# Application of Decline Analysis in Fractured Reservoirs, Field Case Studies

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## Abstract

Decline curve analysis has some advantages over transient well test analysis in which it is not required to shut-in the well and also wellbore storage effects do not exist. Few studies have been done on decline curve analysis of naturally fractured reservoirs but there are even some limitations with available models. On the other hand well test could be expensive and in some operational conditions shutting the well to obtain reservoir parameters is almost impossible. Therefore, investigating the applicability of homogenous reservoir decline models for production data analysis of naturally fractured reservoirs is necessary. In this paper the most important decline models have been used to evaluate reservoir parameters in three Iranian naturally fractured reservoirs and the results have been compared to transient well test analysis. A useful and applicable procedure is also introduced to correct the initial production data when they do not have necessary conditions. The results show that Agarwal-Gardner and Blasingame type curves predict acceptable values for permeability compared to transient well test analysis while Fetkovich type curve cannot predict accurate values. Determined skin values in all wells of the three studied reservoirs are negative. Negative values can be considered to be affected by existing fracture networks in the vicinity of producing wells and also periodic well stimulations. The results also show that Neglecting produced condensates of gas condensate reservoirs with Liquid-Gas Ratio (LGR) less than 100 bbl/MMscf cannot significantly affect decline curve analysis results.

**Keywords**:Decline curve analysis, Naturally fractured reservoir, Permeability, Skin factor, Type curve

## Introduction

Pressure transient data can be costly and may not be available for many wells, while well production data is routinely collected. In the absence of pressure transient data, decline curve analysis (DCA) can be used to predict reservoir parameters from available production data.

Arps [1]developed the empirical standard exponential, hyperbolic and harmonic decline equations.Fetkovich constructed log-log type curves, which combine all equations developed by Arps with the analytical constant pressure solutions of slightly compressible fluids[2, 3]. Traditional Arp's equation and Fetkovich type curve assume highly idealized production conditions such as constant bottom-hole pressure. They also neglect the variations of producing fluid properties with pressure change [4, 5]. Carter [6] presented a new set of type curves developed exclusively for the analysis of gas rate data. He noted that the changes in fluid properties with pressure significantly affect decline curve analysis results. The most important changes are the variations of gas viscosity-compressibility product, $\mu_g c_g$ [7].

Palacio and Blasingame [8, 9, and 10]presented a new solution based on definition of a material balance like time function which allows modeling of actual variable rate/variable pressure drop production conditions. Variations of the producing fluid properties were considered in the type curves and they also contain derivative functions, similar to those used in the well test analysis to help the matching process while applying type curves.

Anash et al. [11] followed the work of Carter and proposed three functional forms to describe the viscosity-compressibility product ($\mu_g c_g$) as a function of pressure.

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They presented the solution in a type curve format.

Agarwal and Gardner [12] used the model of Palacio and Blasingame and demonstrated that in most cases, the solutions for constant rate or constant bottom-hole pressure production can be converted to equivalent constant rate liquid solutions. They developed new type curves which represented advancement over previous works because a clearer distinction can be made between transient and boundary dominated flow periods.

Blasingame [13] used a semi-analytical flow relation and formalized the parameters of Arp's empirical equation for wells producing in high pressure/high temperature reservoirs.

All described decline models were specifically developed for homogenous (conventional) reservoirs. A naturally fractured reservoir is a heterogeneous system consisting of two distinct porosity systems, matrixes and fractures in a same formation [14].

Da Prat. G. and Hebert C. L. found production behavior of infinite and finite acting naturally fractured oil reservoirs for Warren and Root fracture model. Based on their findings, there are two decline rate periods and a constant one between them in production trend of naturally fractured oil reservoirs. They developed decline type curves for naturally fractured reservoirs producing at constant bottom-hole pressure. The production trend for infinite and finite acting naturally fractured reservoirs is shown in figure 1 and figure 2[15].

Shahverdi [15] used Fetkovich type curve to determine the properties of naturally fractured oil reservoirs with an acceptable approximation. Gerami and PooladiDarvish [16] found that material balance pseudo time developed for conventional gas reservoirs can be applied successfully to naturally fractured gas reservoirs using pseudo time evaluated at average reservoir pressure. Zareenejad et al. [17] used decline models of homogenous reservoirs to estimate Expected Ultimate Recovery in a naturally fractured lean gas condensate reservoir.

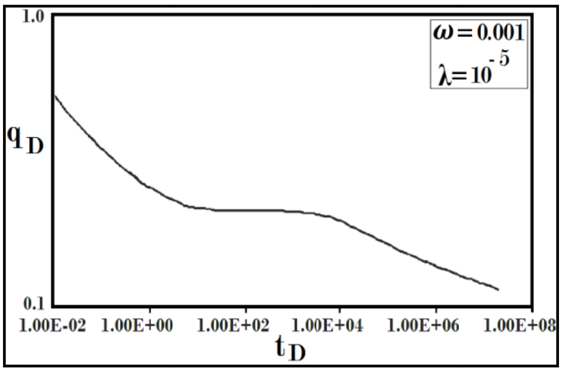



**Figure 1: Production trend of infinite acting naturally fractured reservoirs**

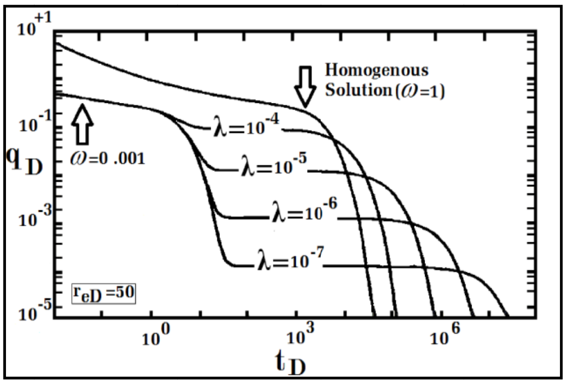



**Figure 2: Production trend of finite acting naturally fractured reservoirs**

As mentioned, few studies have been done on decline curve analysis of naturally fractured reservoirs butthere are even some limitations with available models. On the other hand well test could be expensive and in some operational conditions shutting the well to obtain reservoir parameters is almost impossible. Therefore, investigating the applicability of homogenous reservoir decline models for production data analysis of naturally fractured reservoirs is necessary.

The main purpose of this paper is to see whether conventional decline models are also suitable for naturally fractured reservoirs. The most important decline models, Fetkovich, Blasingame and Agarwal-Gardner type curves have been used to evaluate reservoir parameters in three Iranian naturally fractured reservoirs and the results have been compared to transient well test analysis.

A useful and applicable procedure is also introduced to correct the initial production data when they do not have all necessary conditions to perform decline curve analysis.

## Limitations of production data analysis of naturally fractured reservoirs

Investigations done on naturally fractured reservoirs show that analysis of production data using available decline models of naturally fractured reservoirs is usually impossible due to the following reasons:

- Decline models of naturally fractured reservoirs are not applicable in practical conditions and they cannot model real production data with acceptable accuracy. For example,the variations of fluid properties with pressure or changes of well bottom-hole pressure with time have not been considered in any model. Therefore, it can be said that a perfect and reliable decline model for naturally fractured reservoirs has not yet been developed.
- As mentioned before, the production trend of naturally fractured reservoirs exhibits two decline rate periods and a constant one between them. It is worth noting that some of naturally fractured reservoirs show production trend of homogenous reservoirs.
- In order to analyze production data using decline type curves of naturally fractured reservoirs, values of $\omega$ and $\lambda$ which are determined by transient well test analysis must be available, while exact values of these parameters are rarely determined.

## Case studies

*Naturally fractured gas condensate reservoir "A"*

"A" naturally fractured gas condensate reservoir is located in south west of Iran. Pressure and production trends indicate that there are extended fracture networks through the reservoir. PVT tests have shown almost unchanged fluid composition through the reservoir and initial Liquid-Gas Ratio (LGR) is 12 bbl/MMScf. The reservoir has 30 active producing wells and there is a complete production history for all wells.

*Naturally fractured gas condensate reservoir "B"*

"B" naturally fractured gas condensate reservoir is an anticline with NW-SE axis in south west of Iran. Close agreement of pressure measurements in different wells at the same time periods is indicative of good areal communication through the fracture networks all over the reservoir. Several PVT analyses for different wells indicate unchanged PVT properties with depth and through the reservoir area. Initial LGR is 7.3 bbl/MMScf and there are 24 production wells in the reservoir.

*Naturally fractured oil reservoir "C"*

"C" is a naturally fractured oil reservoir in south west of Iran. This reservoir rock is mostly carbonate and it was proven that there are extended fracture networks through the reservoir. The reservoir has 3 active producing wells. Transient well test analysis results of the three reservoirs are shown in Table 1.

**Table 1: Well test results of the three studied reservoirs**

| Well No. | k, md | Skin |
|---|---|---|
| **2A** | 124 | 3.45 |
| **8A** | 6 | -1.09 |
| **9A** | 7 | -3.5 |
| **14A** | 54.8 | -3.95 |
| **16A** | 35 | -0.88 |
| **27A** | 24.16 | -3.035 |
| **1B** | 16.202 | -0.418 |
| **12B** | 20.36 | 2.38 |
| **20B** | 22.8293 | -4.717 |
| **1C** | 320.602 | -10.02 |
| **2C** | 263.979 | -8.53 |
| **3C** | 208.365 | -11.35 |

## Data preparation procedure

In order to prepare appropriate data, following steps were taken for each well:

- Converting wellhead flowing pressure to bottom-hole flowing pressure considering well geometry using *BeggsandBrill* pressure loss correlation.
- Initial screening of production data.
- Selection of decline periods in production data.
- Identification and elimination of errors and/or anomalies in the selected production data.
- Smoothing production data using *MATLAB* software.
- Time re-initialization of the selected production data.
- Modification of initial reservoir pressure that depends on the type of the reservoir:

1. Naturally fractured gas reservoirs:

There is a linear relation between reservoir pressure and time in both gas reservoirs. "*Least square interpolation technique*" was used to determine the linear functional relation, and then reservoir pressure at the beginning of selected production data was used instead of initial reservoir pressure.

2. Naturally fractured oil reservoir:

Following steps were done:

- Combining material balance equation and oil flow equation presented by Dake (1978) we have:

$$\frac{q}{\Delta p} = \frac{1}{b_{pss}} - \frac{1}{Nc_t b_{pss}} \frac{N_p}{\Delta p} \quad (1)$$

where:

$$\Delta p = (p_i - p_{wf}) \quad (2)$$

and $$b_{pss} = \frac{141.2 B_o \mu_o}{kh} \frac{1}{2} Ln\left(\frac{4}{e^A} \frac{A}{C_A r_{wa}^2}\right) \quad (3)$$

- Plot of $q/\Delta p$ vs. $N_p/\Delta P$; will yield a straight line with y-intercept as $1/b_{pss}$.
- Calculating average reservoir pressure (it was used instead of initial reservoir pressure) from Dake's oil flow equation:

$$\bar{p} = p_{wf} + q b_{pss} \quad (4)$$

- Determination of well temperature by calculating average value of bottom-hole temperatures from reported temperature survey tests.
- Determination of average porosity and water saturation in well drainage area using well petrophysical data.
- Fetkovich type curve assumes constant bottom-hole flowing pressure, so in order to use this type curve, average value of bottom-hole flowing pressures in the selected production data was used.

Based on software recommendation, if LGR of gas condensate reservoirs is more than 100 bbl/MMScf condensate volumes must be converted to equivalent gas volumes and recombined with gas rate stream; otherwise the contribution of condensates is insignificant. LGR of two naturally fractured gas reservoirs were 12 bbl/MMScf and 7.3 bbl/MMScf, therefore produced condensates were neglected [18].

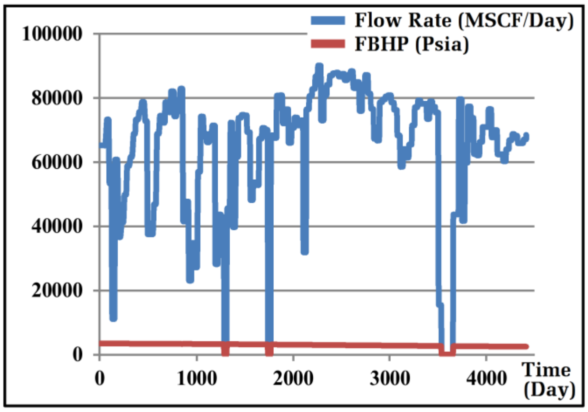
Finally, production data were imported into the software and the analysis were performed for each well using Fetkovich, Blasingame and Agarwal-Gardner type curves.

Steps of preparing appropriate data and applying different decline type curves on production data of well 3A are shown in figure 3.

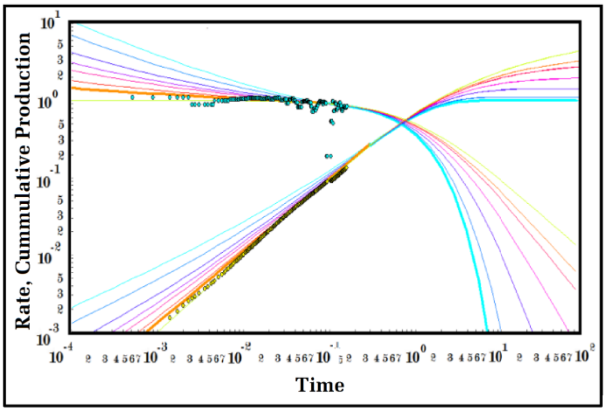
## Results and discussion

Determined values of permeability and skin factor for the three studied reservoirs are shown in Table 2 to Table 4. Relative error percent values of the determined permeability in comparison with transient well test analysis results are also shown in Table 5.

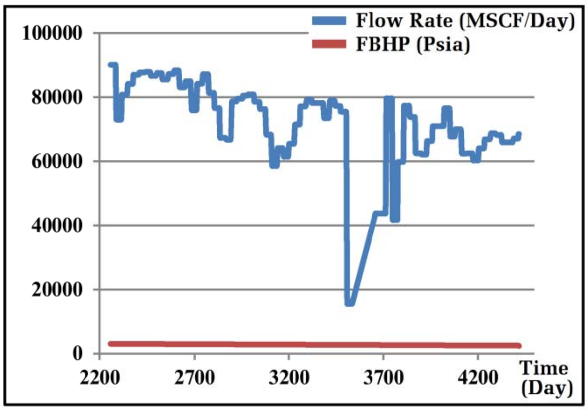
Comparison of decline curve analysis permeability ($k_{DCA}$) with transient well test permeability ($k_{welltest}$) shows that Fetkovich type curve results are not so accurate especifically in gas reservoirs. Average absolute relative error percentage (ARE) of this model is 40.94 (ARE is 24.64 for the oil reservoir and 46.37 for the two gas reservoirs). The reason can be explained by the fact that the variations of producing fluid properties with pressure were neglected.



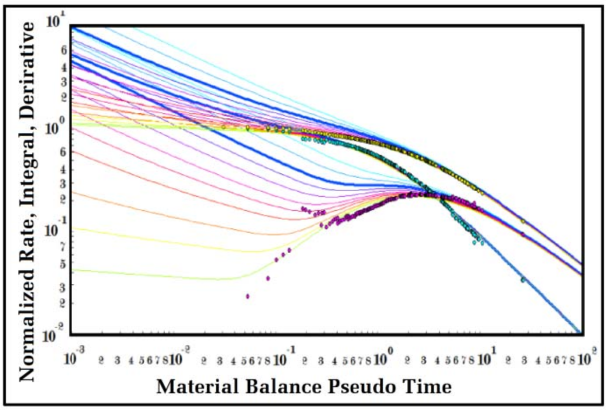

*Well production history*



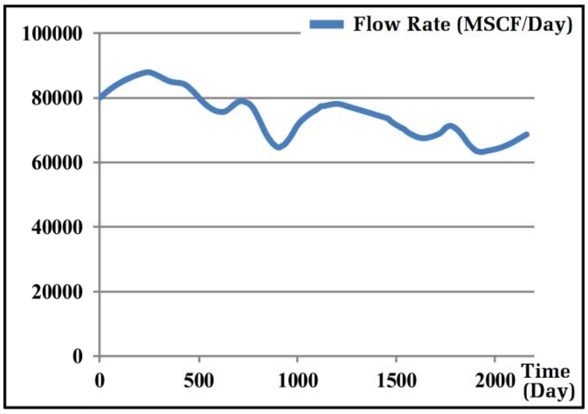

*Production data analysis using Fetkovich type curve*



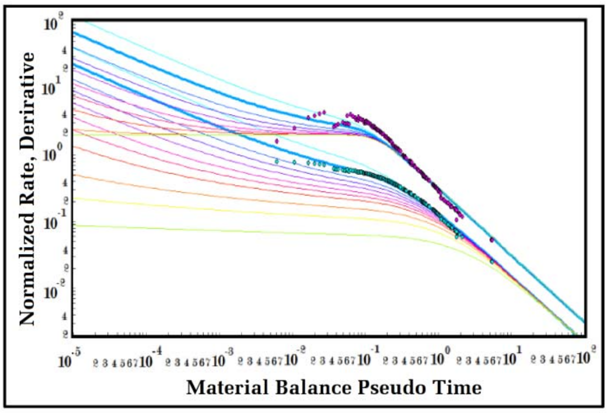

*Selected production data*




*Production data analysis using Blasingame type curve*




*Smoothed production data*




*Production data analysis using Agarwal-Gardner type curve*

**Figure 3: Steps of preparing appropriate data and applying different decline type curves on production data of well#3A**

**Table 2: Permeability and skin factor determined by decline curve analysis for reservoir "A"**

| Well No. | k, md | | | Skin | | |
|---|---|---|---|---|---|---|
| | Fet. TC | B. TC | A-G TC | Fet. TC | B. TC | A-G TC |
| **1A** | 6.8885 | 7.9076 | 9.1109 | -5.66503 | -6.90448 | -6.20845 |
| **2A** | 30.6869 | 93.8293 | 102.3352 | -2.61362 | 4.966629 | 5.001648 |
| **3A** | 67.3022 | 125.409 | 127.7172 | -5.98659 | -4.67953 | -4.68218 |
| **4A** | 11.1367 | 13.5865 | 9.0484 | -2.51694 | -8.0249 | -8.58839 |
| **5A** | 139.1623 | 216.6317 | 182.1184 | -3.41189 | -9.35383 | -9.90422 |
| **6A** | 8.8045 | 14.6639 | 18.5068 | -5.129 | -3.74862 | -1.22445 |
| **7A** | 82.5359 | 61.8933 | 93.4547 | -6.57089 | -8.28133 | -7.23628 |
| **8A** | 7.8695 | 5.3226 | 5.9224 | -4.74381 | -8.43454 | -8.42516 |
| **9A** | 5.8293 | 5.6087 | 6.4642 | -2.3546 | -7.81263 | -8.35071 |
| **10A** | 61.7054 | 119.8991 | 128.2473 | -3.6049 | -4.31813 | -4.32615 |
| **11A** | 53.9324 | 51.5909 | 50.1895 | -5.8916 | -8.15934 | -8.53179 |
| **12A** | 254.9819 | 267.4039 | 249.6313 | -6.32357 | -7.80746 | -7.82115 |
| **13A** | 16.8025 | 19.3715 | 18.2705 | -5.57399 | -8.16388 | -8.70865 |
| **14A** | 61.1795 | 50.535 | 49.6395 | -7.90185 | -9.43835 | -9.38049 |
| **15A** | 16.2701 | 24.8439 | 26.4251 | -4.96912 | -6.37877 | -6.37872 |
| **16A** | 40.0276 | 32.511 | 36.09 | -3.23083 | -9.05867 | -9.07376 |
| **17A** | 21.7633 | 28.9301 | 30.0889 | -7.33241 | -8.32526 | -8.32634 |
| **18A** | 21.5098 | 23.6475 | 28.8943 | -4.96629 | -8.05507 | -8.05262 |
| **19A** | 17.9123 | 23.7803 | 19.3815 | -5.41431 | -7.6914 | -8.09265 |
| **20A** | 12.4163 | 14.563 | 12.4264 | -5.60872 | -7.57357 | -7.98886 |
| **21A** | 24.5069 | 13.806 | 16.8546 | -5.38541 | -7.40001 | -6.95831 |
| **22A** | 12.6997 | 15.5464 | 14.8953 | -6.73486 | -7.49663 | -7.48912 |
| **23A** | 13.9278 | 14.3921 | 16.4293 | -6.68042 | -8.44393 | -8.43935 |
| **24A** | 15.9871 | 17.3248 | 18.2247 | -5.90567 | -6.37804 | -6.36738 |
| **25A** | 135.2833 | 224.3135 | 170.4286 | -6.24969 | -9.59435 | -9.56485 |
| **26A** | 7.3163 | 17.546 | 19.5757 | -6.89308 | -7.25269 | -7.24609 |
| **27A** | 5.508 | 19.9397 | 16.2354 | -6.85901 | -7.68143 | -8.19344 |
| **28A** | 13.4202 | 12.4587 | 13.6229 | -7.53487 | -8.94599 | -8.93185 |
| **29A** | 111.8209 | 112.9497 | 104.022 | -7.86638 | -9.76525 | -9.73379 |
| **30A** | 60.8704 | 25.2471 | 28.9702 | -4.91329 | -8.37276 | -8.35967 |

**Table 3: Permeability and skin factor determined by decline curve analysis for reservoir "B"**

| Well No. | k, md | | | Skin | | |
|---|---|---|---|---|---|---|
| | Fet. TC | B. TC | A-G TC | Fet. TC | B. TC | A-G TC |
| **1B** | 10.7552 | 15.1917 | 14.8303 | -1.83722 | -1.15183 | -1.14513 |
| **2B** | 7.123 | 7.4651 | 9.3039 | -4.55604 | -8.57987 | -9.12958 |
| **3B** | 3.3283 | 34.5422 | 29.9016 | -7.21189 | -8.04553 | -8.59734 |
| **4B** | 4.4469 | 14.878 | 12.9616 | -7.30507 | -9.32682 | -9.29764 |
| **5B** | 3.338 | 39.4188 | 46.1159 | -6.45975 | -0.80302 | -0.7843 |
| **6B** | 6.8586 | 13.9302 | 20.8505 | -4.78132 | -8.05185 | -7.64132 |
| **7B** | 8.851 | 9.5 | 13.5692 | -2.98442 | -8.54888 | -7.69624 |
| **8B** | 6.11 | 7.1263 | 5.6168 | -4.89105 | -8.22855 | -8.76639 |
| **9B** | 11.1847 | 45.2229 | 69.6534 | -2.40142 | -5.33159 | -3.70576 |
| **10B** | 4.7613 | 47.6824 | 50.9019 | -7.26815 | -1.63966 | -1.61952 |
| **11B** | 4.4422 | 80.3116 | 106.6603 | -8.15782 | -1.63034 | -1.62993 |
| **12B** | 2.7417 | 20.5161 | 19.2562 | -7.89159 | -7.81721 | -8.20634 |
| **13B** | 9.1396 | 26.8109 | 34.8829 | -1.88393 | -6.19201 | -5.45782 |
| **14B** | 7.8516 | 23.7618 | 30.8448 | -4.50419 | -8.08718 | -7.62802 |
| **15B** | 10.234 | 14.5952 | 15.3874 | -5.04429 | -8.07623 | -8.9994 |
| **16B** | 6.5286 | 32.9428 | 31.674 | -2.20447 | -5.88494 | -8.88121 |
| **17B** | 4.8337 | 51.6851 | 46.8355 | -4.72741 | -5.37924 | -7.95111 |
| **18B** | 11.5266 | 19.7405 | 12.8798 | -2.51254 | -6.5108 | -8.38209 |
| **19B** | 5.8856 | 11.9603 | 14.4195 | -5.09723 | -7.87327 | -8.80531 |
| **20B** | 6.6447 | 12.3257 | 18.9824 | -6.42578 | -8.83113 | -8.80888 |
| **21B** | 3.1436 | 61.4433 | 59.4476 | -7.19352 | -9.12826 | -7.97446 |
| **22B** | 5.8459 | 24.579 | 27.3683 | -5.18459 | -5.71998 | -7.87796 |
| **23B** | 29.8025 | 58.553 | 53.8405 | -1.71096 | -5.40471 | -5.38095 |
| **24B** | 34.5602 | 15.0968 | 12.5691 | -1.69528 | -9.19391 | -9.14926 |

**Table 4: Permeability and skin factor determined by decline curve analysis for reservoir "C"**

| Well No. | k, md | | | Skin | | |
|---|---|---|---|---|---|---|
| | Fet. TC | B. TC | A-G TC | Fet. TC | B. TC | A-G TC |
| **1C** | 374.2727 | 331.2228 | 306.4296 | -7.67165 | -10.1187 | -9.48481 |
| **2C** | 322.2183 | 226.9318 | 237.3678 | -3.31393 | -10.4611 | -10.0601 |
| **3C** | 281.5824 | 230.3552 | 226.2369 | -7.53572 | -10.348 | -9.97474 |

**Table 5: Values of relative error percent of determined permeability bydifferent decline models in comparison with well test results**

| Well No. | k, md | | | | error percent, $\left\lvert\frac{k_{DCA}-k_{\text{well test}}}{k_{\text{well test}}}\right\rvert\times 100$ | | |
|---|---|---|---|---|---|---|---|
| | Well Test | Fet. TC | B. TC | A-G TC | Fet. TC | B. TC | A-G TC |
| 2A | 124 | 30.6869 | 93.8293 | 102.335 | 75.2525 | 24.3312 | 17.4716 |
| 8A | 6 | 7.8695 | 5.3226 | 5.9224 | 31.1583 | 11.29 | 1.29333 |
| 9A | 7 | 5.8293 | 5.6087 | 6.4642 | 16.7243 | 19.8757 | 7.65429 |
| 14A | 54.8 | 61.1795 | 50.535 | 49.6395 | 11.6414 | 7.78285 | 9.41697 |
| 16A | 35 | 40.0276 | 32.511 | 36.09 | 14.3646 | 7.11143 | 3.11429 |
| 27A | 24.16 | 5.508 | 19.9397 | 16.2354 | 77.202 | 17.4681 | 32.8005 |
| 1B | 16.202 | 10.7552 | 15.1917 | 14.8303 | 33.6181 | 6.23565 | 8.46624 |
| 12B | 20.36 | 2.7417 | 20.5161 | 19.2562 | 86.5339 | 0.7667 | 5.42142 |
| 20B | 22.8293 | 6.6447 | 12.3257 | 18.9824 | 70.8939 | 46.0092 | 16.8505 |
| 1C | 320.602 | 374.273 | 331.223 | 306.43 | 16.7408 | 3.31293 | 4.42041 |
| 2C | 263.979 | 322.218 | 226.932 | 237.368 | 22.0621 | 14.0341 | 10.0808 |
| 3C | 208.365 | 281.582 | 230.355 | 226.237 | 35.139 | 10.5537 | 8.57721 |

In spite of Fetkovich type curve, permeability determined by Blasingame and Agarwal-Gardner type curves have more accuracy. ARE of these models are 14.06 (9.3 for the oil reservoir and 15.65 for the two gas reservoirs) and 10.46, respectively (7.69 for the oil reservoir and 11.38 for the two gas reservoirs).

It is necessary to mention that the amount of decline curve analysis skin factor should be considered qualitatively rather than quantitatively, it means, the sign- negative or positive- is more important than the value. Decline curve analysis skin values in all wells of the three studied reservoirs except one are negative. Negative values can be considered to be affected by existing fracture networks in the vicinity of producing wells and also periodic well stimulations.

However, it is not so reasonable to compare decline curve analysis skin values to those of the well test analysis. It can be explained that well test skin values show the condition of producing well in a short time period and due to damage or stimulation, the values may change with time; while decline curve analysis skin values are results of analyzed production data of a long time period even sometimes the whole production history of the wells.

Results of Agarwal-Gardner and Blasingame type curves also show that neglecting LGR less than 100 bbl/MMscf cannot significantly affect the analysis.

## Conclusions

- Conventional decline curve analysis can be used to analyze production data of naturally fractured reservoirs if data preparation process is done in appropriate procedure and the reservoir fluid has desired conditions.
- Agarwal-Gardner type curve is the best decline model to determine permeability in naturally fractured reservoirs; moreover,Blasingame type curve can be used for estimating permeability in naturally fractured reservoirs with reasonable accuracy.
- Fetkovich type curve cannot determine permeability in naturally fractured reservoirs with good accuracy.

- A useful and applicable procedure was introduced to prepare appropriate production data when the data do not have all necessary conditions to perform decline curve analysis.
- Neglecting produced condensates of gas condensate reservoirs with LGR less than 100 bbl/MMscf cannot affect decline curve analysis results significantly.

## Nomenclature

$A$ Drainage area, $ft^2$
$b_{pss}$ Constant in pseudo steady state Equation for liquid flow as defined by Dake equation, psi/(MMSTB/Day)
$B_o$ Oil formation volume factor, resbbl/STB
$c_A$ Dimensionless reservoir shape factor
$c_t$ Isothermal compressibility factor, $psia^{-1}$
$h$ Formation thickness, ft
$k$ Permeability, md
$N$ Original oil in place, MMSTB
$N_p$ Cumulative oil production, MMSTB
$P_i$ Initial reservoir pressure, psia
$P_{wf}$ Flowing bottom-hole pressure, psia
$\overline{p}$ Average reservoir pressure, psia
$q$ Production flow rate at standard conditions, MMSTB/Day or MMScf/Day
$r_{wa}$ Apparent well radius, ft
$\Delta p$ Pressure difference, psia
$\lambda$ Interaction parameter
$\mu_o$ Oil viscosity, cp
$\omega$ Storativity ratio

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