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Surveying and Analyzing Injection Responses for Patterns with Horizontal Wells

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Abstract

This paper presents a novel method for visualizing injection responses in patterns that include horizontal and/or vertical wells. Horizontal wells can respond to half a dozen or more vertical injectors. Understanding fluid communication between the horizontal well and the surrounding injectors is essential to estimating the effectiveness of the waterflood and helps to predict responses to the waterflood. Armed with the understanding of responses, we can optimize injection patterns, improve production rates, and achieve more efficient oil recovery.

Comparing the produced rates of oil and water to the injected water demonstrates fluid communication through a reservoir. However, typical oilfields can exhibit complex geology in patterns, accidental schedules of wells and/or random changes in the injection and production rates. Together with the shear volume of data, manual analyses may lead to ambiguous and biased associations between producers and injectors. The technique presented in this paper provides a rigorous and unbiased approach. It is based on the Spearman rank correlation between the injected and produced rates over a period of time. The correlation and the time lag between the injection and the associated production rates allow us to compress these two series of rates into a set of two simple parameters.

The advantage of the approach outlined in the paper is the capability to do a quick analysis and interpretation of fields under the waterflood, with a large number of injectors and many years of history. Furthermore, the analysis is based only on the ready available injection and production history. The development of the methodology was originally intended for injection optimization. It may however play an essential role in studies to locate the under-performing fields that may represent the acquisition targets.

Introduction

Fluid communication through a reservoir can be assessed by the response of the oil and water production to the water injection. Given complex production activities and the shear volume of data, manual analyses may lead to ambiguous and biased associations between producers and injectors. The applied technique is based on statistics and provides a rigorous and unbiased approach. Specifically, a correlation between injected and produced rates is analyzed over a period of time. The basis of this analysis is the *Spearman rank correlation* and was presented in an SPE paper (30711) [1] and in a paper by Refunjol and Lake [2].

This paper presents new developments in the correlation analysis between injectors and producers. The main contributions are in finding the time lags of responses, integration of correlations to oil and the total fluid, and in visualising the results of the analysis at local and global scales.

The Spearman rank correlation allows us to compress series of the injection and production rates into a simple parameter. This parameter shows the communication (responsiveness) of oil or the total fluid inside the injection patterns. The simplicity and compression are achieved by linking the strength of the communication to the correlations between the rates and to time lags associated with these correlations. The correlation between injection and production rates during a period of time indicates the communication within the reservoir. The estimates blend and remove most of the artefacts introduced by field activities if the time period does not include major changes in the exploitation strategies.

In regular nine spot patterns with vertical wells the correlations (oil and total fluid responses) and associated time lags can be presented in the form of *star diagrams.* In the simple integration process, these star diagrams are posted on contour maps of facies and netpay[3]. Such presentations help in finding the significant relationships between the producer's responses and the underlying geology.

In this paper we introduce two new graphs and an additional parameter that links the waterflood oil and the total fluid responses (correlations). The correlations for the non-symmetrical patterns can be presented on *spider graphs*, which show both the short and the long distance communication. This type of graph is very useful for presenting communication between injectors and horizontal producers. The new parameter is based on both correlations (correlation to oil and total fluid). We call it *type of the waterflood response*. The response type can be compared with parameters that represent geological, geophysical, and petrophysical properties. This can lead to a better understanding of field behavior. It can also help to evaluate the sweep efficiency estimations, allocation of areas for the infill programs, and better production allocation.

Methodology

The rank correlation is based on the correlation between selected data series of *injector-producer* pairs (see Figure 1).

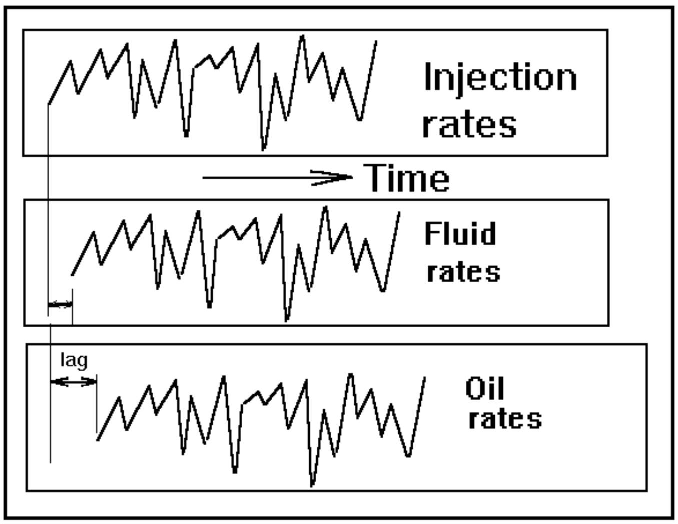

Figure 1. Principles of the correlation analysis.

Rather than use the standard correlation coefficient, which assumes the normal distribution of two variables, the Spearman rank correlation coefficient is based on ranks and gives a measure of the association (relationship) between the variables[4]. Thus, the correlation calculations can be performed without user intervention for hundreds of *injector-producer* pairs.

In the analysis for a specific time period, four variables are estimated and they are obtained for each pair of injector-producer. Two of these parameters represent correlations between the rates of injection and the rate of oil or rate of fluid produced. The next two parameters estimate the time lag of the oil and fluid response. These time lags correspond to lags at which the correlations reached the highest value. In practice, a series of the correlation coefficients to the oil or total fluid rate provide a measure of the delay in the response to the flood. These coefficients are estimated together with the corresponding level of significance at different lag intervals (e.g. 0-12 months) that are applied to the injection rate (see Figure 2). These different estimates were compared if their values were significant. The lag that corresponds to the highest correlation coefficient provided the required information for a specific injector-producer pair (*correlation and the corresponding lag*).

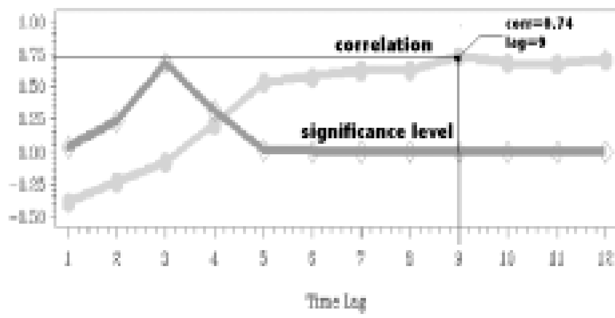

Figure 2. Finding the maximum correlation and the time lag.

As with most statistical tests, we use significance levels of one in twenty (α=0.05). Thus, we allow up to 5% of incorrect decisions (5% of the calculated correlations might not be significantly different than zero).

Most of the patterns are not homogeneous and responses for the same horizontal producer can vary significantly from injector to injector in all four parameters. The type of waterflood response simplifies the analysis because it summarises two correlations (correlation to oil and fluid). Figure 3 presents a cross-plot of two correlations and the process of the response type generation.

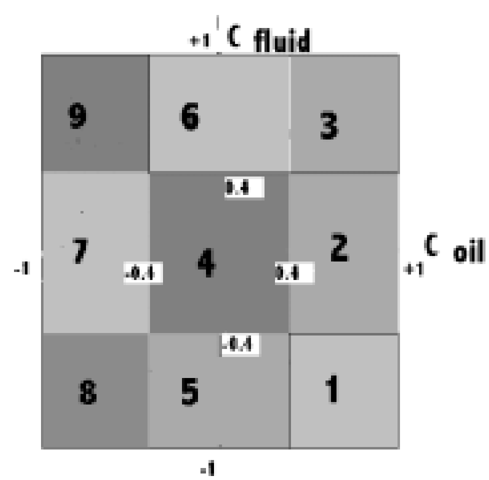

Figure 3. Definition of the waterflood response type.

The response type is actually a set of discrete classes that are based in the simplest case on the two correlations (total fluid and oil). These two parameters can be presented on a cross-plot with the axes ranging from –1 to +1. Nine classes (1-9) result from this 2D-space subdivision using a simple threshold of 0.4 as presented in Figure 3. This threshold value should be selected individually for each study. This new parameter characterizes the well responsiveness and allows an integration (comparison) with the other groups of parameters (geological, geophysical, and completion horizons). This can lead to transform functions that are useful in predicting the response type and its probability [5].

Different response classifications can be implemented. Multivariate cluster analysis [6] can be applied for finding the number of the response classes that are based on all of the six parameters (lag zero correlation to fluid, lag zero correlation to oil, lagged correlation to fluid, lagged correlation to oil, lag of fluid, lag of oil).

Local Scale of Analysis

The injection pattern analysis is performed using two scales. The local scale deals with short distance communication that can be inferred from separate spider diagrams that are drawn for each well. Figure 4 shows an example of a spider diagram for one of the horizontal wells in the field area selected for presentation of the methodology.

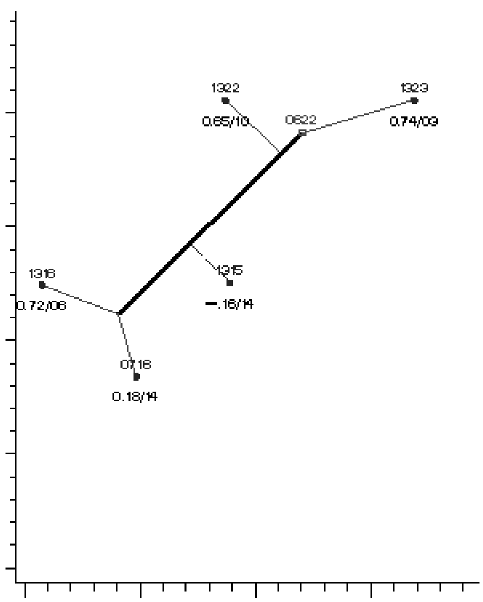

Figure 4. Spider diagram; oil correlation / oil lag time.

Spider graphs show the rank correlations (responses) for horizontal wells or irregular patterns. In this implementation, a horizontal producer is represented as a solid line with an empty square and the well's name to mark the well's entry. In addition, a set of injection wells is presented with solid dots. The producer and injectors are placed on a cross-plot of X and Y coordinates where each injector is connected to the producer with a line to symbolize a relationship (spider web). These connections are perpendicular to the well's line. If the spider line does not fall along the well's extend, then it is connected to the closest endpoint of the well. Solid and dashed lines represent positive and negative correlations respectively. Additional annotations are posted at each injector. The first row of the annotation shows the injector's location (LSD and Section, e.g. 1322, see the most northern injector in Figure 4). The correlation and the time lag are posted in the second line of the annotation (e.g. 0.65/10 means the correlation is 0.65 and the time lag is 10 months). This allows visualization of the spatial relationships and differences between responses as a function of the location and the injector-producer distance. Since annotations require plenty of the space on graphs, the total fluid correlations and the type of waterflood responses are presented on separate graphs as shown in Figure 5 and Figure 6.

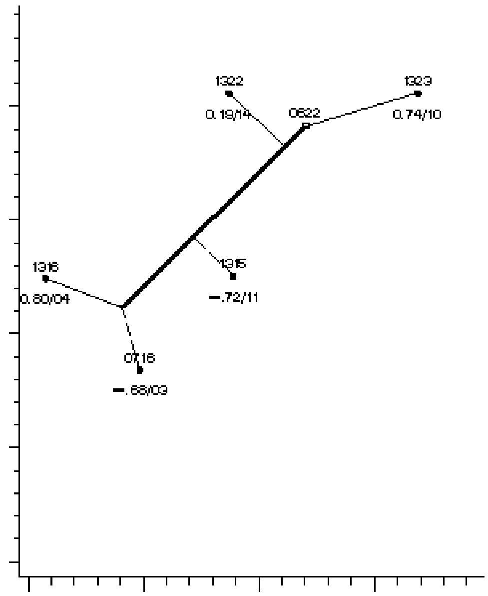

Figure 5. Spider diagram; fluid correlation / fluid lag time.

The same injector (the most northern) shows a very weak correlation (0.19) between the injection rate and the total fluid production rate. The corresponding time lag is 14 months (see Figure 5).

Annotations for the injectors in Figure 6 are extended and they include the response type, fluid lag, and oil lag. In this fashion, each string of numbers characterizes the injector's influence on the specific producer. The whole spider diagram presents characteristic responses from all the injectors that are included in the pattern.

Large Scale of Analysis

Studies of injection patterns that included vertical wells showed in many cases severe interactions of an injector-injector and producer-producer type. They result in some negative correlations that belong to the response type=7 or 8 (a more detailed analysis of the negative correlations can be found in the following section). The responses that are characterized by negative correlations cannot be uniquely explained and in such cases a larger scale view of the field is required.

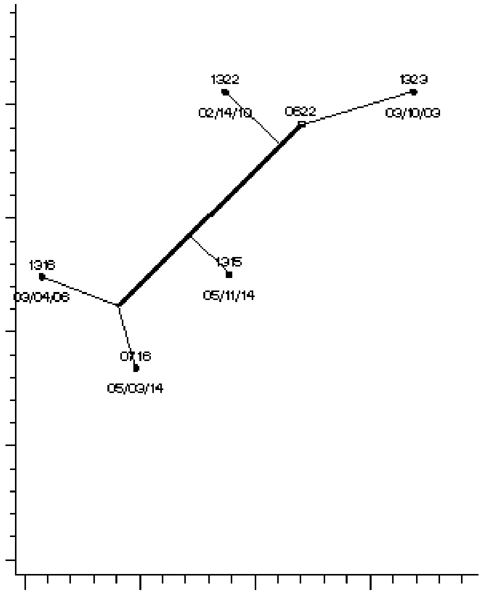

Figure 6. Spider diagram; response type / fluid lag time / oil lag time.

Imposing all spider diagrams on the same cross-plot generates a composite spider diagram. However, each of the injectors can support more than one producer, which results in more than one overlapping annotation. Some of these annotations describe non-significant correlations that can be dropped from the big picture. At this scale most of the details are not important, as long as we know that the correlation is above a predefined cut-off. Thus, a composite spider diagram does not show annotations with correlations and lags, but shows communication lines (web) only for correlations that are stronger than the predefined cut-off.

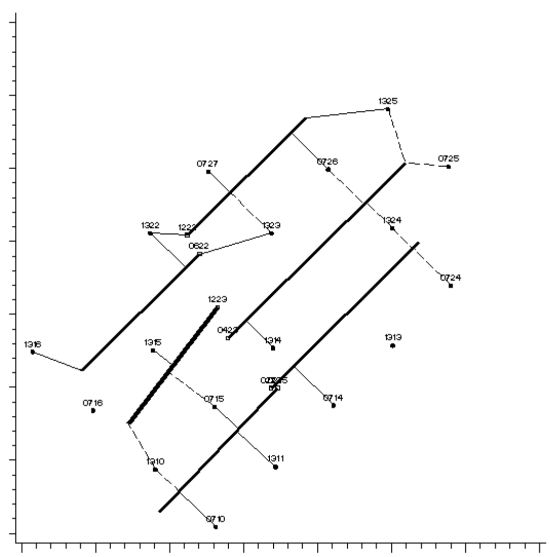

Figure 7. Composite spider diagram; oil correlation.

In Figure 7, solid and dashed lines represent the positive and negative correlations respectively for six horizontal producers. In particular, oil correlations above 0.5 and below –0.5 are shown as the strongest positive and detrimental oil responses.

The well previously illustrated in Figure 4 – Figure 6 is the most left in this diagram. In a color version, a combination of lines and colors allows the visualization of correlations and time lags at the same time. In similar fashion Figure 8 presents positive and negative correlations for the total fluid. The total fluid correlations are very useful in identifying the flow trends and boundaries in large fields.

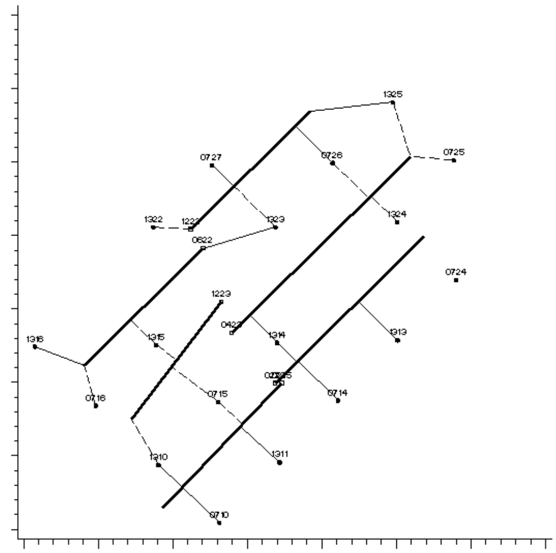

Figure 8. Composite spider diagram; fluid correlation.

The waterflood response type (Figure 3) is always positive. The next composite spider diagram can therefore present responses with the corresponding oil or fluid time lag. In Figure 9, the spider web shows the three best response types (1-3). In this case, solid and dashed lines present two levels of the time lag. Specifically, solid lines connect producers to injectors where the response type was less than or equal to three and the oil time lag was lower than six months. The dashed lines show the same range of the response type, but the oil time lag along the lines was higher than six months.

Analysis of Injection Responses

A negative correlation is equivalent to a detrimental effect on the production rate. This may occur when the producers are constrained. A positive oil correlation and a negative total fluid correlation can identify the constrained wells. In general, any response with the exception of type=4 (Figure 3) indicates a strong communication between the injector and producer. The strong responses can have either a positive (type=1,2,3) or detrimental effect (type=7,8,9) on the oil production.

Responses in the orthogonal direction (type=3,6,9) indicate a positive effect on the total fluid, while responses of type=1,5,8 indicate a detrimental effect on the total fluid. Responses of type=5,6 are neutral (no responses) to oil, but indicate strong positive (type=6) and strong detrimental (type=5) responses to the total fluid.

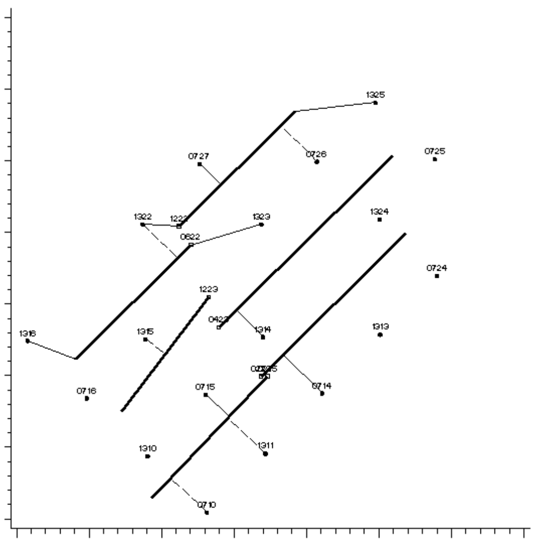

Figure 9. Composite spider diagram; response type >= 3; solid line if oil lag <= 6 months otherwise dashed line.

The most troubling responses are those with negative correlations for both oil and fluid. Provided one of correlations (oil or total fluid) is positive the negative correlation can be explained. For example, response type=9 is characterized by a strong response in the total fluid but a negative response in oil. This situation is characteristic of a break-through condition.

On the diagonal end of the cross-plot (Figure 3.) response type=1 is characterized by a negative correlation to the total fluid but a positive correlation to oil. Such a case can represent a pre-break-through response in immature waterfloods. The next best response, type=2 is often observed in miscible floods. Type=3 is the most common response in the waterflood systems where the oil rate and the total fluid rate are strongly correlated to the injection rates. A well having a short distance response of type=7 (negative oil and no or weak fluid) is most likely having a long distance communication of type=1,2, or 3 with another well.

Furthermore, responses of type=6,9 indicate a break-through behaviour, while type=5,7,8 can indicate the need for a workover, interactions between producers or injectors, fluid losses to other zones, or effects of constrained wells.

The spider diagram in Figure 10 shows an injection response of type=8, which is often observed in areas with heterogeneity inside of the injector pattern or patterns that are too small. Strong heterogeneity can lead to strong influence of distant injectors. For example, a well can have strong positive long distance responses from injectors along a trend, but negative short distance correlations in the off-trend direction.

Application and Integration of Responses

Results from the injection pattern analysis can be applied to:

- Testing the effectiveness of either the waterflood or re-injection.
- Identifying trends, boundaries, effective distances, and the optimal pattern shapes.
- Optimizing injection patterns (identifying inefficient injectors, over-injecting injectors, wells that are too close to injectors, etc.).
- Inferring preferential flow directions of oil and water.
- Inferring response time to injection (oil and water).
- Changing the allocation numbers and improving efflux calculations.
- Predicting the future waterflood responses.
- Identifying infill areas.
- Identifying acquisition targets.

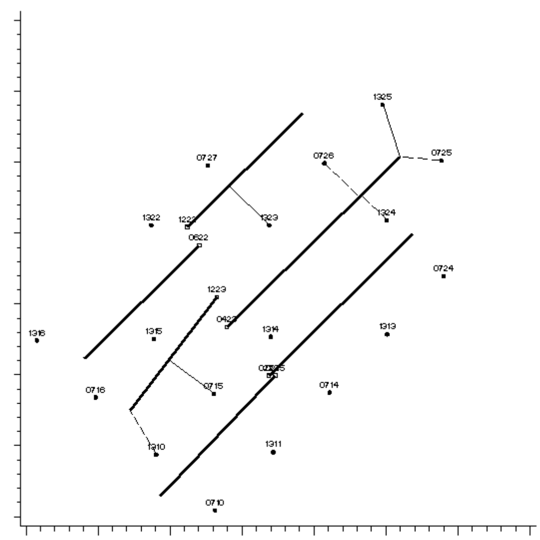

Figure 10. Composite spider diagram; response type = 8; solid line if oil lag <= 6 months otherwise dashed line.

An example on the response type is provided below. A spider diagram with response types 1, 2, and 3 (Figure 9) is very helpful in determining the allocation of the infill wells. The areas where there is a strong communication and the lags of responses are long (dash lines) probably require a long time to be drained. Thus, the production acceleration may be accomplished by infill wells in these areas. Areas with solid lines are characterized by fast and strong responses, which means that they are already drained or will require little time to reach that stage.

The correlations represent standardized responses that summarize large amounts of data. Their estimates or the derived types of responses can be integrated with geological, geophysical, petrophysical, and completion parameters. A multivariate analysis [6] can identify the relationships between these different data sources and the most important factors in each of the sets.

Finally, in reservoir simulations for the waterflooded reservoirs, the correlations, their lags, and the response type can be applied as communication parameters (e.g. permeability correction factor).

Summary

Spearman rank correlations between injection rates and production rates (oil and total fluid) summarize the communication during the enhanced oil recovery.

In this paper, time lags of correlations and a new parameter *the waterflood response type* are introduced. The response type is based on the oil and total fluid responses. In addition, spider diagrams are introduced for visualizing the correlations, time lags, and the response types. These diagrams provide detailed information about the short and long distance connectivity (communication) for each specific pattern. The composite diagrams show the waterflood responses across large fields.

Integration of the above results with geology, petrophysics, and completion techniques can help in finding the *cause and effect* rules in waterflooded fields.

The presented methodology is still in its infancy when applied to horizontal wells and requires more research. Some of the areas of application that are presented in this paper were identified during several studies of fields with vertical wells in Western Canada.

Acknowledgments

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