Methods of Calculation

There are several empirical methods that are designed to predict the non-linearity behavior of the IPR for solution gas drive reservoirs. Most of these methods require at least one stabilized flow test in which $\mathbf{Q_o}$ and $\mathbf{P_{wf}}$ are measured. All the methods include the following two computational steps:

- Using the stabilized flow test data, construct the IPR curve at the current average reservoir pressure $\mathbf{P_r}$.
- Predict future inflow performance relationships as to the function of average reservoir pressures.

The following empirical methods that are designed to generate the current and future inflow performance relationships:

1. Vogel's method
2. Standing's method
3. Couto`s Method
4. Al saadoon`s Method
5. Fetkovich's method
6. Wiggins' method
7. The Klins-Clark method

1) Vogel's Method

Vogel (1968) based on a computer simulation of dissolved gas drive reservoirs, where in his calculated IPRs using a wide range of reservoir and fluid parameters, proposed the general IPR curve of Figure (1-29). Often this same Vogel relation is successfully applied to other types of reservoir drive systems.

Vogel normalized the calculated IPRs and expressed the relationships in a dimensionless form. He normalized the IPRs by introducing the following dimensionless parameters:

- Dimensionless pressure = $\frac{P_{wf}}{P_r}$
- Dimensionless flow rate = $\frac{Q_o}{(Q_o)_{max}}$

Where $(Q_o)_{max}$ is the flow rate at zero wellbore pressure (100% drawdown), i.e., AOF.

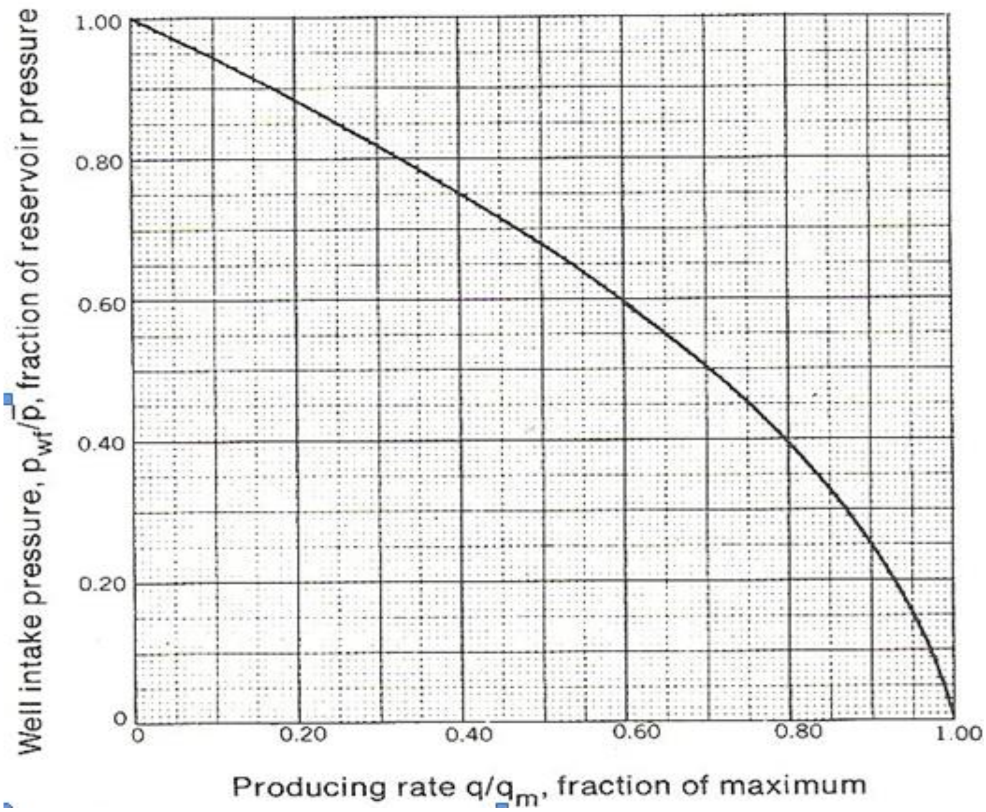


Fig. (1-29): Inflow performance relation (Vogel).

Vogel plotted the dimensionless IPR curves for all the reservoir cases as shown in Figure (1-29) and arrived at the following relationship between the above dimensionless parameter:

$$\frac{Q_o}{(Q_o)_{max}} = 1 - 0.2\left(\frac{P_{wf}}{P_r}\right) - 0.8\left(\frac{P_{wf}}{P_r}\right)^2 \text{ ------------------------- } \mathbf{(1.13)}$$

Where:

Q_o = oil rate at P_{wf}

$(Q_o)_{max}$ = maximum oil flow rate at zero wellbore pressure, i.e., AOF

P_r = current average reservoir pressure, psig

P_{wf} = wellbore pressure, psig

Vogel's method can be extended to account for water production by replacing the dimensionless rate with $Q_L/(Q_L)max$ where $Q_L = Q_o + Q_w$.

This has proved to be valid for wells producing at water cuts as high as 97%.
The method requires the following data:

- Current average reservoir pressure P_r
- Bubble-point pressure P_b
- Stabilized flow test data that include Q_o at P_{wf}

Vogel's methodology can be used to predict the IPR curve for the following two types of reservoirs:

- Saturated oil reservoirs $P_r \le P_b$
- Undersaturated oil reservoirs $P_r > P_b$

➢ **Saturated Oil Reservoirs**

When the reservoir pressure equals the bubble-point pressure, the oil reservoir is referred to as a ***saturated oil reservoir***. The computational procedure of applying Vogel's method in a saturated oil reservoir to generate the IPR curve for a well with a stabilized flow data point, i.e., a recorded Q_o value at P_{wf}, is summarized below:

Step 1: Using the stabilized flow data, i.e., Q_o and P_{wf}, calculate: $(Q_o)_{max}$ from Equation

$$(Q_o)_{max} = \frac{Q_o}{1-0.2\left(\frac{P_{wf}}{P_r}\right)-0.8\left(\frac{P_{wf}}{P_r}\right)^2} \quad \text{------------} \quad (1.14)$$

Step 2: Construct the IPR curve by assuming various values for P_{wf} and calculating the corresponding Q_o from:

$$Q_o = (Q_o)_{max}\left[1 - 0.2\left(\frac{P_{wf}}{P_r}\right) - 0.8\left(\frac{P_{wf}}{P_r}\right)^2\right] \quad \text{------------} \quad (1.15)$$

Problem (1-3): A well is producing from a saturated reservoir with an average reservoir pressure of **2500** psig. Stabilized production test data indicated that the stabilized rate and wellbore pressure are **350** STB/day and **2000** psig, respectively. Calculate:

1. Oil flow rate at P_{wf} = **1850** psig
2. Calculate oil flow rate assuming constant J
3. Construct the IPR by using Vogel's method and the constant productivity index approach.

Solution:

Part A.

Step 1: Calculate $(Q_o)_{max}$:

$$(Q_o)_{max} = \frac{350}{1 - 0.2\left(\frac{2000}{2500}\right) - 0.8\left(\frac{2000}{2500}\right)^2} = \mathbf{1076.1}\ \text{STB /day}$$

Step 2: Calculate Q_o at p_{wf} = 1850 psig by using Vogel's equation

$$Q_o = (Q_o)_{max}\left[1 - 0.2\left(\frac{P_{wf}}{P_r}\right) - 0.8\left(\frac{P_{wf}}{P_r}\right)^2\right]$$

$$Q_o = 1076.1\left[1 - 0.2\left(\frac{1850}{2500}\right) - 0.8\left(\frac{1850}{2500}\right)^2\right] = \mathbf{441.7}\ \text{STB/day}$$

Part B.

Calculating oil flow rate by using the constant **J** approach
Step 1: Apply Equation (1.1) to determine **J**

$$J = \frac{Q_o}{P_r - P_{wf}}$$

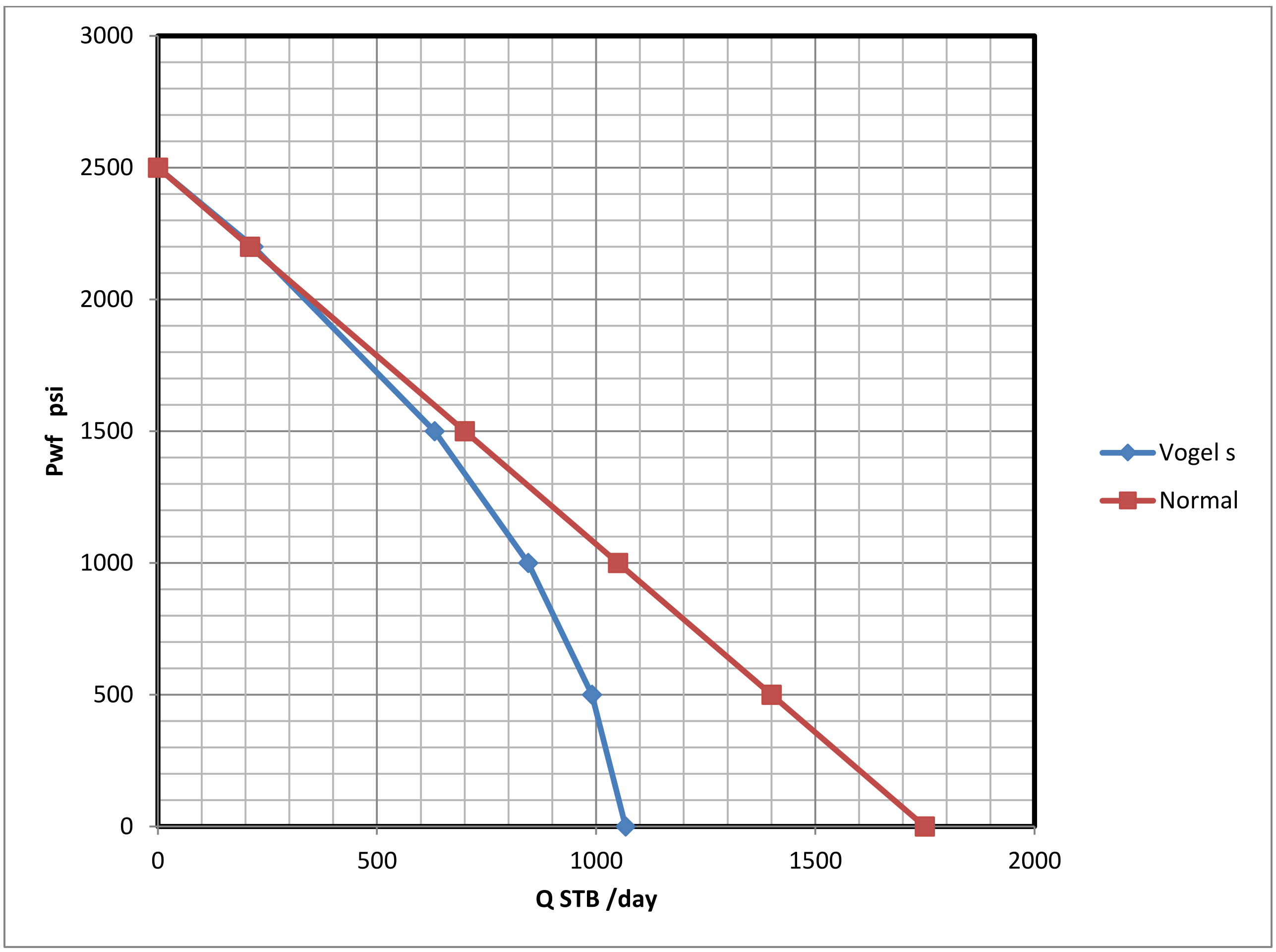
$$J = \frac{350}{2500 - 2000} = 0.7\ \text{STB /day / psi}$$

Step 2: Calculate Q_o
$Q_o = J\ (Pr - P_{wf}) = 0.7\ (2500 - 1850) = 455$ STB/day

Part C.

Generating the IPR by using the constant **J** approach and Vogel's method:
Assume several values for $\mathbf{P_{wf}}$ and calculate the corresponding $\mathbf{Q_o}$.

p_{wf}	Vogel`s	$Q_o = J(p_r - p_{wf})$
2500	0	0
2200	218.2	210
1500	631.7	700
1000	845.1	1050
500	990.3	1400
0	1067.1	1750



➢ Under-saturated Oil Reservoirs

Beggs (1991) pointed out that in applying Vogel's method for under-saturated reservoirs, there are **two possible outcomes to the recorded stabilized flow test data** that must be considered, as shown schematically in Figure (1-30):

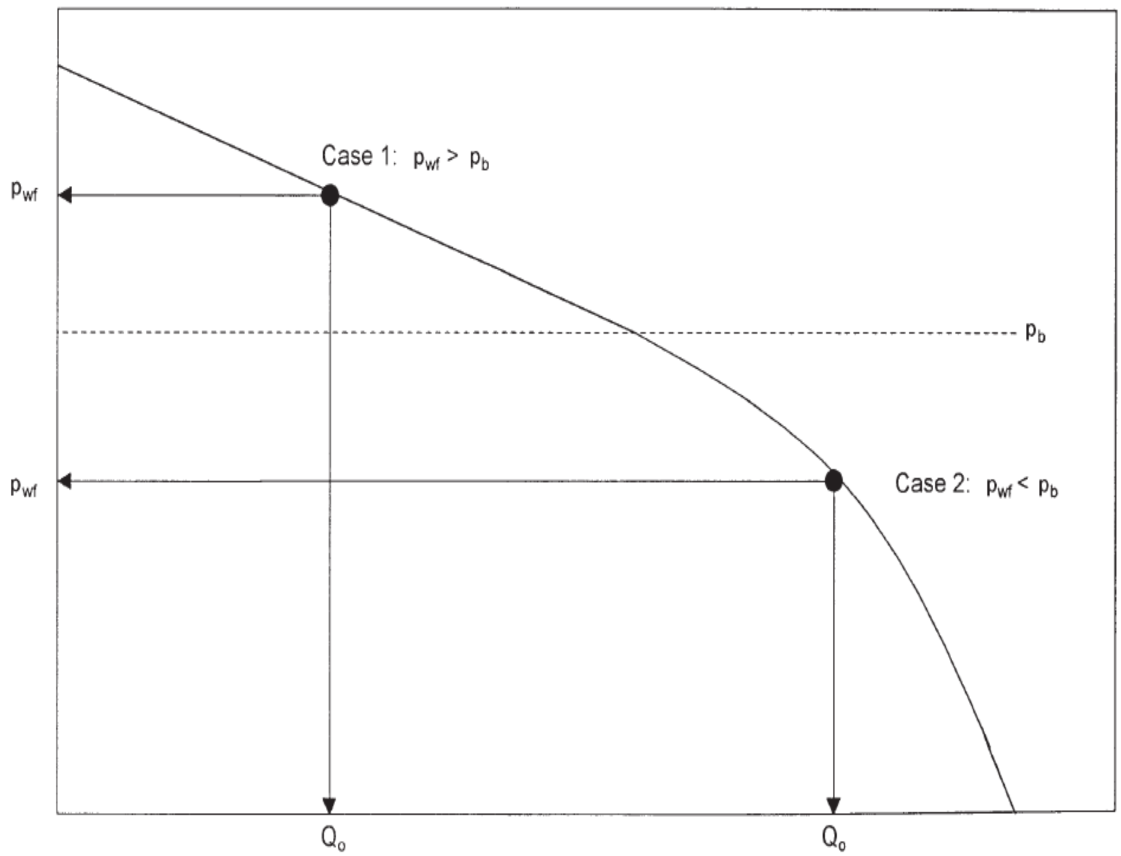


Fig. (1-30): Stabilized flow test data.

- The recorded stabilized bottom-hole flowing pressure is greater than or equal to the bubble-point pressure, i.e. $\mathbf{P_{wf} \geq P_b}$
- The recorded stabilized bottom-hole flowing pressure is less than the bubble-point pressure $\mathbf{P_{wf} < P_b}$

Case 1: The Value of the Recorded Stabilized $\mathbf{P_{wf} \geq P_b}$

Beggs outlined the following procedure for determining the IPR when the stabilized bottom-hole pressure is greater than or equal to the bubble point pressure Figure (1-30):

Step 1: Using the stabilized test data point ($\mathbf{Q_o}$ and $\mathbf{P_{wf}}$) calculate the productivity index **J**:

$$\mathbf{J = \frac{Q_o}{P_r - P_{wf}}}$$

Step 2: Calculate the oil flow rate at the bubble-point pressure:

$\mathbf{Q_{ob} = J\,(P_r - P_b)}$ -- **(1.16)**

Where:

Q_{ob}: is the oil flow rate at $\mathbf{P_b}$

Step 3: Generate the IPR values below the bubble-point pressure by assuming different values of $\mathbf{P_{wf} < P_b}$ and calculating the corresponding oil flow rates by applying the following relationship:

$$\mathbf{Q_o = Q_{ob} + \frac{JP_b}{1.8}\left[1 - 0.2\left(\frac{P_{wf}}{P_r}\right) - 0.8\left(\frac{P_{wf}}{P_r}\right)^2\right]} \quad \text{-- } \mathbf{(1.17)}$$

The maximum oil flow rate (Q_{omax} or AOF) occurs when the bottomhole flowing pressure is zero, i.e. $P_{wf} = 0$, which can be determined from the above expression as:

$$\mathbf{Q_o = Q_{ob} + \frac{JP_b}{1.8}} \quad \text{--- } \mathbf{(1.18)}$$

It should be pointed out that when $\mathbf{P_{wf} \geq P_b}$, the IPR is linear and is described by:

$$\mathbf{Q_o = J(P_r - P_{wf})}$$

Problem (1-4): An oil well is producing from an under-saturated reservoir that is characterized by a bubble-point pressure of **2130** psig. The current average reservoir pressure is **3000** psig. Available flow test data show that the well produced **250** STB/day at a stabilized P_{wf} of **2500** psig. Construct the IPR data.

Solution:

The problem indicates that the flow test data were recorded above the bubble-point pressure; therefore, the Case 1 procedure for under-saturated reservoirs as outlined previously must be used.

Step 1: Calculate J using the flow test data.

$$J = \frac{Q_o}{P_r - P_{wf}}$$

$$J = \frac{250}{3000 - 2500} = 0.5 \text{ STB/day/psi}$$

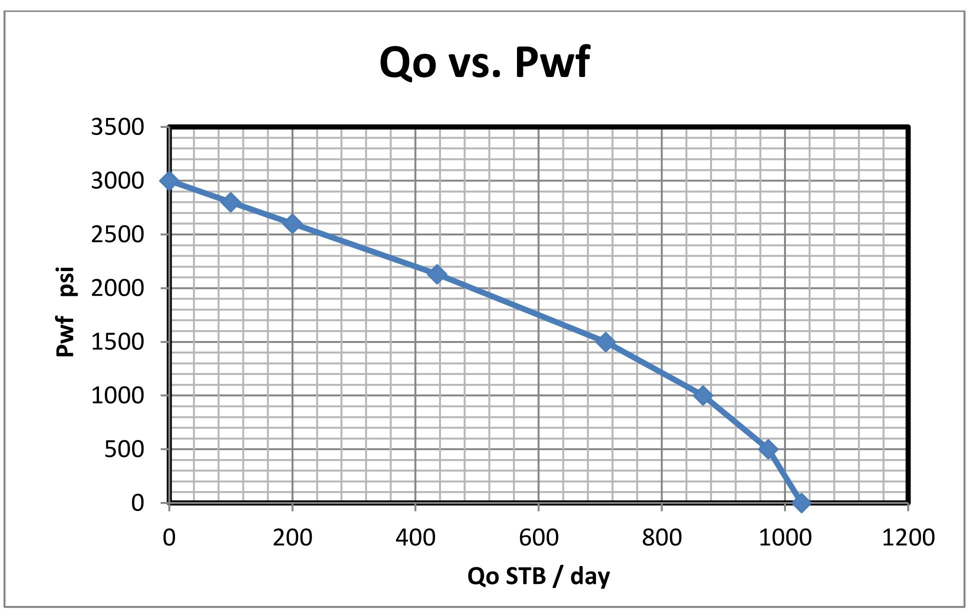
Step 2: Calculate the oil flow rate at the bubble-point pressure by applying

$Q_{ob} = J\,(P_r - P_b)$

$Q_{ob} = 0.5\,(3000 - 2130) = 435$ STB/day

Step 3: Generate the IPR data by applying the constant J approach for all pressures above $\mathbf{P_b}$ and equation (1.17) for all pressures below $\mathbf{P_b}$.

P_{wf}	Equation	Q_o
3000	(1.4)	0
2800	(1.4)	100
2600	(1.4)	200
2130	(1.4)	435
1500	(1.17)	709
1000	(1.17)	867
500	(1.17)	973
0	(1.17)	1027



Case 2: The Value of the Recorded Stabilized $P_{wf} < P_b$

When the recorded P_{wf} from the stabilized flow test is below the bubble- point pressure, as shown in Figure (1-30), the following procedure for generating the IPR data is proposed:

Step 1: Using the stabilized well flow test data and combining Equation (1.16) with (1.17), solve for the productivity index **J** to give:

$$J = \frac{Q_o}{(P_r - P_b) + \frac{P_b}{1.8}\left[1 - 0.2\left(\frac{P_{wf}}{P_r}\right) - 0.8\left(\frac{P_{wf}}{P_r}\right)^2\right]} \quad \text{---------- (1.19)}$$

Step 2: Calculate Q_{ob} by using Equation (1.16), or:

$$Q_{ob} = J\,(P_r - P_b)$$

Step 3: Generate the IPR for $P_{wf} \geq P_b$ by assuming several values for P_{wf} above the bubble point pressure and calculating the corresponding Q_o from:

$$Q_o = J\,(P_r - P_{wf})$$

Step 4: Use equation (1.17) to calculate Q_o at various values of P_{wf} below P_b, or:

$$Q_o = Q_{ob} + \frac{JP_b}{1.8}\left[1 - 0.2\left(\frac{P_{wf}}{P_r}\right) - 0.8\left(\frac{P_{wf}}{P_r}\right)^2\right]$$

Problem (1-5): The well described in problem (1-4) was retested and the following results obtained:

P_{wf} = **1700** psig, Q_o = **630.7** STB/day

Generate the IPR data using the new test data.

Solution:

Notice that the stabilized P_{wf} is less than P_b

Step 1: Solve for J by applying equation (1.19).

$$J = \frac{Q_o}{(P_r - P_b) + \frac{P_b}{1.8}\left[1 - 0.2\left(\frac{P_{wf}}{P_r}\right) - 0.8\left(\frac{P_{wf}}{P_r}\right)^2\right]}$$

$$J = \frac{630.7}{(3000 - 2130) + \frac{2130}{1.8}\left[1 - 0.2\left(\frac{1700}{3000}\right) - 0.8\left(\frac{1700}{3000}\right)^2\right]} = \mathbf{0.5}\ \text{STB/day/psi}$$

Step 2: Q_{ob} = 0.5 (3000 − 2130) = **435** STB/day

Step 3: Generate the IPR data.

P_{wf}	Equation	Q_o
3000	(1.4)	0
2800	(1.4)	100
2600	(1.4)	200
2130	(1.4)	435
1500	(1.17)	709
1000	(1.17)	867
500	(1.17)	973
0	(1.17)	1027