Case Study: Performance Prediction of a Horizontal Well in a Fractured Reservoir

A. Jahanbani G. #1, S. R. Shadizadeh #2, T. A. Jelmert #3, O. Torsæter #4, M. Moradi #5

#1,3,4,5 Norwegian University of Science and Technology (NTNU)
S.P. Andersens vei 15 A, 7491 Trondheim, Norway

#2Abadan Faculty of Petroleum Engineering, Petroleum University of Technology, Abadan, Iran

Abstract *Investigation of the rate-pressure behaviour of oil wells is of great importance in well performance evaluation and optimization. Several authors reported that for horizontal wells, the shape of the inflow performance relationship (IPR) curves is similar to those predicted by the Vogel or Fetkovich methods or a combination of them. However, the complex flow regime existing around a horizontal well precludes using simple empirical methods that are limited in applications. This paper presents an analytical approach for determination of inflow performance for horizontal wells in fractured reservoirs producing during the boundary dominated flow regime using the results of well test analysis. The proposed method, which is an extension of a general approach previously presented by the authors, is then applied to an example horizontal well in a naturally fractured reservoir. The developed IPR curve is then compared with selected methods of horizontal well performance analysis. Results of comparison show that this study is in good agreement with Joshi method which is a widely accepted method.*

Keywords— *Inflow Performance Relationship, Well Test Analysis, Pseudo Steady State, Horizontal Well, Naturally Fractured Reservoir*

I. INTRODUCTION

It is often required to predict the pressure-rate relationship of a well to estimate its producing potential and to use it in production optimization. This relationship is called Inflow Performance Relationship (IPR). Different empirical relationships have been proposed for determination of IPR in homogeneous reservoirs ([1]-[4]). Vogel relationship ([5]) for solution-gas drive reservoirs gained much popularity in the industry. These methods are not general and have some limitations in application.

Naturally fractured reservoirs constitute huge portion of hydrocarbon reserves and are generally assumed to be composed of two systems of different porosities and permeabilities, a matrix system and a fracture or fissure system. In a previous work, Jahanbani and Shadizadeh [6] proposed a general analytical approach for determination of IPR curve by well testing and then in another work ([7]), they further extended the method to particularly include vertical oil wells in naturally fractured reservoirs.

Some combination of linear and radial flow around a horizontal well makes the analysis complicated and empirical methods may not be appropriate for performance analysis. Therefore, to further extend the previous studies, the general approach is first modified in this paper to include horizontal wells, and then it is applied to an example horizontal well in a fractured reservoir and results of the analysis will be compared with some selected methods available.

II. DEVELOPMENT OF IPR CURVE

The method presented in this paper is based on well test analysis results. Well test analysis in fractured reservoirs has been covered thoroughly in the literature (e.g. in [8]-[10]). In this study, it is assumed that the well produces during boundary dominated flow regime. Productivity index (defined as the ratio of liquid flow rate to pressure drawdown) is constant during the pseudo steady state flow regime since the rate of pressure decline is constant. For single phase flow (above the bubble point pressure), a straight line IPR curve is obtained, but this is not the case for two phase flow conditions.

The equation proposed by Aguilera [10] for the analysis of pressure data in finite naturally fractured reservoirs (pseudo steady state flow regime), can be modified to account for two phase flow by including relative permeability. In the case of a horizontal well, effect of anisotropy is included in the definition of permeability, as the geometric average of horizontal (k_h) and vertical (k_z) permeabilities, and equivalent wellbore radius suggested by [11] as:

$$(r_w)_{eq} = r_w(\sqrt[4]{k_h / k_z} + \sqrt[4]{k_z / k_h})/2 \qquad 1$$

Using this approach, an analytical inflow equation is obtained, expressing the relation between flow rate (q_o) and flowing wellbore pressure (p_{wf}) and considering the effect of anisotropy (oil field units):

$$q_o=\frac{0.00708\sqrt{k_h.k_z}\,h(p_R-p_{wf})}{\left[\ln\left(\dfrac{r_e}{r_w(\sqrt[4]{k_h/k_z}+\sqrt[4]{k_z/k_h})/2}\right)+s-0.75\right]}\times\lambda(p_{av}) \tag{2}$$

Pressure dependent properties (among them mobility function, $\lambda = k_{ro} / \mu_o B_o$) are evaluated at arithmetic average of wellbore and reservoir pressure. This method uses the results of well test analysis along with relative permeability and fluid properties in the flow equation for generation of IPR curves, as will be explained in the following example. It is also capable of predicting future IPRs.

III. CASE STUDY

Maleh-Kuh oilfield, an asymmetric anticline approximately 35 km long and 5 km wide, is located in Lorestan region (South west of Iran) and extended along the northwest-southeast trend. Bangestan reservoir of this field was explored in 1969 by drilling well No. 1. It contains a huge amount of oil and gas. Based on petrophysical and geological information, this reservoir is composed of Ilam, Surgah and Sarvak formations. The well selected for analysis in this study, on which a buildup test was conducted, is well No. 3 in this field. This oil well was drilled in 2005 to characterize Ilam formation and provide oil for Serkan production unit. Vertical drilling was continued to 5223 feet in Surgah formation and directional drilling was commenced from 4239 feet in Ilam formation and continued to 4600 feet. The rock type of the producing formation (Ilam) is fractured limestone with matrix porosity of 0.036. Presence of an initial gas cap (4.44 times larger than the initial oil volume) is also evident in this reservoir. After running different casing strings and cementing, the well was completed open hole in the horizontal section. Horizontal well length is 1855 feet, and net pay thickness is 459 feet.

A buildup test was conducted on well No. 3 (February 20th, 2007). After 26.5 hours production at constant rate of 500 STB/D, the well was shut in for 12.73 hours. A commercial well test analysis software was used for estimation of reservoir parameters. Semi-log and log-log plots are shown in Figs. 1 and 2, respectively. The presence of two parallel straight lines is not clear on the semi-log plot and derivative data is pretty noisy at early times. The actual production mechanisms and reservoir flow regimes around horizontal wells are considered more complicated than those for vertical wells, especially if the horizontal section of the well is of considerable length. Some combination of both linear and radial flow may exist, and the well may behave in a manner similar to a well that has been extensively fractured.

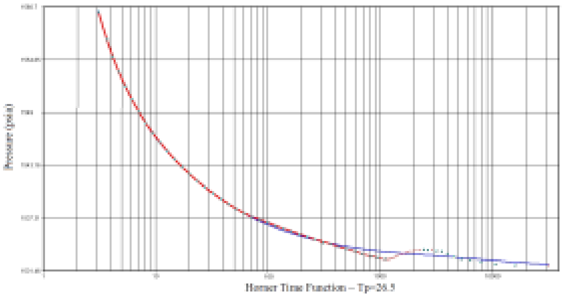

Fig. 1 Semi-log plot of pressure data of well No. 3

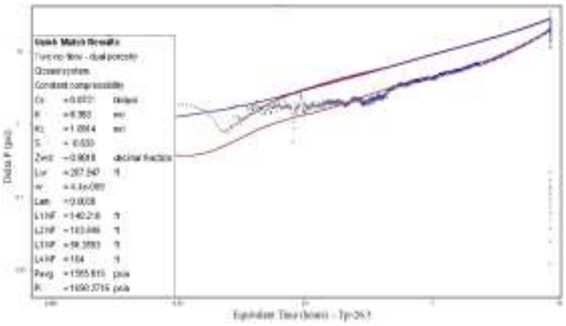

Fig. 2 Log-log plot of pressure and derivative data of well No. 3

Detailed well test analysis of this example is given in [12]. Initial reservoir pressure and bubble point pressure are 1680 and 1607.5 psia, respectively. Current reservoir pressure (p_R) is 1565.62 psia. Results of well test analysis indicate horizontal and vertical permeability of 6.36 and 1.09 md. Using the material balance below bubble point pressure:

$$1-\frac{S_o}{S_{ob}}\frac{B_{ob}}{B_o}=\frac{B_t-B_{tb}+m\,B_{ob}\left(\dfrac{B_g}{B_{gb}}-1\right)}{B_t+B_g\,(R_p-R_{sb})} \tag{3}$$

And knowledge of fluid properties and relative permeability data, a relationship is established between reservoir pressure and mobility function. Substituting for reservoir parameters (from well test analysis) and other terms in equation 2, gives the IPR curve at current average reservoir pressure (1565.62 psia) as shown in Fig. 3.

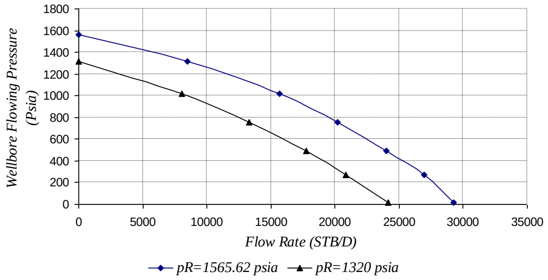

Fig. 3 Generated IPR curves for well No. 3

Future inflow performance at declined average reservoir pressure can be predicted using equation 2.

Fig. 3 shows the predicted IPR curve at 1320 psia. It is assumed that the mobility function (λ) at future time has the same mathematical form (as a function of average pressure) as at present time. Some of the data used in the generation of IPR curves are shown in Fig. 4.

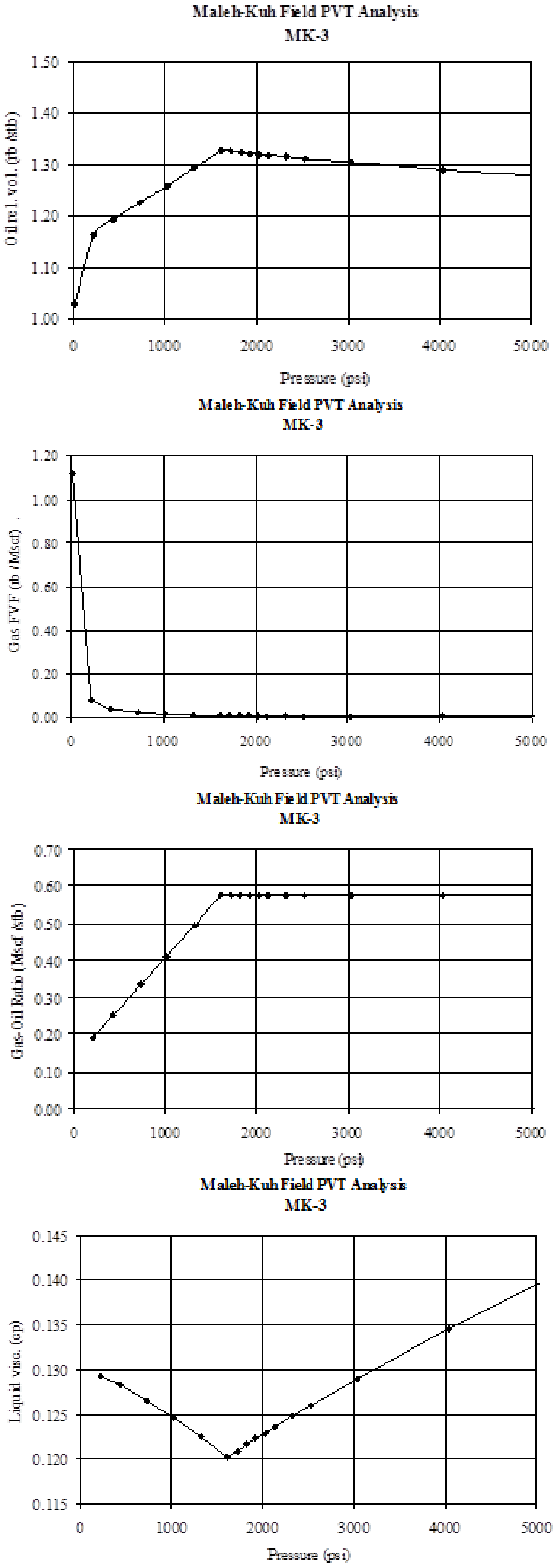

Fig. 4 Some of the PVT data for well No. 3 [12]

IV. COMPARISON WITH OTHER METHODS

It is generally believed that the shape of IPR curves for horizontal wells is similar to those predicted by Vogel or Fetkovich methods. In this section, IPR curves for well No. 3 are generated by two different methods and are compared with the IPR obtained in this work. Among different methods designed to predict the well performance using the knowledge of fluid and reservoir properties, Borisov [13] and Joshi [14] methods are used for comparison purpose.

Incorporating the effect of relative permeability and evaluating pressure dependent properties at average pressure, the following expression for pseudo steady state inflow is obtained, based on Borisov equation for predicting the performance of a horizontal well in an anisotropic reservoir [13]:

$$q_o = \frac{0.00708\, h\, k_h\, (p_R - p_{wf})}{\left[\ln\left(\frac{4r_e}{L}\right) + B^2\left(\frac{h}{L}\right)\ln\left(\frac{h}{2\pi r_w}\right) + s - 0.75\right]} \times \left(\frac{k_{ro}}{\mu_o\, B_o}\right)_{pav} \tag{4}$$

Where

$$B = \sqrt{\frac{k_h}{k_z}} \tag{5}$$

After some manipulation, the following expression for pseudo steady state oil production is obtained based on Joshi equation for performance analysis of a horizontal well in an anisotropic reservoir [14]:

$$q_o = \frac{0.00708\, h\, k_h\, (p_R - p_{wf})}{\left[\ln R + B^2\left(\frac{h}{L}\right)\ln\left(\frac{h}{2r_w}\right) + s - 0.75\right]} \times \left(\frac{k_{ro}}{\mu_o\, B_o}\right)_{pav} \tag{6}$$

Where

$$R = \frac{a + \sqrt{a^2 - (L/2)^2}}{(L/2)} \tag{7}$$

And

$$a = (L/2)[0.5 + \sqrt{0.25 + (2r_e/L)^4}\,]^{0.5} \tag{8}$$

Substitution for the parameters in equations 4 and 6 gives Borisov and Joshi IPR curves as plotted in Fig. 5. It can be observed that Joshi IPR curve is in good agreement with the result of this study.

In this study, the value of AOF (Absolute Open Flow potential or the maximum possible flow rate of the well at atmospheric pressure) was calculated 29277 STB/D, very close to Joshi estimate of 27985 STB/D. However, Borisov method highly overestimated the flow rates, almost two times the other methods.

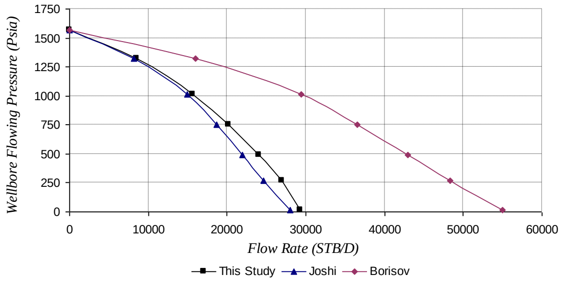

Fig. 5 Comparison of IPR curves for well No. 3 obtained by different methods

V. CONCLUSIONS

In this study, an analytical method previously proposed for generation of IPR curves in naturally fractured reservoirs was modified to be applied to horizontal wells, considering the effect of anisotropy. The modified method was applied to a horizontal oil well in a fractured limestone reservoir and the resulting IPR curve was compared with results of other methods of performance analysis of horizontal wells. While Borisov method highly overestimated the flow rates, Joshi method (a widely accepted method) was very close to this study.

The method used in this paper depends on the accuracy of the results of parameter estimation by well test analysis. Quite often, if properly conducted and interpreted, well test interpretation methods yield the most representative values of the reservoir parameters. These values are normally the volumetric average values in the radius of investigation, whereas other sources of information (e.g. core analysis) give the values at discrete points around the wellbore.

NOMENCLATURE

B_g	Gas Formation Volume Factor, bbl/scf
B_o	Oil Formation Volume Factor, bbl/STB
B_t	Total Formation Volume Factor, bbl/STB
h	Formation Thickness, ft
k	Permeability, md
k_{ro}	Oil Relative Permeability, Dimensionless
L	Horizontal well length, ft
p_{av}	Average Pressure, psia
p_i	Initial Reservoir Pressure, psia
p_R	Average Reservoir Pressure, psia
p_{wf}	Flowing Wellbore Pressure, psia
q_o	Oil Flow Rate, STB/D
r_e	Drainage Radius, ft
R_p	Cumulative Produced Gas/Oil Ratio, scf/STB
R_s	Solution Gas/Oil Ratio, scf/STB
r_w	Wellbore Radius, ft
s	Skin Factor
S_o	Oil Saturation, Fraction
t_p	Production Time, hours
λ	Mobility Function, STB/cp.bbl
μ	Viscosity, cp

ACKNOWLEDGMENT

Authors would like to gratefully thank National Iranian Central Fields Oil Company (NICFOC) and Department of Petroleum Engineering and Applied Geophysics at NTNU (Trondheim) for the support to present this work.

REFERENCES

[1] H. H. Evinger and M. Muskat, “Calculation of theoretical productivity factor,” *Trans. AIME*, vol. 146 (1), pp. 126–139, 1942.

[2] M. B. Standing, “Concerning the calculation of inflow performance of wells producing from solution-gas drive reservoirs,” *Journal of Petroleum Technology*, vol. 23 (9), pp. 1141–1142, 1971.

[3] M. J. Fetkovich, “The isochronal testing of oil wells,” in *SPE 48th Annual Meeting, Las Vegas, Nevada*, 30 September – 3 October, 1973, paper SPE 4529.

[4] M. Golan and C. H. Whitson, *Well Performance*, Second Edition, Trondheim, Norway: Tapir Publishing Company, 1996.

[5] J. V. Vogel, “Inflow performance relationship for solution-gas drive wells,” *Journal of Petroleum Technology*, vol. 20 (1), pp. 83–92, 1968.

[6] A. Jahanbani G. and S. R. Shadizadeh, “Determination of Inflow Performance Relationship (IPR) by Well Testing,” in *CIPC (Canadian International Petroleum Conference) Annual Technical Meeting of the Petroleum Society, Calgary, Alberta, Canada*, 16 – 18 June, 2009, paper CIPC 2009-086.

[7] A. Jahanbani G. and S. R. Shadizadeh, “Determination of the Inflow Performance Relationship in Naturally Fractured Oil Reservoirs: Analytical Considerations,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 35 (8), pp. 762-777, 2013.

[8] A. de Swaan O., “Analytic solutions for determining naturally fractured reservoir properties by well testing,” *SPE Journal*, vol. 16, pp. 117–122, 1976.

[9] T. D. Van Golf-Racht, *Fundamentals of Fractured Reservoir Engineering*, Amsterdam, Netherlands: Elsevier Scientific Publishing Company, 1982.

[10] R. Aguilera, “Well test analysis of naturally fractured reservoirs,” *SPE Formation Evaluation*, vol. 2 (3), pp. 239–252, 1987.

[11] W. E. Brigham, “Discussion of Productivity of a Horizontal Well,” *SPE Reservoir Engineering*, vol. 4 (4), pp. 254-255, 1990.

[12] A. Jahanbani G., “Determination of IPR Curve by Well Testing,” Master of Science dissertation, Petroleum University of Technology, Tehran, Iran, December 2008.

[13] J. P. Borisov, *Oil Production Using Horizontal and Multiple Deviation Wells*, Moscow, Russia: Nedra Publishing Company, 1964.

[14] S. D. Joshi, “Augmentation of Well Productivity with Slant and Horizontal Wells,” *Journal of Petroleum Technology*, vol. 40 (6), pp. 729-739, 1988.