Abstract

Intelligent Production Data Analysis – IPDA, is a new methodology for Reservoir Characterization based only on monthly production rate data. This technique combines conventional methods of production data analysis (decline curve analysis, type curve matching and history matching) with intelligent systems. The study targets the validation of this methodology under a controlled environment, attempting three main objectives: Identifying Sweet Spots, Forecasting Reserves and recognizing under-performer wells.

The study investigates the behavior of five different reservoirs, modeled using a commercial simulator. The structure, parameters and heterogeneity of each configuration was inspired by existing formations. Records of production rate data were generated from the simulated fields (both single and multi-layer formations) and used as input to perform an “Intelligent Production Data Analysis”.

The findings highlight strength of this technique in tracking the fluid movement in the reservoir as a function of time. Furthermore, this study identifies some limitations and circumstances under which the analysis may not result in correct recommendations.

1. Introduction

The recent rise in the global demand for energy has significantly increased oil and gas prices. In the last few years E&P companies have reported record profits. A new reality rules the energy market, and large amounts of money have been invested in order to increase the production capacity. Now, mature fields, which were not profitable in the late 90s, have become very attractive for major oil and gas producers. An effective revitalization of this type of reservoirs has come to play a big role in the industry.

Recovery techniques have been tremendously improved over the last decade. However, lack of data is a problem with mature fields. Production Rate is about the only data that can be easily accessed in most of the brown fields. But, what can be done with this data?

Recently, a new technique for production analysis was introduced. The procedure is called Intelligent Production Data Analysis (IPDA). It combines the well-known methods for production data analysis (Decline Curve Analysis, Type Curve Matching and History Matching) with intelligent systems (Neural Networks, Genetic Algorithms and Fuzzy Logic). The results provide a unified set of reservoir characteristics based only on records of monthly production rate data. The fact that this information can be found in public records, projects IPDA as a valuable tool for independent asset evaluation, prior to lease acquisitions.

The IPDA technique has been applied in several fields throughout the United States (Rockies and Mid-Continent). One of these cases was the Golden Trend fields in Oklahoma\(^1\). The only available data in this field was monthly production rate data. The application of IPDA technique provided both reservoir intrinsic properties and remaining reserves distribution throughout the field.

In 2006 Jalali applied IPDA technique to characterize Carthage Field in the Cotton Valley Formation in Texas. Production records from 349 wells were employed during this analysis. The result was a unified set of reservoir indicators such as, Estimated Ultimate Recovery (EUR), remaining reserves at different times, permeability distribution, drainage area, etc.

Gaskari\(^3\) conducted an Intelligent Production Data Analysis using records from the Wattenberg field...
producing from Codell and Niobrara formations in the D.J. Basin of Rockies. Gaskari validated the Fuzzy Pattern Recognition as a feasible method to map the reservoir properties of the entire field. He was able to characterize the reservoir and recognize underperformer wells. Furthermore, using IPDA technique he assessed potential locations for infill drilling.

The findings aforementioned led to several questions: How reliable is this technique? What are its limitations? What information is required to perform an IPDA analysis? What other information might prove useful? Does this technique work in reservoirs with multiple pay zones?

It was decided to conduct a study regarding the reach and limitations of IPDA technique as well as its applicability over a wide range of mature fields. This study assesses the accuracy of IPDA technique under different reservoir configurations (single and multi-layered formations) with heterogeneous distribution of reservoir properties (porosity, permeability, thickness) have been evaluated.

2. Methodology

The validation of IPDA technique required a controlled environment of the formation under evaluation, thus it was decided to use a reservoir simulator. Different models were developed, all of them inspired by existing formations. Production rate data was generated and these records were used as input to perform the IPDA analysis.

A set of reservoir parameters was employed for measuring the accuracy of IPDA technique. Initial gas distribution, remaining reserves at different times, permeability and drainage area, are examples of assessed variables. Fig. 1 describes the procedure followed.

2.1 Creating the models under controlled environment

This study targets low permeability gas reservoirs. The formation selected for assessing IPDA technique is called Plum Bush Creek Field. It is located in Washington County, CO and consists of a single face (Dry gas) reservoir with high levels of heterogeneity. Two different configurations, a Single-layer and a Two-layer, were modeled. Both designs had heterogeneous distribution of intrinsic properties (porosity, permeability and thickness). Some of the reservoir characteristics were similar. In both cases, they had a single face composition (gas), located at a depth of 5000 ft. The overall size of each model was about 10,000 acres and the initial pressure was set to be 3000 psi.

In all the reservoirs modeled the characteristics of this field were quite diverse that even having all the property maps, it was complex to predict which zone in had the higher concentration of hydrocarbon.

Table-1 summarizes the properties of the Single-Layer Model (SLM). In this case, the thickness distribution is heterogeneous and was ranged between 75 and 300 ft (Fig. 2). The permeability was set within an interval of 0.5 and 3 mD, having three spots with high permeability in the reservoir (Fig. 3). The isotropicity, which is the ratio of Kx over Ky, was equal to 1. Finally, the porosity was distributed from 8 to 12% throughout the field (Fig. 4).

The Two-layer model (TLM) was developed in order to examine the performance of IPDA in multi-layer formations. This reservoir consists of two isolated layers, each 75 ft. thick, and separated by 75 ft. A unique distribution of reservoir properties was assigned for each layer. As a result, the reservoir properties of the top layer had a different distribution than the bottom layer.

Table-2 summarizes the properties of the Two-Layer Model (TLM). The permeability was heterogeneously distributed within an interval of 1 and 5 mD, having one spot with high permeability in each layer (Fig. 5). Finally, the porosity was distributed from 8 to 12% in the bottom layer and 13 to 25% in the top layer (Fig. 6).

Both models SLM and TLM had 100 wells uniformly distributed throughout the reservoir (Fig. 7).

2.2 Generating records of monthly production rate data

Once each reservoir was modeled in the simulator, a production strategy was necessary to generate monthly production rate data, so these records could be entered into the IPDA.

Many variables such as type of completion, well diameter, production control mode (constant rate, constant pressure), drilling schedule, etc. were required.
Therefore, a literature review of production in mature fields was performed in order to identify common practices in this type of formations. It was found that the majority of the wells in mature fields have an open-hole completion. It is also common that the production in these wells is controlled by constant pressure.

Finally the wells drilled had the following characteristics:

- Vertical trajectory
- Diameter of 0.5 ft
- Open-hole completion.
- Controlled by constant Bottom-Hole Pressure @100 psi.

In both cases (SLM and TLM) the wells were drilled in groups of ten, with intervals of three months between each group. Therefore, drilling the 100 wells took about two and a half years. (See Table-3)

An Intelligent Production Data Analysis can be performed at any time in the life of a field. However, better results can be obtained once the pseudo-steady state has been achieved. Essentially this occurs due to the fact that production analysis techniques (decline curve analysis, type curve matching and history matching) provide better results once the transient period has passed.

The wells drilled had a minimum of 40 acres spacing. As a result, it took several years to reach the pseudo-steady condition. The Single Layer Model was produced for 30 years while the Two Layer Model was produced for 26 years. Records of monthly production rate data were generated and stored in order to use them for performing an Intelligent Production Data Analysis.

2.3 Performing the IPDA analysis.

Performing an IPDA analysis required five variables:

- Well Name
- Latitude
- Longitude
- Gas Production Rate (Mscf/month)
- Date (mm/dd/yy)

Also, other parameters were necessary to conduct the analysis:

- Initial Reservoir Pressure
- Average Reservoir Temperature
- Gas Specific Gravity
- Isotropicity (Kx - Ky ratio)
- Drainage Shape Factor
- Average Porosity
- Average Pay Thickness
- Average Gas Saturation
- Average Bottom Hole Pressure

The first step was performing decline curve analysis for each well. After that, the type curve matching process took place. Once the type curve process was finished, the history matching was accomplished.

The three aforementioned procedures have to be performed on a well-to-well basis through an iterative process (while performing one task, the other two were monitored). This reduced the subjectivity associated with these methods when they are applied individually.

For Decline Curve Analysis Arps\textsuperscript{5} equations were used. This method is one of the most common practices in petroleum engineering and it has been explained in detail in previous publications\textsuperscript{1,2,3}. Fig. 8 describes the procedure of decline curve analysis applied in one of the wells under evaluation. The graph shown represents a semi-log plot of Gas Flow Rate vs. Time. In both pictures, the green line is the actual data (simulator) and the blue line is the modeled curve. The left picture illustrates the initial step. Then, by adjusting the decline parameters (Qi – Initial flowrate, Di – Initial decline rate, b hyperbolic exponent) the curve was matched. The right picture shows the final results once the curve was corrected.

Since the reservoirs modeled represented a low permeability gas reservoir, it was decided to use the Cox\textsuperscript{6} approach for type curve matching. Cox developed a set of type curves specifically for low permeability gas reservoirs with hydraulically fractured wells.

As noted above, IPDA uses an iterative process to reduce the subjectivity attached to conventional production data analysis techniques. The same variables (EUR, permeability, drainage area, etc.) are calculated using three different methods. However, it is necessary to monitor the results achieved in every step to make sure that they agree with the values obtained in the previous stages.

For example, the EUR is one of the variables employed for monitoring the convergence of decline curve analysis and type curve matching. It is important to
verify that the EUR obtained during the type curve matching is similar to the EUR calculated through decline curve analysis. If a significant difference is found (between the EUR estimated from DCA and TCM), one easily recognizes this incompatibility. Many times this issue simply requires going back to DCA and performing this process again. This contrast permitted the identification of those wells that had inconsistent data, which can be isolated and excluded from further steps in the analysis. Fig. 9 is an example of a Type Curve Matching performed in one of the wells under evaluation.

The next step is the History Matching where a single-well radial simulator is used to match the observed records of production data. In order to connect this process with the previous steps of the analysis (DCA and TCM) the permeability and the drainage area (calculated during previous phases) were imported and employed with other parameters for performing the history matching.

Since History Matching was the last step of the conventional analysis, it was a good opportunity for optimizing the quality of the evaluations. If a reservoir parameter needed to be modified during the History Matching process, these modifications were adjusted in the previous steps (DCA and TCM). This iterative process finished when the same parameters were used for the three methods and the results were converged in an integrated value.

Once the three techniques have been completed and the results have been optimized, the next step is the application of intelligent systems to analyze the data. This routine integrates the information obtained from all wells in order to predict Field-Wide behavior. The procedure is called Field-wide Pattern Recognition FPR and it deduces a pattern in data that apparently does not register any relationship.

FPR gathers information about all the wells. Several production indicators can be evaluated. The variables that can be evaluated are:

- Initial Gas distribution
- Cumulative Production
- Remaining Reserves
- Remaining Life of wells
- Estimated Ultimate Recovery
- Incremental Cumulative Production
- Permeability
- Drainage Area
- Fracture Half Length
- Under Performer Wells

Results of FPR are presented in a colored map called Relative Reservoir Quality Index (RRQI Map).

3. Results and Discussion

Using IPDA technique, a set of formation parameters, well properties and performance indicators were calculated for each reservoir configuration. However, the purpose of this investigation was to determine if the values encountered corresponded to the actual situation in the reservoir.

Up to this point, an enormous amount of information has been collected. Therefore, is necessary to organize the presentation of the results in accordance with the objectives stated for this investigation. Results will be shown in two groups. The first set of results will prove that the IPDA technique is capable of characterizing a reservoir and forecasting its future behavior. The variables assigned to this section are: initial gas distribution, remaining gas distribution, estimated ultimate recovery and permeability. The second set of results will demonstrate that the IPDA recognizes under-performer wells and predicts the behavior of future wells (infill drilling) regardless the location.

3.1 First set of results – Reservoir properties

a. Initial gas distribution

First, it was necessary to find the actual initial gas distribution of each model. This information was read from the simulator. Then, it was compared with the result obtained through the application of an Intelligent Production Data Analysis.

For the SLM the results for initial gas distribution are shown in Fig. 10. On the left you will find the Relative Reservoir Quality Index or RRQI. To facilitate the interpretation of the results, at the right you will find a map indicating the actual value (read from the simulator) of this parameter. IPDA technique was able to identify the sweet spot, recommending the mid-left region as the region with highest concentration of hydrocarbon. The same delineation (grid) was used for partitioning both maps, so the zones can be contrasted.
The Initial Gas Distribution was successfully recognized through IPDA in the Two Layer Model as well. Results are shown in Fig. 11. The RRQI map (left) identified the best zone in the mid-left. When this finding was compared to the Actual Initial Gas Distribution (right) the results showed notorious similarity.

b. Remaining Reserves

Once the initial gas distribution was verified, it was time to determine if the IPDA technique was capable of tracking the migration of the sweet spots in the reservoir. To do so, the remaining gas distribution after 30 years of production was assessed.

For the Sinlge Layer Model results are shown in Fig. 12. As is illustrated, the premium zone (dark brown) has moved to the center region of the reservoir. At the right, you will find the actual gas distribution read from the simulator. This proved that IPDA recognized the migration of the sweet spots in the reservoir.

For the two layer model the remaining gas distribution was calculated. The results are shown in Fig. 13. The RRQI map has a remarkable coincidence with the actual situation found in the simulator. Not only the premium zone, but also the depleted regions were successfully identified.

c. Estimated ultimate Recovery

To validate the ability of IPDA to successfully estimate this indicator, the 45 year EUR of the wells was compared with the cumulative production (after the same period of time) recorded in the simulator. This process was performed in a well-to-well basis. To quantify the error of this prediction, the percentage of difference between EUR (estimated using the IPDA) and the actual cumulative production (reported by the simulator) was calculated. For the SLM the percentage of error was 6.44 % (Fig. 14) while for the TLM it was measured to be 3.63 % (Fig. 15).

d. Permeability.

The permeability distribution of the single layer model was estimated based on the information provided during the process of type curve matching. For the SLM the results proved that IPDA technique effectively characterize this property in a reservoir. Fig. 16 shows the permeability distribution according to IPDA. This result has a notable similarity with the actual permeability distribution shown in Fig. 3.

For the TLM the permeability distribution calculated with the IPDA technique is shown in Fig. 17. The map indicates two zones with high permeability in the formation. This result makes sense, because it integrates the permeability distributions of the two layers in a single map. It proves that this methodology generates an equivalent reservoir that reproduces the behavior of the field under evaluation. (Actual permeability distribution shown in Fig. 5).

In both models, it was found that the permeability obtained through the IPDA technique reflected a fall when compared to the actual $k$ values. However, this difference was consistently present in all the calculations. The predicted $k$ and the actual $k$ followed a similar trend. Both indicators were plotted in Fig. 18. The blue line represents the actual permeability (inputted in the simulator), and the orange line represents the values estimated by the IPDA. The correspondence observed in Fig. 18 demonstrates that IPDA technique recognizes the permeability variations in the reservoir. Therefore, it has been proved that IPDA technique stands for a qualitative (but not quantitative) analysis of the reservoir.

3.2 Second set of results – Well performance.

a. Under-performer wells

In order to identify under-performer wells, a positive skin (+4) was added to ten wells randomly selected in model TLM. The high skin value affected the production capacity of these wells negatively, decreasing their performance. The IPDA technique recognized eight of the ten wells evaluated. However, some of the wells located at the boundaries were marked as under-performers. This malfunction is due to the fact that this technique is not aware of reservoir boundaries. Normally the wells located close to a reservoir boundary experience a reduction in the potential drainage area (Fig. 19).

Using the IPDA technique one is capable to predict the decline parameters ($qi, di, b$) in any location of the reservoir. To verify the accuracy of this tool ten locations were selected for infill drilling. In this case, some wells were located close to the boundaries while some others were in the mid-region of the reservoir. Applying the IPDA technique, the decline parameters ($Qi, Di$ and $b$) were estimated. Then the decline curves of these wells were reproduced. To assess the accuracy of this feature, it was necessary to drill these ten wells in...
the simulator, using exactly the same location. After that, the results of the simulator were compared to the predicted decline curves.

Results indicated that the wells located close to the boundaries did not reproduce the behavior predicted by IPDA. On the other hand, the production of the wells located in the zones separated from the boundaries had a notable similarity to the decline curve modeled using the IPDA technique.

4. Conclusions

The findings of this study are the result of a thorough and comprehensive effort. The results achieved required constructing 13 reservoirs models and performing decline curve analysis, type curve matching and history matching over approximately 1600 wells.

This study verifies that Intelligent Production Data Analysis:

a. Identifies sweet spots in a reservoir at any time.
b. Provides unified set of reservoir characteristics (initial gas distribution, permeability, etc).
c. May be applied in both single and multi-layer formations.
d. Estimates accurately the distribution of the remaining reserves at any time.
e. Forecasts Estimated Ultimate Recovery with precision.
f. Identifies under-performer wells.
g. Assesses potential locations for infill drilling.

The following limitations were found:

a. The accuracy of the recommendations depends on the quality of the conventional analysis performed (decline curve analysis, type curve matching and history matching). Therefore, the technique provides better results once the condition of pseudo-steady state has been reached.
b. Intelligent Production Data Analysis stands for a qualitative analysis of the reservoir. Therefore, the figures estimated are not necessarily correct.
c. The proximity of the wells to the reservoir boundaries might affect the accuracy of the predictions.

5. References

Table 3 – Drilling Schedule for 100 wells

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Fig. 2 - Isopach Map (SLM)

Fig. 3 - Isopermeability Map (SLM)

Fig. 4 - Isoporosity Map (SLM)

Fig. 5 - Isopermeability Map (TLM)

Fig. 6 - Isoporosity Map (TLM)

Fig. 7 – Well Distribution.
Fig. 10 – Initial Gas Distribution (SLM)

Fig. 11 – Initial Gas Distribution (TLM)

Fig. 12 – Remaining Reserves after 30 years (SLM)
Fig. 16 – Permeability distribution according to IPDA technique (SLM)

Fig. 17 – Permeability distribution according to IPDA technique (TLM)

Fig. 16 – Permeability correspondence (IPDA - Stimulator)