Integrated reservoir study using well-test deconvolution analysis and well-logging data in a gas condensate carbonate reservoir

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Abstract. This paper presents an integrated approach to characterize a gas-condensate carbonate reservoir using the combination of well-test deconvolution analysis, and well logging interpretation. Each set of data from the subject well, namely, petrophysical logs, production logs, surface well tests and drill-stem tests was analysed. Well test analyses was implemented using both pressure-derivative and variable-rate deconvolution techniques. An integrated analysis and interpretation of the results from different sources was performed. This approach was especially beneficial in reducing some uncertainties such as the layered nature of the reservoir, the heterogeneous behaviour, and boundary-dominated flow regimes. The application of deconvolved derivative increased the radius of investigation and duration of original constant-rate pressure from 24 hours to 140 hours, enabling us to detect the possible fault effect at late-times. This method was also used for performance evaluation of an acid treatment job in the wellbore. It was found that after acidizing, the total skin factor was severely reduced from 33 to 1.2, indicating a successful performance of the acidizing job.

1. Introduction

Identifying the rock and flow properties of a hydrocarbon reservoir is necessary in reservoir studies to manage the reservoir characteristic. Engineers have used several tools and methods in order to study the characteristic of the reservoir. The integration of various data from different resources including wireline formation tester, petrophysical logging, production logging, and drill stem test for gas condensate in carbonate reservoir is quite challenging. The integrated reservoir studies can be found in open literature source. In 1994, Domelen et al. provided integration of pressure transient analysis, core flood testing and dynamic simulation model to design and evaluate the fracture acidizing in a high-temperature carbonate formation [1]. Clarkson and Jensen conducted an integrated study to evaluate unconventional gas reservoirs [2]. Meanwhile, Noah and Shazly presented the integration of well logs and core analysis results to analyse the petrophysical properties of the rock in an oil sandstone reservoir [3]. The well-test data analysis (using deconvolution technique) together with production logging data to investigate the remedial water shut-off operation in a gas-condensate layer reservoir was implemented by Kgogo [4]. Deconvolution offers a powerful technique that has extensively
improved the quality of the well-test data analysis. Gringarten presented the practical use of deconvolution, which had hardly ever been used before by engineers in well test analysis [5]. Ilk et al. and ILK applied a B-spline deconvolution algorithm to several field cases including wellbore storage dominated pressure data, multi-rate test, permanent downhole gauge data and production data [6, 7].

Experience with multi-disciplinary reservoir characterization has shown that the individual analysis of field data such as well test and logging data particularly in a complex gas condensate carbonate reservoirs is not always satisfactory and often contains some ambiguities, which needs to be confirmed with another complementary data. Furthermore, the complexity of well test analysis in such reservoirs and also the short duration of constant-pressure build-ups, have made us to consider the deconvolution approach for analysing the pressure transient data as well, that can increase the radius of investigation and help to identify the possible boundary effect dominated flow regimes at late times. In this paper, the main objective is to conduct an integrated reservoir study and characterization using a combination set of data including drill stem test (DST) as a well test tool, wireline formation tester, production logging and petrophysical logging from a gas condensate carbonate reservoir in Middle East. This study also intended to obtain a more reliable result that can contributes in the future practice with more accurate estimation of the well condition and reservoir specification for the well performance prediction and nearby wells/field development plan.

In the following sections, the methodology used in this work is discussed first. Then, the individual and integrated well-testing analysis and well logging interpretation in a vertical well in the gas condensate field will be elaborated. Finally, the conclusions will be presented.

2. Methodology
In this paper, the commercial softwares of Ecrin-Saphir, Emeraude and Geolog for well test analysis, production logging and petrophysical logging interpretation, respectively have been used. In this work, each single reservoir data from the subject well was individually analysed. Then, the integration of all the interpretation results performed in order to achieve more accurate findings. Well test analysis implemented using both pressure-derivative and variable-rate deconvolution methods. Deconvolution process can convert the observed variable-rate pressure response into a constant-rate pressure response, which makes more data available for analysis compared to the original data set [8-11]. The pressure/rate deconvolution model is given by the well-known convolution integral:

\[
p(t) = p_0 - \int_0^t q(\tau) \frac{dp_\tau(t-\tau)}{dt} d\tau
\]

In the equation above, \( p(t) \) and \( q(t) \) are the measured pressure and flow rate, and \( p_0 \) is the reservoir initial pressure. The deconvolved curve \( p_d(t) \) corresponds to the constant/unit rate drawdown pressure response [12-14].

3. Results and discussion
A series of data collected from the reservoir layer of an appraisal/vertical well in a gas condensate carbonate reservoir, are analysed here. The reservoir interval is from depth 2909-3027 m (the reservoir thickness is 118 m), which was perforated uniformly from depth 2920-3015 m. In this section, firstly the interpretation results for the wireline formation tester and petrophysical logging are presented and then the well test analysis and production logging are discussed as well.

The formation pressure test has been run to record the sand-face pressure of the well. Figure 1 shows all 14 test points along with petrophysical logs including resistivity, lithology and porosity log across the open hole logging interval. This plot (from left to right) presents Gamma Ray (GR) in track 1, True Vertical Depth in track 2, formation quartz-pressure (QCP) in track 3, drawdown mobility with blue colour points and resistivity curves in track 4 and neutron, Photoelectric (PE) and density in track 5. The interpretation results identified that most of the test points have relatively high mobility while interval 2968-2972 m has the highest mobility in comparison to other zones. Gas gradient 0.108 has been fitted on test points with moderate quality points in zone 2945-2972 m as shown in figure 1, track 3. Below 2980 m, the test points are scattered and no gradient line can be fitted on them. From
petrophysical log interpretation, it can be inferred that the reservoir layer mostly consisted of dolomite, limestone with some portion of anhydrite, which divided the reservoir zone into three sub-zone (upper, middle and lower). The middle zone (2945-2972 m) has the highest reservoir quality, which is mostly consisted of limestone-dolomite.

![Graph](image)

**Figure 1.** Test points from wireline formation tester along with open hole petrophysical logs.

DST has been conducted to determine the well and reservoir parameters including (kh product, skin factor, and reservoir pressure) and also to characterize reservoir behaviour such as layering, heterogeneities and flow regimes diagnosis. It is worth for mentioning that a stimulation acid job has been done during DST, to remove the formation damage. The acid treatment job has been followed by post-acid clean-up, intermediate build up, flow after flow test and the final build up respectively, as shown in the history plot in figure 2.

![Graph](image)

**Figure 2.** Drill stem test history plot.
There were three main build up (BU) which needed to be considered, initial BU before acidizing, intermediate BU and final BU after acid treatment job. At initial and final BU, the well had been shut-in at the surface which shows higher wellbore storage effects in comparison to intermediate BU in which well is shut at downhole as shown in figure 3(a). The wide separation between initial BU (before acid) and intermediate or final BU (after acid) in both pressure-derivative and semi-log type-curves signifies the high positive skin before stimulation in the well as shown in figure 3(a) and (b). The total skin factor is reduced from 33 to 1.2 after acidizing. Then, the infinite acting radial flow, IARF (#1) occurs at earlier time in intermediate BU compared to initial and final BU, as the graph shows the IARF (#2) at a later time because of the wellbore storage effect (Figure 3(a)). At final BU with duration 24 hr, two radial flow stabilization can be seen at late time, however, it needs to be verified with other reservoir data. Moreover, the initial and intermediate BU periods are not long enough to see the heterogeneous behaviour. The model interpretation of final BU is supposed to be two layers with two kh product in which the skin factor is around 0.9 and 9.8 for each zone indicating that one layer has a high skin. The total kh product for the reservoir system is estimated to be around 3500 md.ft.

![Figure 3](image)

**Figure 3.** (a) Log-log pressure derivative plot and (b) Semi-log plot.

Then, deconvolution analysis was run to verify the pressure-derivative results as shown in figure 4. The deconvolved derivative increased the radius of investigation (ROI) and the duration of original constant-rate pressure increased from 24 hr to 140 hr, which enabled us to detect the boundary dominated flow regime at late time showing probably the effect of fault/faults.

Production logging (PL) was also run while performing DST, to determine the zonal contribution of each zone and conduct the flow profile of the well, as shown in figure 5. Based on density, water hold-up, pressure and temperature sensors, it is understood to have a stagnant column in the bottom of well, below depth 2985 m which identifies with a sharp change in pressure gradient, density around 1 g/cc and hold up number around 1. The temperature proposes an upward crossflow from the bottom of the layer to the middle zone. Reservoir zone 2953-2979 with 85 percent downhole zonal contribution, is the most contributor zone in production, which is approximately consistent with formation pressure test and petrophysical log results, and also the heterogeneity effect identified on derivative plot of the well test analysis. The uppermost and the bottommost inflow zones have no contribution in production.
4. Integrated study findings
As mentioned before, the final BU derivative showed two radial flow stabilization which indicated a multi-layered reservoir behaviour with different skin factor and kh, while the boundary dominated effects could not be seen. However, the deconvolved derivative enabled us to identify one IARF followed by ¼ slope and then slightly rolls over at late time which is possibly an indication of limited/leaky faults. Therefore, to overcome the issue/uncertainty between well test results from both pressure-derivative and deconvolution in such complex reservoir, integration with the well logging interpretation results is taken into account as well.

The production logging interpretation results presented different reservoir behaviour in three distinct zones including the lower part of perforation below depth 2985 m, the middle zone around 2940-2985 (divided into three sub-zone with zonal contribution 11, 85 and 4 percent in production, respectively), and upper zone above 2940 m which suggests to have a multi-layered reservoir. In other words, PL was also presented the heterogeneous behaviour (the porous media with two or more than...
two storativity and mobility) while one reservoir layer (middle zone) has different sub-layers zonal contribution leading to have mobility contrast between sub-layers. After that, this mobility contrast verified with the results of formation pressure tester and petrophysical logging, which considered the middle zone as the highest mobility zone as was shown in figure 1. The uppermost and the bottommost inflow zones had no contribution in production, particularly the uppermost inflow zone had no reliable test points which could act as a barrier/fault so that this fault effect on deconvolved derivatives did not allow the second IARF in final BU pressure-derivative, to be appeared as well.

To summarize, the integrated well-test and well-log results verified the heterogeneous reservoir behaviour and the possible fault/boundary dominated effects, although it was a very complicated and complex case.

5. Conclusion

- The heterogeneous reservoir behaviour (three distinct zones including below depth 2985 m, the middle zone around 2940-2985, and upper zone above 2940 m) was verified by the integrated reservoir study of the well test analysis and well log interpretation results.
- Reservoir zone 2953-2979 with 85 percent production, was the most contributor. It involved the highest mobility zone, 2945-2972 m with limestone-dolomite lithology.
- The total flow capacity for the reservoir system estimated to be around 3500 md.ft.
- The results showed a high positive total skin factor before stimulation. It was reduced from 33 to 1.2 after acidizing, which indicated the good performance of the acid treatment job. Nevertheless, the two-layers reservoir model proposed that one layer had a high skin as it verified by the PL findings that showed a stagnant water column at the bottom of well.
- The deconvolved derivative increased the ROI and duration of original constant-rate pressure from 24 hours to 140 hours, which enabled us to detect the boundary dominated flow regime at late times, probably, to be a limited fault effect.

References

[1] Van Domelen M, Gdanski R, and Finley D 1994 The application of core and well testing to fracture acidizing treatment design: a case study, Society of Petroleum Engineers, European Production Operations Conference and Exhibition.
[2] Clarkson C R, Jensen J L, and Blasingame T 2011 Reservoir engineering for unconventional reservoirs: what do we have to consider? North American Unconventional Gas Conference and Exhibition.
[3] NOAH A and Shazly T 2014 Integration of Well Logging Analysis with Petrophysical Laboratory Measurements for Nukhul Formation at Lagia-8 Well, Sinai, Egypt, American Journal of Research Communication, 2, 139-166.
[4] Kgogo T C 2011 Well test analysis of low permeability medium-rich to rich gas condensate homogeneous and layered reservoirs, PhD Thesis, Imperial College London.
[5] Gringarten A C 2010 Practical use of well-test deconvolution SPE Annual Technical Conference and Exhibition.
[6] Ilk D 2005 Deconvolution of variable rate reservoir performance data using B-splines, Texas A&M University.
[7] Ilk D 2010 Well performance analysis for low to ultra-low permeability reservoir systems, Texas A&M University.
[8] Von Schroeter T, Hollaender F, and Gringarten A C 2001 Deconvolution of well test data as a nonlinear total least squares problem SPE Annual Technical Conference and Exhibition.
[9] Von Schroeter T, Hollaender F, and Gringarten A C 2002 Analysis of well test data from permanent downhole gauges by deconvolution SPE Annual Technical Conference and Exhibition.
[10] Levitan M 2005 Practical Application of Pressure/Rate Deconvolution to Analysis of Real Well Tests SPE 84290-PA, 8, 113–121.
[11] Gringarten A C 2008 From straight lines to deconvolution: The evolution of the state of the art in well test analysis, *SPE Reservoir Evaluation & Engineering*, 11, 41-62.

[12] Onur M, Cinar M, Ilk D, Valko P P, Blasingame T A, and Hegeman P S 2008 An investigation of recent deconvolution methods for well-test data analysis, *SPE Journal*, 13, 226-247.

[13] Liu W, Liu Y, Han G, Zhang J, and Wan Y 2017 An improved deconvolution algorithm using B-splines for well-test data analysis in petroleum engineering, *Journal of Petroleum Science and Engineering*, 149, 306-314.

[14] Ecrin 4.10. Software Tutorial 2008 *Kappa Engineering, France*. 