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**PETRO-IPR: A COMPUTATIONAL TOOL FOR INFLOW
PERFORMANCE RELATIONSHIP ANALYSIS**

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Abstract. *The Inflow Performance Relationship (IPR) curve is one of the main tools that production and reservoir engineers use to represent the reservoir delivery capacity at different flow rates for each pressure differential between the reservoir and the well. In this context, the IPR curve is necessary for the well design completion, production optimization, nodal analysis calculations, and artificial lift design. In this sense, this work aims to present two case studies using the simulator PETRO-IPR to predict the IPR and Productivity Index (PI) curves. The PETRO-IPR's algorithms were built from the Vogel and Mass Quadratic models to calculate the IPR and PI curves for undersaturated and saturated reservoirs, and field data were used to validate these algorithms in previous works. In this paper, the simulator was used to predict IPR curves for PI in transient flow and analyze the influence of the skin effect on the IPR curve. The results showed a decrease of the flows over time when considering the PI in transient flow. Regarding skin factor effects on the IPR curve, it was possible to check damage and stimulation depending on the skin values adopted.*

Keywords: *Well/Reservoir, Productivity Index, IPR, Software*

1. INTRODUCTION

Due to the increased petroleum production and demand in the last hundred years, the reserves characterized as easy to access and with a lower operational cost were already depleted. Consequently, the petroleum companies needed to deal with more complex environments for oil and gas exploration, such as long distances from the coast, deep reservoirs, low temperatures, high pressures, and high Gas-Oil Ratios (GOR), among others (Carneiro et al., 2015). This is especially true for Brazilian Pre-Salt environments. For this reason, financial return optimization related to all stages of the petroleum and natural gas exploration chain and the production cycle has become mandatory. From a technical point of view, the exploration of the field is associated with a specific minimum flow rate that will indicate the lower limit for that project to be economically viable. Thus, the production flow rate can be optimized using available tools in the oil and gas area (Xiang and Kabir, 2019).

Building the Inflow Performance Relationship (IPR) is a necessary and available tool for production optimization. The IPR describes the behavior of both bottom flowing pressure and flow rate concerning production well (Elias et al., 2009). IPRs are used to determine the optimum production of fluid flow rate in a well for any specified value of average reservoir pressure and predict its performance, which is an essential parameter to understanding the reservoir-well behavior and quantifying the production flow rate (Andreolli, 2016; Daoud et al., 2017; Faraji et al., 2019).

The IPR curve is essential for developing projects of well completion, artificial lift, and nodal analysis studies. Among the advantages of studying IPR curves is the possibility of maximizing financial return, estimating the optimal dimensioning of the equipment that will be used during the well's production, and identifying the best period to operate the well using an artificial lift (Klins and Clark, 1993; Elias et al., 2009).

Different models are proposed in the literature (Andreolli, 2016; Guo; Lyons; Ghalambor, 2007) to simulate the IPR curve that can be classified into empirical and analytical models. Empirical models are derived from either field or experimental data. For example, both Vogel (1968) and Fetkovich (1973) models are empirical models often used in the

oil and gas industry (Fattah et al., 2014). The analytical models are obtained from conservation equations and closing relationships describing the reservoir's flow (Elias et al., 2009; Daoud et al., 2017).

It is essential to calculate the depletion of the reservoir and analyze whether there is no damage preventing the flow rate through the porous medium. Then, Weller (1966) estimated the productivity based on bottom-hole pressure as a function of the flow rate. Among the results, the author observed the influence of the skin factor (S) on the productivity index values. This factor represents the presence of an altered production zone around the well. Thereby, measuring the production efficiency of a well, in which the productivity index value was reduced for a damaged well ($S > 0$). In this situation, the IPR curve has a worse performance, decreasing the production of the well. On the other hand, there was an increase in the productivity index for a stimulated well ($S < 0$), consequently increasing the well's production.

From this context, Araújo Júnior et al. (2022) presented the development of the simulator PETRO-IPR. The authors showed IPR and PI curves simulated to Vogel, Mass Quadratic, and Fetkovich models in different scenarios. These studies considered data from the literature to validate the PETRO-IPR's algorithms, and the results found were satisfactory for applications in field operations. However, the authors didn't explore other computational tools' available features, such as skin factor and PI curves in transient flow analyses. Thus, this paper presents the use of the PETRO-IPR to predict IPR and PI curves in transient flow and investigates the influence of skin factors on the IPR curves.

2. METHODOLOGY

2.1 PI model

The Productivity Index (PI) is an essential parameter to determine the production capacity of a well. Mathematically, the PI is defined as the ratio between the produced liquid flow rate under surface conditions (Q_{sc}) and pressure differential, as shown in Equation (1). In addition, this equation is used to predict the IPR curve for the linear model (Andreolli, 2016).

$$PI = \frac{Q_{sc}}{(P_e - P_{wf})} \quad (1)$$

In the Equation (1) P_e is the reservoir pressure (bar) and P_{wf} is the bottom-hole flowing pressure (bar). PI is given in $\text{sm}^3/\text{d}/\text{bar}$ once Q_{sc} is measured at sm^3/d . On the other hand, if the recorded P_{wf} is lower than the bubble pressure (P_b), the PI is obtained from Equation (2):

$$PI = \frac{Q_b}{(P_b - P_{wf})} \quad (2)$$

in which Q_b (sm^3/d) is the flow rate at P_b defined by Vogel's model and it is determined from:

$$Q_b = \frac{1.8 \cdot Q_x \cdot (P_e - P_b)}{P_b} \quad (3)$$

in which Q_x (sm^3/d) represents the subtraction between the maximum flow rate and the flow rate at P_b :

$$Q_x = Q_{max} - Q_b \quad (4)$$

with Q_{max} (sm^3/d) representing the well's maximum flow rate when P_{wf} equals to zero.

2.1.1 Steady-state flow

The steady-state flow is defined as a flow condition under which the pressure at any point in the reservoir remains constant over time. Equation (5) demonstrates the PI calculation of steady-state flow around a vertical well (Andreolli, 2016).

$$PI = \frac{2 \cdot \pi \cdot k \cdot h}{\mu_o \cdot B_o \cdot \left[\ln \left(\frac{r_e}{r_w} \right) + S \right]} \quad (5)$$

in which, k is the absolute permeability (m^2), h is the reservoir thickness (m), μ_o is the absolute viscosity ($\text{Pa} \cdot \text{s}$), B_o is the liquid's formation volume factor (m^3/sm^3), r_e is the reservoir radius (m), r_w is the well radius (m), and S is the skin factor, resulting in PI unit as $\text{sm}^3/\text{s}/\text{Pa}$.

2.1.2 Transient flow

The transient flow is used when the pressure depends on the radius and time once the reservoir limits are not reached. Then, the reservoir acts similar as an infinitely large reservoir. Equation (6) shows the PI for the transient flow around a vertical well (Guo; Lyons; Ghalambor, 2007; Andreolli, 2016).

$$PI = \frac{2 \cdot \pi \cdot k \cdot h}{\mu_o \cdot B_o \cdot \left[\log(t) + \log\left(\frac{k}{\phi \cdot \mu_o \cdot c_t \cdot r_w^2}\right) - 3.23 + 0.87 \cdot S \right]} \quad (6)$$

In Equation (6), t is the flow time (s), ϕ is the porosity (%), c_t is the total compressibility (Pa⁻¹).

2.2 Vogel model for IPR curve

To simulate IPR curves by the Vogel model, Equation (7) was applied (Andreolli, 2016).

$$\frac{Q_{sc}}{Q_{max}} = 1 - 0.2 \cdot \left(\frac{P_{wf}}{P_e}\right) - 0.8 \cdot \left(\frac{P_{wf}}{P_e}\right)^2 \quad (7)$$

Equation (8) represents the expression to construct the IPR curve by the Generalized Vogel Model (GVM). This method contemplates different scenarios according to the different flow conditions present in the reservoir throughout production (Andreolli, 2016).

$$Q_{sc} = Q_x \cdot \left[1.8 \cdot \left(\frac{P_e}{P_b}\right) - 0.8 - 0.2 \cdot \left(\frac{P_{wf}}{P_b}\right) - 0.8 \cdot \left(\frac{P_{wf}}{P_b}\right)^2 \right] \quad (8)$$

More details about the different scenarios modeled by PETRO-IPR using the GVM can be found at Araújo Júnior et al. (2022).

3 RESULTS AND DISCUSSIONS

This section exposes and discusses the results obtained by PETRO-IPR using the Vogel model to simulate the IPR curves considering PI in transient flow. Further, it presents the functionalities of PETRO-IPR through simulation of IPR and PI for different skin factors.

3.1 IPR curves for PI in transient flow

Data from Economides and Hill (1994) were used to simulate the IPR curve with PI in the transient flow. This case was applied in a vertical well, in which the reservoir condition is undersaturated, without skin effect, and the oil has an °API of 28. The production test presented in Table 1 was applied to simulate IPR curves using Vogel's model for PI in the transient flow.

Table 1. Production test for transient flow.

P_e (bar)	P_b (bar)	P_{wf} (bar)	Q_{sc} (sm ³ /d)
389.62	310.27	270.62	105.9

The fluid properties and reservoir data reservoir parameters are described in Table 2.

Table 2. Reservoir parameters used to calculate PI at transient flow conditions.

Variable	Value
k (m ²)	$7.89 \cdot 10^{-15}$
ϕ (%)	19
B_o (m ³ /sm ³)	1.1
h (m)	16.15

Variable	Value
μ_o (Pa·s)	$1.7 \cdot 10^{-3}$
t (s)	$2.59 \cdot 10^6 - 3.46 \cdot 10^7$
r_e (m)	908.31
r_w (m)	0.01
c_t (Pa ⁻¹)	$1.87 \cdot 10^{-9}$

It is important to highlight the influence of the PI on the IPR curve. Then, different times were considered in the determination of PI values and the results are shown in Table 3.

Table 3. PI simulated for the transient flow condition in the IPR model.

Time (day)	PI (sm ³ /d/bar)
30	0.4784
90	0.4474
150	0.4343
400	0.4112

IPR curves were simulated with the PI of each time of Table 3 using the Vogel model, as illustrated in Figure 1.

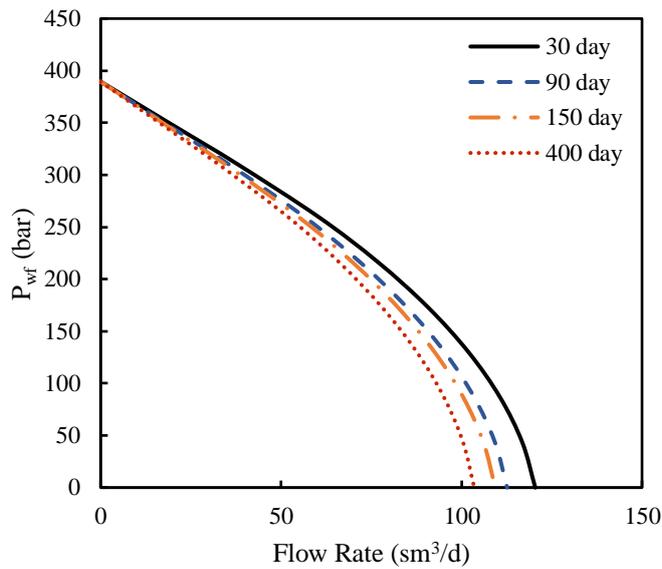


Figure 1. IPR curves for each time value with PI in the transient flow.

The IPR curve's behavior, illustrated in Figure 1, shows a linear section until the saturation point, 310.27 bar. After, a curved shape is observed. This is because PI is constant in the linear section, by presenting a single-phase flow, and later there is a variation of PI due achieve to two-phase flow when the pressure become less than bubble pressure.

Both PI values in Table 3 and the IPR curves in Figure 1 it is notorious for the decrease of the flows over time, and this occurs due to the reduction of the productivity index of the well throughout the production, following the decline analysis of the well/reservoir according to the chosen time.

3.2 Skin factor analysis

In this section, the same case study in the previous section was applied. However, focusing on the influence of the skin factor on IPR and PI curves in the steady-state flow. The production test presented in Table 1 was applied to simulate IPR curves. The other parameters used to determine the productivity index in the steady-state flow are shown in Table 4.

Table 4. Reservoir parameters for the steady-state flow with skin factor.

Variable	Value
k (m ²)	$7.89 \cdot 10^{-15}$
B_o (m ³ /sm ³)	2.80
h (m)	16.15
μ_o (Pa·s)	$1.7 \cdot 10^{-3}$
r_e (m)	908.31
r_w (m)	0.01
Skin Factor	(-2) – (+2)

In the case study referenced, the reservoir is characterized as undersaturated, therefore, Vogel's model was applied, as shown in Figure 2 and Figure 3.

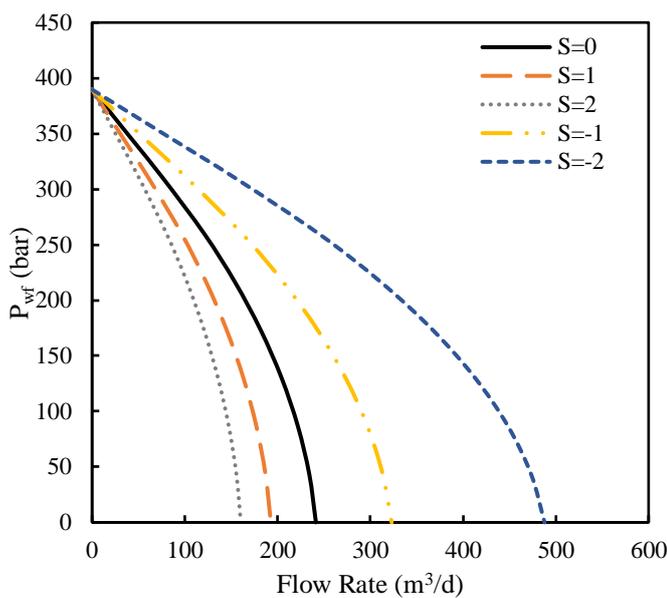


Figure 2. IPR curves for the Vogel model with skin factor.

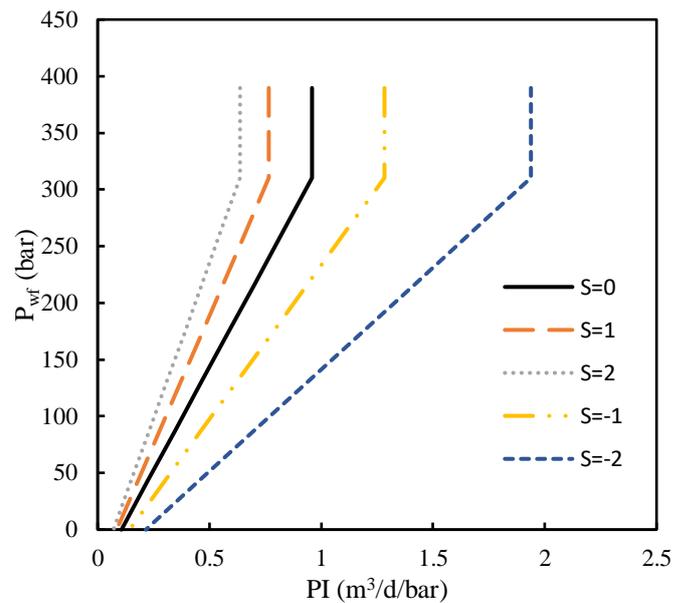


Figure 3. PI curves for the Vogel model with skin factor.

In Figure 2, the IPR curve with $S = 0$ represents a well without any damage or stimulation. There is a stimulation in the IPR curves with $S = (-1)$ and $S = (-2)$, as waited. Therefore, the effective radius of the well is increased and the deliverability of the reservoir to the well reaches higher flow rate values. The IPR curves $S = 1$ and $S = 2$ indicate a damaged well, so the effective radius decreases, representing for example a poorly executed perforation, by decreasing the fluid flow rate.

Figure 3 shows the representation of the same values of bottom-hole pressure but related to productivity index values. Therefore, it is possible to observe a higher production rate in $S = (-1)$ and $S = (-2)$, due to a lower loss of energy for the fluid flow rate once the effective radius increased. On the other hand, in $S = 1$ and $S = 2$ it is possible to observe a lower production rate, due to a higher loss of energy for the fluid flow into well once the effective radius decreased.

4 CONCLUSION

It is important to emphasize that PETRO-IPR allowed the simulation of Vogel model for saturated and undersaturated reservoirs. Further, it allowed to perform sensitivity analysis on IPR curves for PI in transient flow and analyzing of the

influence of skin factor. Thus, the simulator was able to assess the influence of these parameters presented in the equations to model and simulate IPR and PI curves.

It is concluded that the simulator PETRO-IPR used in this work is capable of modeling and simulating several IPR conditions and models and, furthermore, it could be used both for academic purposes and applied to the oil and gas industry problems.

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6 RESPONSIBILITY NOTICE

The authors R. R. Araújo Júnior, M. C. Costa, and A. M. Barbosa Neto are the only responsible for the printed material included in this paper.