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A Comparison of the Calculation Methods for Inflow Curves Creation to Software Prosper

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Abstract : The oil reservoir behavior and evaluation of its deliverability belongs to the fundamental role of production engineers in the petroleum industry. The ability of the well to produce is characterized by the relationship between the total liquid flow rate and bottom-hole flowing pressure. This relationship is so-called IPR – inflow performance relationship. Nowadays, there are many different IPR correlations in petroleum industry but the most common use model is Vogel's method. With the development of computer technology were created computer softwares for this purpose. In this article, Prosper 14.0 was used to compare the results obtained by manual calculation using the Vogel's method. At the same time, a manual calculation based on Darcy's reservoir model was created and compared with the software in which it was used as the main reservoir model.

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1 Introduction

One of the most important components of the entire production system is reservoir. If it is not possible to predict current and future liquid flow rate into the well, the entire system cannot be analyzed. The flow into the well depends on the drawdown or pressure drop in the reservoir (Δp). The pressure drawdown is characterized as a difference between reservoir pressure (P_R) and bottom-hole flowing pressure (P_{wf}). The relationship between drawdown and liquid flow rate (Q) occurring in the porous medium depends on many parameters such as rock properties, fluid properties, compressibility of the flowing fluids, fluid saturations in the rock, reservoir energy. In petroleum terminology, this relationship is graphically illustrated and named as inflow curves [1]. The simplest shape of the inflow curves is a straight line in the undersaturated oil reservoir ($P_R>P_b$). The inflow into a well is directly proportional to the pressure drawdown and the constant of proportionality is the productivity index (PI or J). The numerical value of the productivity index is given by the ((7), (8)) or under Darcy's law by ((15)), from the flowing bottom-hole pressures and flow rates measured during production tests. Its calculations are only suitable for undersaturated reservoir because variables that affect the productivity index and in turn the inflow performance are the pressure-dependent parameters, e.g.: oil permeability (k_o), oil viscosity (μ_o) and oil formation volume factor (B_o or FVF). Above the P_b, the term ($k_o/\mu_o B_o$) from ((15)) is almost constant. As the pressure drops below the bubble point pressure, the dissolved gas is released from solution and the gas bubbles form in pores which can cause a large decrease this term. The overall effect of changing the pressure on this term is illustrated in (Figure 1)[2].

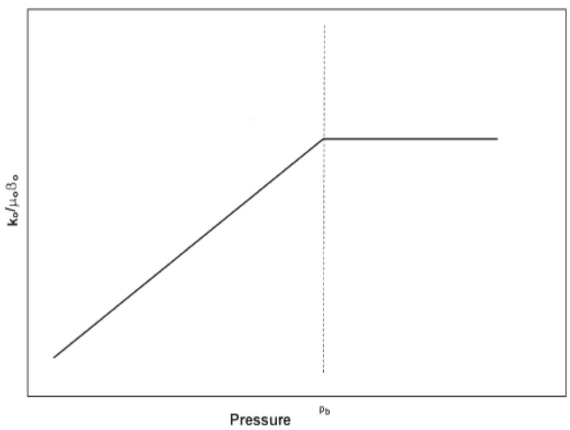


Figure 1 The term ($k_o/\mu_o B_o$) as a function of pressure

Evinger and Muskat (1942) observed that when the pressure drops below the P_b, the inflow curve deviate from the simple straight-line relationship (Figure 2)[3].

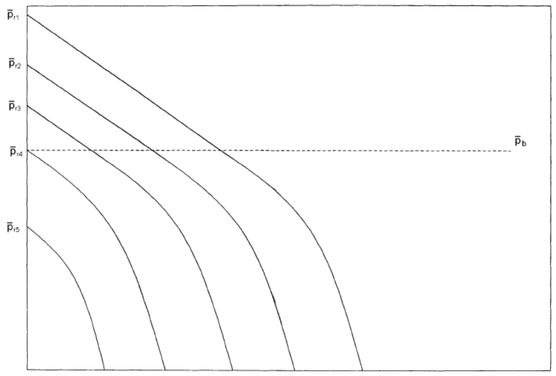


Figure 2 Effect of reservoir pressure

The flow from the reservoir into a well has been called inflow performance by Gilbert (1954). The Gilbert methodology was used to determination of well productivity by W.T.Weller (1966), who proposed a method to calculate the decline tendency of reservoir based on bottom-hole pressure and production rate[4]. The development and analysis of the first method to generate IPR´s was carried out by Vogel, who made an important innovation to Weller´s method, incorporating dimensionless terms. The other expressions for the inflow curves currently in use: M.B.Standing, M.J.Fetkovich, M.L.Wiggins, M.A.Klins and L.Clark.

2 Methods

The use of the IPR curves began in the middle of the 20th century to establish practical criteria for the exploitation of hydrocarbon reservoirs. The techniques used in these methods were based on the results of analyzes from real reservoirs. Currently, there are several basic methods for creating inflow curves based on earlier studies. The main essence of all empirical methods is:

- Using the stabilized flow test data, construct the IPR curve at the current reservoir pressure,
- Predict future inflow performance relationship as to the function of reservoir pressure.

The Vogel‘s research was developed by using the reservoir model proposed by Weller [5]. The resulting expression was based on calculations made from 21 different reservoirs, from which a dimensionless pressure and dimensionless oil flow rate, was developed [6].

$$\frac{Q}{Q_{max}} = 1 - 0{,}2\left(\frac{P_{wf}}{P_R}\right) - 0{,}8\left(\frac{P_{wf}}{P_R}\right)^2 \qquad (1)$$

Standing noted that Vogel‘s equation can be extended by introducing the productivity index in order to predict future inflow performance relationship [7].

$$Q_f = \frac{J_f P_{Rf}}{1{,}8}\left[1 - 0{,}2\left(\frac{P_{wf}}{P_{Rf}}\right) - 0{,}8\left(\frac{P_{wf}}{P_{Rf}}\right)^2\right] \qquad (2)$$

where the subscript (f) refers to future condition.

The development of the inflow curve equation was based on 40 different oil wells from 6 different reservoirs. Fetkovich proposed a method for calculating the IPR for oil wells using the same type of equation that has been used for gas wells [8].

$$Q = C\left(P_R^2 - P_{wf}^2\right)^n \qquad (3)$$

where:

C – performance coefficient (determined from production test data);

n – exponent depending on well characteristics (the value is ranged from 0,568 to 1).

Wiggins used principles of relative permeability and fluid physical properties as a basic input for the development of the IPR equation. His suggested relation is similar to Vogel´s expression [9].

$$\frac{Q}{Q_{max}} = 1 - 0{,}52\left(\frac{P_{wf}}{P_R}\right) - 0{,}48\left(\frac{P_{wf}}{P_R}\right)^2 \qquad (4)$$

The resulting expression is similar in form to that of Vogel‘s. Klins and Clark proposed to improve the predictive capability of Vogel‘s equation by introducing a new exponent (d). The final equation is [10]:

$$\frac{Q}{Q_{max}} = 1 - 0{,}295\left(\frac{P_{wf}}{P_R}\right) - 0{,}705\left(\frac{P_{wf}}{P_R}\right)^d \qquad (5)$$

where:

$$d = \left[0{,}28 + 0{,}72\left(\frac{P_{wf}}{P_R}\right)\right](1{,}24 + 0{,}001P_b) \qquad (6)$$

3 Calculation

The reservoir deliverability depends on the efficient use of reservoir energy, which allows the fluid flow from the underground reservoir to the wellbore, separator and ultimately to the stock tank. The monitoring of the inflow to the wellbore is determined as the functional dependence of the flow rate and the pressure drawdown (Q = fΔp), also known as the inflow performance relationship. One of the most common used methods of constructing inflow curves is Vogel´s method. The calculation algorithm by this method for a given reservoir type ($P_R > P_b$) is:

1) Calculation of productivity index by using the stabilized test data point (Q and P_{wf}). When recorded stabilized P_{wf} is less than the P_b:

$$J = \frac{Q}{(P_R-P_b)+\frac{P_b}{1,8}\left[1-0,2\frac{P_{wf}}{P_b}-0,8\left(\frac{P_{wf}}{P_b}\right)^2\right]} \quad (7)$$

when recorded stabilized $P_{wf} \geq P_b$:

$$J = \frac{Q}{P_R-P_{wf}} \quad (8)$$

2) Calculation of oil flow rate at the bubble point pressure:

$$Q_b = J(P_R - P_b) \quad (9)$$

3) Generation of IPR values above the P_b by different values of P_{wf} (P_{wf}>P_b):

$$Q = J\left(P_R - P_{wf}\right) \quad (10)$$

Generation of IPR values below the P_b by different values of Pwf (P_{wf}<P_b):

$$Q = Q_b + \frac{JP_b}{1,8}\left[1 - 0,2\left(\frac{P_{wf}}{P_b}\right) - 0,8\left(\frac{P_{wf}}{P_b}\right)^2\right] \quad (11)$$

4) Calculation of maximum oil flow rate (Q_{max}), when the P_{wf} is zero:

$$Q_{max} = Q_b + \frac{JP_b}{1,8} \quad (12)$$

5) Calculation of future oil flow rate at the specified future reservoir pressure. It consists of two steps:
Step 1. Calculate Q_{maxf} at P_{Rf}:

$$(Q_{max})_f = (Q_{max})\left(\frac{P_{Rf}}{P_R}\right)\left[0,2 + 0,8\left(\frac{P_{Rf}}{P_R}\right)\right] \quad (13)$$

Step 2. Calculate Q_f at different values of P_{wf}:

$$Q_f = (Q_{max})_f\left[1 - 0,2\frac{P_{wf}}{P_{Rf}} - 0,8\left(\frac{P_{wf}}{P_{Rf}}\right)^2\right] \quad (14)$$

where subscript (f) represent future conditions.

Darcy‘s IPR model for undersaturated oil reservoir is based on the calculation of the oil flow rate using Darcy‘s equation for bottom-hole flowing pressure above bubble-point pressure, and the use of the Vogel‘s equation for P_{wf} below the P_b. This model is also the most widely used in software Prosper in view of reservoir behavior in the future because it contains wider reservoir characteristics. The calculation procedure is the following:

1) Calculation of productivity index:

$$J = \frac{2\pi k_o h}{\mu_o.B_o.\ln\left(\frac{r_e}{r_w}\right)} \quad (15)$$

where:

h – thickness (m);

r_e – drainage radius (m);

r_w – wellbore radius (m).

2) Generation of IPR values above the P_b by different values of P_{wf} ($P_{wf} > P_b$):

$$Q = J\left(P_R - P_{wf}\right) = J\Delta p \quad (16)$$

3) Calculation of Q_{max} by using the stabilized test data point (Q and P_{wf}):

$$Q_{max} = \frac{Q}{1-0,2\left(\frac{P_{wf}}{P_R}\right)-0,8\left(\frac{P_{wf}}{P_R}\right)^2} \quad (17)$$

4) Generation of IPR values below the P_b by different values of P_{wf} ($P_{wf} < P_b$):

$$Q = Q_{max}\left[1 - 0,2\left(\frac{P_{wf}}{P_R}\right) - 0,8\left(\frac{P_{wf}}{P_R}\right)^2\right] \quad (18)$$

5) Calculation of future oil flow rate at the specified future reservoir pressure consists of two steps:
Step 1. For $P_{wf} > P_b$: P_R is replaced by P_{Rf} in ((16)).
Step 2. For $P_{wf} < P_b$: ((13), (14)) are used.

Based on the above calculations, we are able to construct the inflow curve at the current reservoir pressure and to predict the future behavior of the given reservoir, when the reservoir pressure drops. These calculations are a great help to the production engineers because pressure drop is necessary and irreversible part of reservoir life. If we can predict the future oil flow rate, we can correcly use a secondary or tertiary recovery method, sometimes referred to as enhanced oil recovery.

4 Results

In this article, the manual calculations of the inflow curve at the current reservoir pressure and its decrease according to the Vogel‘s and Darcy‘s methods are compared with software Prosper 14.0. The data necessary for their construction can be found in Table 1.

Table 1 Input data

P_R	35,8	MPa
P_b	23,8	MPa
P_{wf}	16	MPa
Q	3375	$m^3.24hod^{-1}$
k_o	$5,1.10^{-14}$	m^2
μ_o	$3,9.10^{-4}$	Pa.s
B_o	1,41	$m^3.m^{-3}$
R_e	802,6	m
R_w	0,1079	m
T	98,8	°C

where T is a reservoir temeperature.

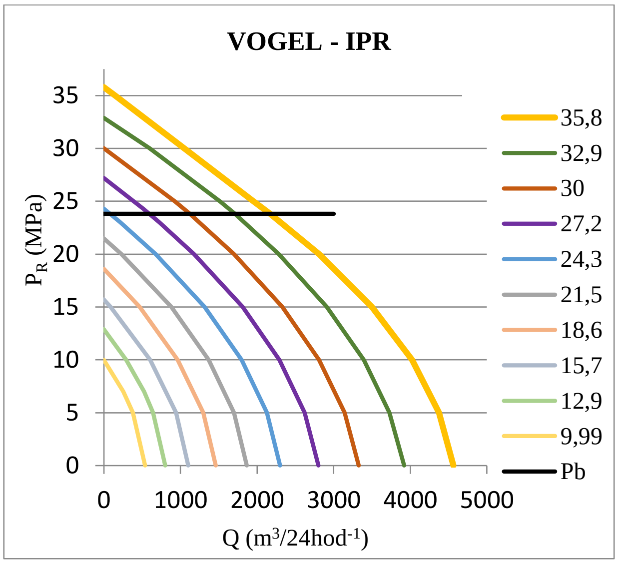


Figure 3 Vogel's inflow performance relationship

The calculations, in this case (Figure 3), consists of the equations ((7)-(14)). The oil reservoir is undersaturated, which determines the value of reservoir pressure that is higher than the bubble point pressure. Four dates are required to process the calculation: reservoir pressure, bubble-point pressure, stabilized bottom-hole flowing pressure, stabilized oil flow rate. A total of 10 inflow curves were constructed at a current reservoir pressure value 35,8MPa, up to a value of reservoir pressure 9,99MPa.

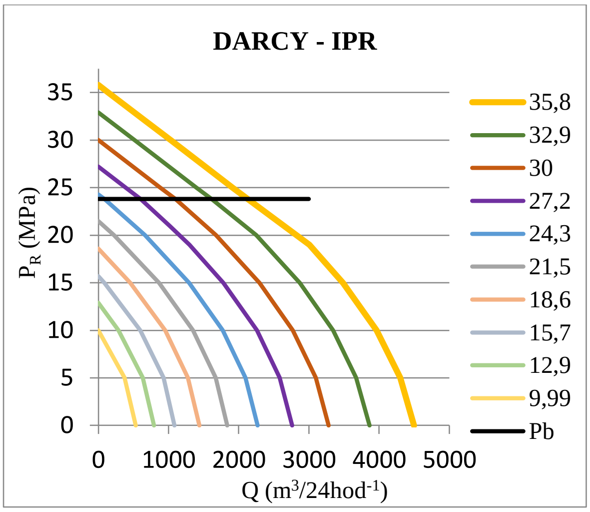


Figure 4 Darcy's inflow performance relationship

The calculation was performed at the same reservoir pressure value to be able to compare their results. Equations ((13)-(18)) were used to process the results. The data required for the calculation are shown in (Table 1). The resulting values of the total oil flow rate according to Vogel's and Darcy's methods are shown in (Table 2). To verify the results, the inflow curves were created in Prosper 14.0, which is a part of most petroleum companies today. Therefore, the resulting value obtained from this software will be considered as initial values. The design section of the software is shown in the (Figure 5) and the resulting inflow curves in the (Figure6).

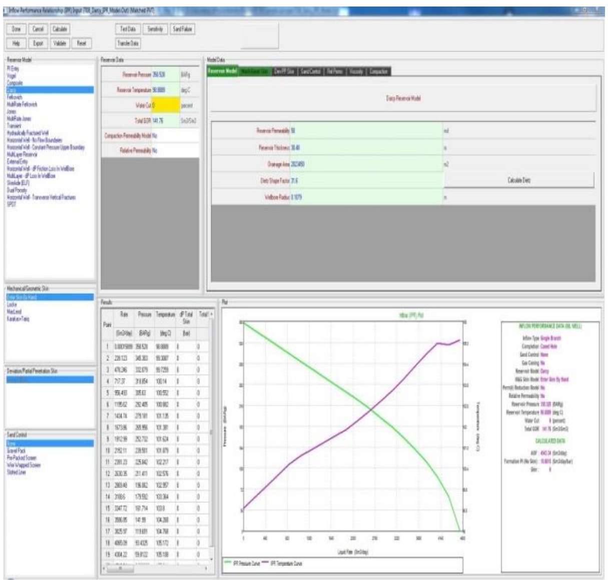


Figure 5 The Prosper IPR input screen

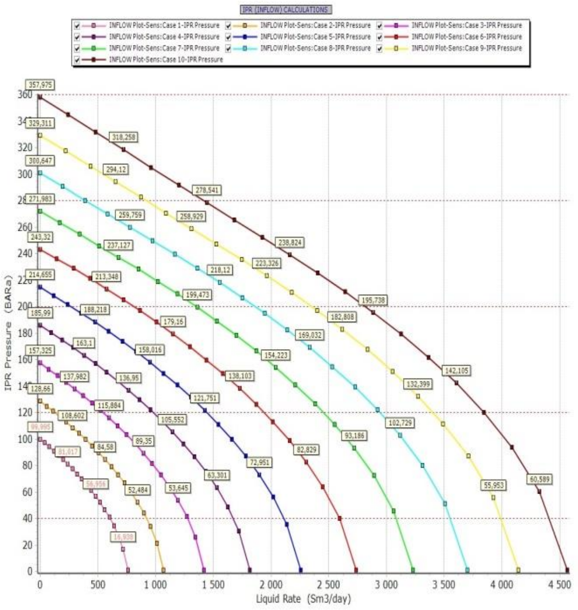


Figure 6 The Darcy IPR model in Prosper

Table 2 The resulting values of Q and calculation errors

P_R (MPa)	Q_{max} (P)	Q_{max} (V)	Error (%)	Q_{max} (D)	Error (%)
35,8	4543	4561	0,39	4495	1,1
32,9	4100	3920	4,6	3863	5,8
30	3650	3327	9	3279	10,1
27,2	3280	2799	14,7	2759	16
24,3	2700	2300	14,9	2267	16,1
21,5	2250	1864	17,2	1837	18
18,6	1800	1459	19	1438	20
15,7	1450	1102	24	1086	25
12,9	1050	802	24	791	25
9,99	750	539	28	531	29

where:

P – Prosper model;

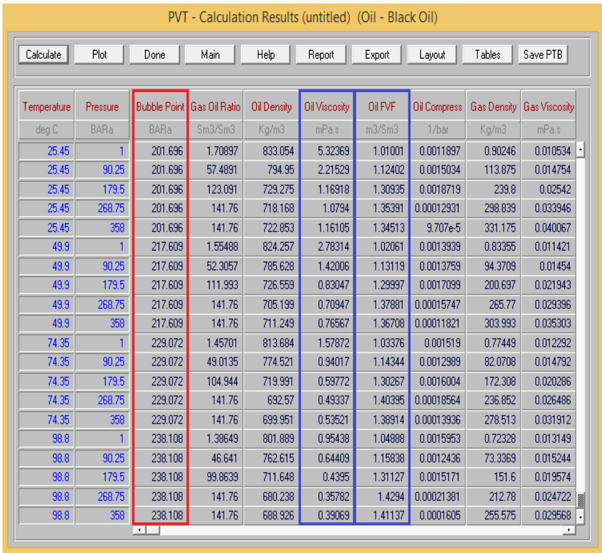
V – Vogel‘s method;

D – Darcy‘s method;

Q – total oil flow rate ($m^3.24hod^{-1}$).

5 Discussion

Based on the above results in (Table 2), we can say that in manual calculations of inflow curves we make a maximum error in both cases of approximately 30%. At the specified 10 reservoir pressure values, the error increases by about 4%. The main factor affecting the accuracy of the results in the first case (Vogel) is the value of bubble-point pressure. In manual calculations, a constant value of P_b is used, but this value is, in fact, dependent on the reservoir temperature change. The change of P_b value is indicated by a red box in (Figure 7). As in the first method, also in the second (Darcy), the main factor of the errors is a change of values depending on pressure and temperature. In this case, the change of the P_b will be supplemented by the changes of μ_o and B_o, used in the equation. This change of values is indicated in the (Figure 7) by a blue box.



PVT - Calculation Results (untitled) (Oil - Black Oil)

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Temperature	Pressure	Bubble Point	Gas Oil Ratio	Oil Density	Oil Viscosity	Oil FVF	Oil Compress	Gas Density	Gas Viscosity
deg C	BARa	BARa	Sm3/Sm3	Kg/m3	mPa.s	m3/Sm3	1/bar	Kg/m3	mPa.s
25.45	1	201.696	1.70897	833.054	5.32369	1.01001	0.0011897	0.90246	0.010534
25.45	90.25	201.696	57.4891	794.95	2.21529	1.12402	0.0015034	113.875	0.014754
25.45	179.5	201.696	123.091	729.275	1.16918	1.30935	0.0018719	239.8	0.02542
25.45	268.75	201.696	141.76	718.168	1.0794	1.35391	0.00012931	298.839	0.033946
25.45	358	201.696	141.76	722.853	1.16105	1.34513	9.707e-5	331.175	0.040067
49.9	1	217.609	1.55488	824.257	2.78314	1.02061	0.0013939	0.83355	0.011421
49.9	90.25	217.609	52.3057	785.628	1.42006	1.13119	0.0013759	94.3709	0.01454
49.9	179.5	217.609	111.993	726.559	0.83047	1.29997	0.0017099	200.697	0.021943
49.9	268.75	217.609	141.76	705.199	0.70947	1.37881	0.00015747	265.77	0.029396
49.9	358	217.609	141.76	711.249	0.76567	1.36708	0.00011821	303.993	0.035303
74.35	1	229.072	1.45701	813.684	1.57872	1.03376	0.001519	0.77449	0.012292
74.35	90.25	229.072	49.0135	774.521	0.94017	1.14344	0.0012989	82.0708	0.014792
74.35	179.5	229.072	104.944	719.991	0.59772	1.30267	0.0016004	172.308	0.020286
74.35	268.75	229.072	141.76	692.57	0.49337	1.40395	0.00018564	236.852	0.026486
74.35	358	229.072	141.76	699.951	0.53521	1.38914	0.00013936	278.513	0.031912
98.8	1	238.108	1.38649	801.889	0.95438	1.04888	0.0015953	0.72328	0.013149
98.8	90.25	238.108	46.641	762.615	0.64409	1.15838	0.0012436	73.3369	0.015244
98.8	179.5	238.108	99.8639	711.648	0.4395	1.31127	0.0015171	151.6	0.019574
98.8	268.75	238.108	141.76	680.238	0.35782	1.4294	0.00021381	212.78	0.024722
98.8	358	238.108	141.76	688.926	0.39069	1.41137	0.0001605	255.575	0.029568

Figure 7 Change of P_b, μ_o, B_o values obtained from software Prosper

Considering that the Darcy‘s method, since a wider reservoir characteristic is used (15), the resulting error will be less than in the first case (Vogel), a comparative analysis of the selected values of P_R and P_{wf} in the Darcy method was performed with the software Prosper (Figure 8), (Table 3). By performing this analysis, it was found that for $P_{wf}>P_b$ the maximum error was 2,7%, but for $P_{wf}<P_b$ the maximum error was significantly greater (16,4%). Based on this fact, we can conclude that the measurement inaccuracy in the Darcy method occurs mainly when the P_{wf} falls below the P_b, when the Vogel equations are used ((13), (14)).

Table 3 The resulting values of Q and calculation errors

P_R (MPa)	P_{wf} (MPa)	Q (P)	Q (D)	Error (%)
35,8	25	1950	1914	1,9
32,9	25	1420	1400	1,5
30	25	910	886	2,7
27,2	25	400	390	2,5
P_R (MPa)	P_{wf} (MPa)	Q (P)	Q (D)	Error (%)
35,8	10	4020	3963	1,5
32,9	10	3600	3342	7,1
30	10	3125	2768	11,5
27,2	10	2700	2258	16,4

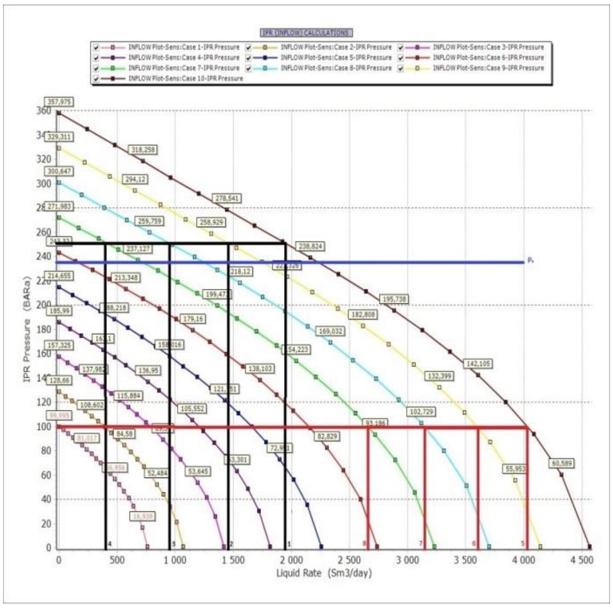

Figure 8 The Darcy IPR model in Prosper with selected values of P_R and P_{wf}

6 Conclusion

In view of the above results, analyzes and comparisons, the following findings can be made. Creating of inflow curves by manual calculations of Vogel‘s method, the resulting values of the oil flow rate differ from the values obtained by modeling in software Prosper in the range from 0,39% to 28%. Using the Darcy‘s method the errors are roughly at the same level (1,1-29%). As in the first method and in the second, the variation of the obtained results with the Prosper begins at a low level, but by gradually decreasing the reservoir pressure, the errors increases. Therefore, both methods offer good results of the oil flow rate in the early stage of well life. The main reason for the inaccuracies is that when the $P_{wf} < P_b$, the Vogel‘s equations in both cases are used. The resulting errors are also due to the fact that the used software Prosper takes into account any minimal changes in the physical properties of liquid and gaseous hydrocarbons as a function of the change in pressure and temperature.

The reference list

[1] BEGGS, H.: *Production optimization using nodal^{TM} analysis*, Oklahoma, Copyright, 1991.

[2] AHMED, T.: *Reservoir engineering handbook*, Elsevier, 2010

[3] EVINGER, H.H., MUSKAT, M.: Calculation of theoretical productivity factors, *Trans.AIME*, pp. 126-146, 1942.

[4] GILBERT, W.E.: Flowing and gas-lift well performance, *API drilling and production practise*, New York, 1 January, 1954.

[5] WELLER, W.T.: Reservoir performance during two-phase flow, *J.petrol.technol.*, pp. 240-246, 1966.

[6] VOGEL, J.V.: Inflow performance relationship for solution gas drive wells, *Journal of petroleum technology*, January, 1968.

[7] STANDING, M.B.: Inflow performance relationship for damaged wells producing by solutions-gas drive, *J.petrol.technol.*, Vol. 22, pp. 1399-1400, 1970.

[8] FETKOVICH, M.J.: The isochronal testing of oil wells, Society of petroleum engineers, Dallas, pp.7, 1973.

[9] WIGGINS, M.L.: Generalized inflow performance relationship for three-phase flow, *Proceeding of the SPE production operations symposium*, USA, pp. 275-286, 1993.

[10] KLINS, M.A., CLARK, L.: An improved method to predict future IPR curves, *SPE reserv.eng.*, Vol.8, pp. 243-248, 1993.