 (which has to be rearranged) is used to determine $q_{o,max}$. Using the test information at 150 BOPD, $q_{o,max}$ is determined as follows.

$$q_{o,max} = \frac{q_o}{\left[1 - \left(\frac{p_{wf}}{\bar{p}_r}\right)^2\right]^n}$$

$$q_{o,max} = \frac{150}{\left[1 - \left(\frac{2023}{2883}\right)^2\right]^{1.0377}} = 303 \text{ BOPD}$$

To estimate production rates at other flowing wellbore pressures, one can use Eq. 2 directly with the appropriate p_{wf} or by rearranging Eq. 3 in the following manner.

$$q_o = q_{o,max}\left[1 - \left(\frac{p_{wf}}{\bar{p}_r}\right)^2\right]^n$$

$$q_o = 303\left[1 - \left(\frac{930}{2883}\right)^2\right]^{1.0377} = 271 \text{ BOPD}$$

It should be noted that after n is determined from the graph, C can be determined by using Eq. 2. Knowing n and C allows Eq. 2 to be used to estimate production rates at other pressures of interest, including $q_{o,max}$.

Jones, Blount and Glaze Method. Like Fetkovich, Jones, Blount and Glaze proposed a multipoint method for determining the pressure-production behavior of an oil well. Using the test data in Table 1, the information is prepared for plotting by generating a table similar to the one presented.

q_o, BOPD	p_{wf}, psi	$p_r - p_{wf}/q$, psi/BOPD
25.0	2755	5.12
150.0	2023	5.73
250.0	1339	6.18

The information is plotted on coordinate paper to determine the intercept which is the laminar flow coefficient, C, and the slope which is the turbulence coefficient, D. Fig. 2 is a plot of this information which indicates that C = 0.0047 and D = 5.0188. The maximum oil production rate is found by using Eq. 5 with the appropriate values of C, D and reservoir pressure and by letting $p_{wf} = 0$.

$$q_o = \frac{-C + \sqrt{C^2 + 4\,D\,(\bar{p}_r - p_{wf})}}{2\,D}$$

$$q_{o,max} = \frac{-5.0188 + \sqrt{5.0188^2 + 4\,(.0047)(2883 - 0)}}{2\,(.0047)} = 414 \text{ BOPD}$$

Flow rates at other values of p_{wf} can be determined by also using Eq. 5. For example, at $p_{wf} = 930$ psi, q_o would be determined as

$$q_o = \frac{-5.0188 + \sqrt{5.0188^2 + 4\,(.0047)(2883 - 930)}}{2\,(.0047)} = 303 \text{ BOPD}$$

Klins and Majcher Method. To use the method of Klins and Majcher, one must have an estimate of the bubble point pressure of the produced oil to estimate the pressure-production behavior from well test information. Knowing the bubble point pressure from Table 1, the d exponent can be estimated from Eq. 7.

$$d = \left(0.28 + \frac{0.72\,\bar{p}_r}{p_b}\right)(1.24 + 0.001\,p_b)$$

$$d = \left(0.28 + \frac{0.72\,(2883)}{3500}\right)(1.24 + 0.001\,(3500)) = 4.1384$$

Eq. 6 is now used to estimate the maximum flow rate. Rearranging and applying Eq. 6 yields

$$q_{o,max} = \frac{q_o}{1 - 0.295\left(\frac{p_{wf}}{\bar{p}_r}\right) - 0.705\left(\frac{p_{wf}}{\bar{p}_r}\right)^d}$$

$$q_{o,max} = \frac{150}{1 - 0.295\left(\frac{2023}{2883}\right) - 0.705\left(\frac{2023}{2883}\right)^{4.1384}} = 238 \text{ BOPD}$$

From this estimate of $q_{o,max}$, estimates of flow rates at other flowing pressures such as 930 psi can be made as follows.

$$q_o = q_{o,max}\left(1 - 0.295\left(\frac{p_{wf}}{\bar{p}_r}\right) - 0.705\left(\frac{p_{wf}}{\bar{p}_r}\right)^d\right)$$

$$q_o = 238\left(1 - 0.295\left(\frac{930}{2883}\right) - 0.705\left(\frac{930}{2883}\right)^{4.1384}\right) = 214 \text{ BOPD}$$

Future Performance Methods

Fetkovich Method. To estimate future performance by Fetkovich's method, we need an estimate of the exponent n from the well test as well as our predicted $q_{o,max}$. From our earlier calculations, n = 1.0377 and $q_{o,max}$ = 303 BOPD. We can calculate the maximum flow rate at a future reservoir pressure of 2008 psi by using Eq. 10.

$$q_{o,max,f} = q_{o,max,p}\frac{\bar{p}_{r,f}}{\bar{p}_{r,p}}\left(\frac{\bar{p}_{r,f}^2}{\bar{p}_{r,p}^2}\right)^n$$

$$q_{o,max,f} = 303\left(\frac{2008}{2883}\right)\left[\frac{(2008)^2}{(2883)^2}\right]^{1.0377} = 100 \text{ BOPD}$$

Uhri and Blount Method. The method proposed by Uhri and Blount requires that two estimates of $q_{o,max}$ at two different reservoir pressures be available. From the information provided in Table 2, we can calculate $q_{o,max}$ at time 1 and time 2 by using Vogel's relationship. From our earlier calculations we know $q_{o,max,2}$ = 322 BOPD. In a similar manner, we can determine $q_{o,max,1}$ = 425 BOPD from the information for test 1 in the Table 2.

Using these rates and the reservoir pressures, A and n are determined from Eqs. 11 and 12.

$$A = \frac{\overline{p}_{r,1} - \overline{p}_{r,2}}{\dfrac{\overline{p}_{r,1}^2}{q_{o,max,1}} - \dfrac{\overline{p}_{r,2}^2}{q_{o,max,2}}}$$

$$A = \frac{3409 - 2883}{\dfrac{(3409)^2}{425} - \dfrac{(2883)^2}{322}} = 0.3435$$

$$n = \overline{p}_{r,1}\left(\frac{A\,\overline{p}_{r,1}}{q_{o,max,1}} - 1\right)$$

$$n = 3409\left(\frac{.3435\,(3409)}{425} - 1\right) = 5983$$

The maximum flow rate at a future reservoir pressure is calculated from Eq. 13. At an average reservoir pressure of 2008 psi, the future rate is

$$q_{o,max,f} = \frac{A\,\overline{p}_{r,f}^2}{\overline{p}_{r,f} + n}$$

$$q_{o,max,f} = \frac{(.3435)\,(2008)^2}{2008 + 5983} = 172 \text{ BOPD}$$

Kelkar and Cox Method. The method of Kelkar and Cox is another multipoint method for predicting future performance. Using the maximum flow rates determined in the example of Uhri and Blount's method, Eq. 13 is used to determine J* for each reservoir pressure.

$$J^* = \frac{q_{o,max}}{\overline{p}_r}$$

$$J^*_1 = \frac{425}{3409} = 0.1247$$

$$J^*_2 = \frac{322}{2883} = 0.1117$$

These values of J* are used to determine A' and B' from Eq. 15 and 16.

$$A' = \frac{J^*_1 - J^*_2}{\overline{p}^2_{r,1} - \overline{p}^2_{r,2}}$$

$$A' = \frac{0.1247 - 0.1117}{(3409)^2 - (2883)^2} = 3.9 \times 10^{-9}$$

$$B' = \frac{\frac{J^*_1}{\overline{p}^2_{r,1}} - \frac{J^*_2}{\overline{p}^2_{r,2}}}{\frac{1}{\overline{p}^2_{r,1}} - \frac{1}{\overline{p}^2_{r,2}}}$$

$$B' = \frac{\frac{0.1247}{(3409)^2} - \frac{0.1117}{(2883)^2}}{\frac{1}{(3409)^2} - \frac{1}{(2883)^2}} = 0.0791$$

The maximum production rate at a reservoir pressure of 2008 psi is estimated from Eq. 17.

$$q_{o,max,f} = A' \, \overline{p}^3_{r,f} + B' \, \overline{p}_{r,f}$$

$$q_{o,max,f} = 3.9 \times 10^{-9} (2008)^3 + 0.0791 (2008) = 190 \text{ BOPD}$$

Klins and Clark Method. To use the method of Klins and Clark to predict future performance, we need estimates of C and n for Fetkovich's equation. These were determined in the Fetkovich IPR example. If only n is determined from the multipoint well test, C can be determined by using Eq. 2. If one estimates C in this manner, he must make sure the information he uses in the calculation lies on the straight line and not an actual data point.

$$C = \frac{q_o}{(\overline{p}^2_r - p^2_{wf})^n}$$

$$C = \frac{303}{[(2883)^2 - (0)^2]^{1.0377}} = 1.999 \times 10^{-5}$$

Once the n and C are determined, Eqs. 18 and 19 are used to determine the n/n_{pb} and C/C_{pb} ratios.

$$\frac{n}{n_{P_b}} = 1.0 + 0.0577\left(1 - \frac{\overline{P}_r}{P_b}\right) - 0.2459\left(1 - \frac{\overline{P}_r}{P_b}\right)^2 + 0.5030\left(1 - \frac{\overline{P}_r}{P_b}\right)^3$$

$$\frac{n}{n_{P_b}} = 1.0 + 0.0577\left(1 - \frac{2883}{3500}\right) - 0.2459\left(1 - \frac{2883}{3500}\right)^2 + 0.5030\left(1 - \frac{2883}{3500}\right)^3 = 1.0053$$

$$\frac{C}{C_{P_b}} = 1.0 - 3.5718\left(1 - \frac{\overline{P}_r}{P_b}\right) + 4.7981\left(1 - \frac{\overline{P}_r}{P_b}\right)^2 - 2.3066\left(1 - \frac{\overline{P}_r}{P_b}\right)^3$$

$$\frac{C}{C_{P_b}} = 1.0 - 3.5718\left(1 - \frac{2883}{3500}\right) + 4.7981\left(1 - \frac{2883}{3500}\right)^2 - 2.3066\left(1 - \frac{2883}{3500}\right)^3 = 0.5068$$

These ratios allow n and C at the bubble point pressure to be estimated from Eqs. 20 and 21.

$$n_{P_b} = n \Big/ \left(\frac{n}{n_{P_b}}\right)$$

$$n_{P_b} = \frac{1.0377}{1.0053} = 1.0322$$

$$C_{P_b} = C \Big/ \left(\frac{C}{C_{P_b}}\right)$$

$$C_{P_b} = \frac{1.999 \times 10^{-5}}{0.5068} = 3.945 \times 10^{-5}$$

We again use Eqs. 18 and 19 to determine the n and C ratios at the future reservoir pressure of 2008 psi.

$$\frac{n}{n_{P_b}} = 1.0 + 0.0577\left(1 - \frac{2008}{3500}\right) - 0.2459\left(1 - \frac{2008}{3500}\right)^2 + 0.5030\left(1 - \frac{2008}{3500}\right)^3 = 1.0189$$

$$\frac{C}{C_{P_b}} = 1.0 - 3.5718\left(1 - \frac{2008}{3500}\right) + 4.7981\left(1 - \frac{2008}{3500}\right)^2 - 2.3066\left(1 - \frac{2008}{3500}\right)^3 = 0.1706$$

With these new ratios, we can estimate n and C at the future conditions by using Eqs. 22 and 23.

$$n_f = n_{P_b}\left(\frac{n}{n_{P_b}}\right)_f$$

$$n_f = 1.0322(1.0189) = 1.0517$$

$$C_f = C_{P_b}\left(\frac{C}{C_{P_b}}\right)_f$$

$$C_f = 3.945 \times 10^{-5}(0.1706) = 6.730 \times 10^{-6}$$

The maximum future production rate can now be calculated by using Fetkovich's relation in the form of Eq. 24.

$$q_{o,max,f} = C_f\left(\bar{p}^2_{r,f}\right)^{n_f}$$

$$q_{o,max,f} = 6.730 \times 10^{-6}\left[(2008)^2\right]^{1.0517} = 59 \text{ BOPD}$$

DISCUSSION

In this section we will briefly review and compare results obtained by the methods presented. The purpose in doing this is to develop an intuitive feel for how the different methods compare based on a single case which may not be representative for all situations. This is important since all the methods are only estimates and simply because one method appears better or worse for this particular example does not mean it is superior or inferior to the other methods in all cases.

There are two major effects on the methods that we want to investigate. They are the effect of pressure drawdown on the IPR methods and the effect of depletion on the IPR and future performance methods. For the purpose of this comparison, a general purpose reservoir simulator has been used to generate pressure-production performance information to be used in the calculations.

One concern in using IPR's is that information is taken from a well test and then used to extrapolate to zero flowing wellbore pressure. Test information might be from a test that experienced a large pressure drawdown or one where there is limited pressure drawdown. Table 3 compares the effect of pressure drawdown on pressure-performance predictions for the various IPR methods. The calculations in this table came from a simulated well test for three different pressure drawdowns at a depletion stage of 4%. In general it appears that improved estimates of pressure-production performance occurs with increasing pressure drawdowns in test information. This observation agrees with the work of Vogel who noted that maximum errors in the use of his IPR were obtained at low pressure drawdowns and corresponding low production rates. Consequently one should exercise caution in extrapolating well test information from low pressure drawdowns to very high pressure drawdowns. Based on observation, it is suggested that a minimum of 20% pressure drawdown be achieved when obtaining well test information for use with an IPR method.

Vogel noted, and Klins and Majcher confirmed, that depletion does affect the IPR curve. Table 4 shows the effect of depletion on the predictions made by the various IPR methods. For this example, the methods yield increasing better estimates of performance as depletion proceeds. This is not entirely surprising since the reservoir pressure decreases with depletion and we extrapolate over a shorter interval. Consequently we would expect improved estimates.

Depletion also affects predictions of future performance by the methods presented. As one would expect, we are again concerned about making extrapolations over large pressure ranges. Camacho and Raghavan[12] recently reviewed several of the future performance prediction methods presented here. They concluded that all work reasonably well if predictions are made over short stages of depletion but that for longer periods care should be exercised. Table 5 presents calculations of $q_{o,max}$ at various future reservoir conditions or stage of depletion. As indicated, as one makes estimates of future performance at increasing stages of depletion the methods do a less reliable job of estimating the future maximum production rate. Based on this analysis, one should avoid making future performance predictions over long ranges of depletion. It is recommended that initial test information be used to make the first estimates of future performance. Then every six months to a year, new test information be obtained to update the future performance predictions. In this manner, the estimates should become progressively better.

SUMMARY

In this paper we have presented four methods to predict the pressure-production performance of oil wells producing from solution-gas drive reservoirs. These methods are those proposed by Vogel, Fetkovich, Jones, Blount and Glaze and Klins and Majcher. The methods of Vogel and Klins and Majcher require a single point well test where flowing wellbore pressure and production rates are measured along with an estimate of average reservoir pressure to estimate performance. In addition, the bubble point pressure is required to use Klins and Majcher's method. A multipoint test is required to use the methods of Fetkovich and Jones, Blount and Glaze.

Four methods have been presented to predict future performance. These methods were proposed by Fetkovich, Uhri and Blount, Kelkar and Cox and Klins and Clark. The method of Fetkovich and Klins and Clark require information at a single reservoir condition to estimate performance at a future reservoir condition. The methods of Uhri and Blount and Kelkar and Cox require information at two different reservoir conditions to estimate future performance.

The example used in this paper indicates that production-pressure performance predictions are affected by pressure drawdowns during testing and stage of reservoir depletion. Increasingly improved estimates of performance should be expected if well test information is obtained at larger pressure drawdowns. In general, it is recommended that test information be obtained at pressure drawdowns greater than 20%. Performance estimates also tend to improve as reservoir depletion progresses. These effects appear to be a consequence of extrapolating information over smaller intervals.

Future performance prediction methods can be expected to yield reliable results if extrapolations are not made over long periods of reservoir depletion. Camacho and Raghavan have studied future performance methods in some detail and readers are referred to them for further discussion.

NOMENCLATURE

A = variable in Uhri and Blount method, defined by Eq. 11
A' = variable in Kelkar and Cox method, defined by Eq. 15
B' = variable in Kelkar and Cox method, defined by Eq. 16
C = Fetkovich's coefficient in Eq. 2
C = Jones *et al.*'s laminar flow coefficient in Eq. 4
C_{pb} = Klins and Clark flow coefficient at bubble point pressure in Eq. 2
D = Jones *et al.*'s turbulence coefficient in Eq. 4
d = Klins and Majcher flow exponent in Eqs. 6 and 7
J^* = Standing's modified productivity index in Eq. 8
J^* = Kelkar and Cox's modified productivity index in Eq. 14
n = Fetkovich's flow exponent in Eqs. 2 and 3
n = variable in Uhri and Blount method, defined by Eq. 12
n_{pb} = Klins and Clark flow exponent at bubble point pressure in Eq. 2
p_b = bubble point pressure, psi
$\bar{p}_r, p_r$ = average reservoir pressure, psi
p_{wf} = flowing wellbore pressure, psi
q_o = oil production rate, BOPD
$q_{o,max}$ = maximum oil production rate

Subscripts

f = future reservoir conditions
p = present reservoir conditions
1 = test 1 reservoir conditions
2 = test 2 reservoir conditions

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Table 1
Well Test Information Used in Sample
IPR Calculations

p_r = 2883 psi p_b = 3500 psi

Test Rate	q_o, BOPD	p_{wf}, psi
1	25	2755
2	150	2023
3	250	1339

Table 2
Well Test Information Used in Sample
Future Performance Calculations

Test	p_r, psi	p_{wf}, psi	q_o, BOPD
1	3409	2670	150
2	2883	2023	150

Table 3
Effect of Pressure Drawdown on the IPR Methods

Test Information:
q_o = 25 BOPD p_{wf} = 2755 psi p_r = 2883 psi p_{bp} = 3500 psi

p_{wf}, psi	Simulator q_o, BOPD	Vogel q_o, BOPD	Fetkovich q_o, BOPD	Jones *et al.* q_o, BOPD	Klins q_o, BOPD
2327	100	101	105	101	88
1698	200	193	203	199	139
1339	250	234	245	249	155
930	300	271	281	303	167
386	350	305	309	370	179

Test Information:
q_o = 150 BOPD p_{wf} = 2024 psi p_r = 2883 psi p_{bp} = 3500 psi

p_{wf}, psi	Simulator q_o, BOPD	Vogel q_o, BOPD	Fetkovich q_o, BOPD	Jones *et al.* q_o, BOPD	Klins q_o, BOPD
1864	175	173	173	175	165
1698	200	195	195	199	178
1339	250	237	236	249	198
930	300	275	271	303	214
386	350	309	298	370	229

Test Information:
q_o = 250 BOPD p_{wf} = 1339 psi p_r = 2883 psi p_{bp} = 3500 psi

p_{wf}, psi	Simulator q_o, BOPD	Vogel q_o, BOPD	Fetkovich q_o, BOPD	Jones *et al.* q_o, BOPD	Klins q_o, BOPD
930	300	290	287	303	269
386	350	326	316	370	288

Table 4
Effect of Depletion on the IPR Methods

Test Information: 1% Depletion
q_o = 150 BOPD p_{wf} = 2670 psi p_r = 3409 psi p_{bp} = 3500 psi

p_{wf}, psi	Simulator q_o, BOPD	Vogel q_o, BOPD	Fetkovich q_o, BOPD	Jones *et al.* q_o, BOPD	Klins q_o, BOPD
2400	200	197	197	199	181
1805	300	285	283	299	223
1470	350	326	321	352	237
1091	400	363	354	408	249
625	450	398	392	474	261

Test Information: 4% Depletion
q_o = 150 BOPD p_{wf} = 2024 psi p_r = 2883 psi p_{bp} = 3500 psi

p_{wf}, psi	Simulator q_o, BOPD	Vogel q_o, BOPD	Fetkovich q_o, BOPD	Jones *et al.* q_o, BOPD	Klins q_o, BOPD
1864	175	173	173	175	165
1698	200	195	195	199	178
1339	250	237	236	249	198
930	300	275	271	303	214
386	350	309	298	370	229

Test Information: 8% Depletion
q_o = 75 BOPD p_{wf} = 1466 psi p_r = 2008 psi p_{bp} = 3500 psi

p_{wf}, psi	Simulator q_o, BOPD	Vogel q_o, BOPD	Fetkovich q_o, BOPD	Jones *et al.* q_o, BOPD	Klins q_o, BOPD
1257	100	98	99	98	93
1034	125	120	120	122	108
777	150	141	140	147	121
460	175	160	156	176	130

Table 5
Effect of Depletion on Future Performance Prediction Methods

Depletion Stage	Test Information $q_{o,max}$, BOPD	p_r, psi
1.0%	515	3409
2.0%	481	3253

Predictions at 2% Depletion

p_r, psi	Simulator $q_{o,max}$, BOPD	Fetkovich $q_{o,max}$, BOPD	Uhri $q_{o,max}$, BOPD	Kelkar $q_{o,max}$, BOPD	Klins $q_{o,max}$, BOPD
2883	407	333	402	407	200
2461	306	206	316	330	92
2008	212	111	230	257	40
1543	135	50	151	189	20
1089	77	17	84	130	11

Depletion Stage	Test Information $q_{o,max}$, BOPD	p_r, psi
2.0%	481	3253
4.0%	407	2883

Predictions at 4% Depletion

p_r, psi	Simulator $q_{o,max}$, BOPD	Fetkovich $q_{o,max}$, BOPD	Uhri $q_{o,max}$, BOPD	Kelkar $q_{o,max}$, BOPD	Klins $q_{o,max}$, BOPD
2461	306	250	326	329	348
2008	212	134	243	258	151
1543	135	60	164	191	73
1089	77	20	94	131	41

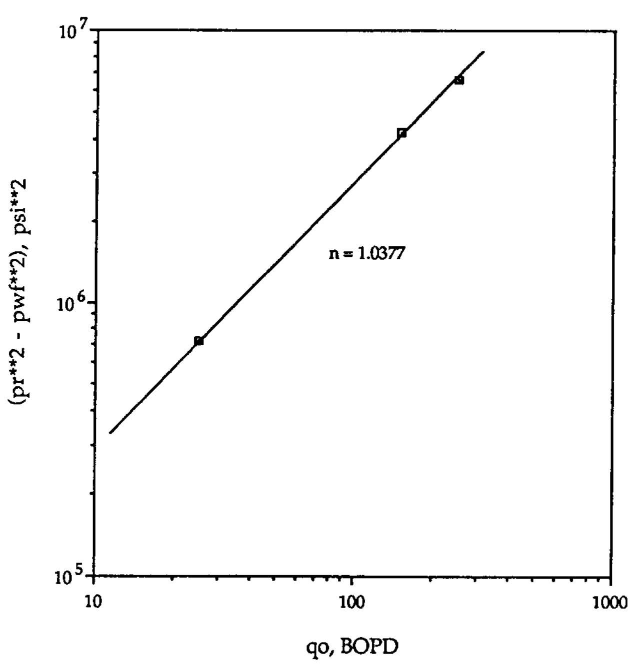

Figure 1 - Fetkovich log-log plot for determining n

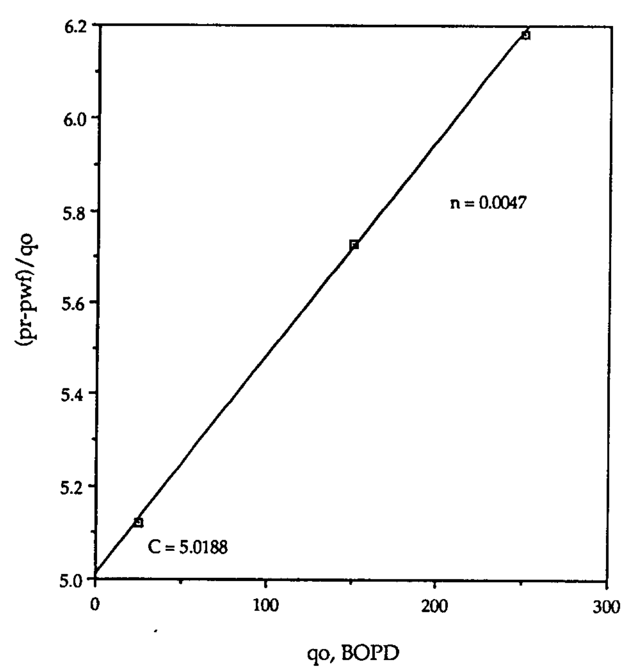

Figure 2 - Jones, Blount and Glaze plot for determining n and C