Medium-High Permeability, Mature Reservoir Management Study: An Innovative Methodology and Case Study
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Abstract

Field-wide flow patterns for the 25-year waterflood production history of the medium-high permeability Gudong field, China have been carefully studied using a flow-based numerical simulation process. Through a history matching, field-wide streamline patterns and the cumulative flow between injector/producer well pairs can be displayed graphically and quantitatively via well allocation factors. By analyzing the flow pattern or streamline fields (field-wide and locally) for each time step through the reservoir production history, Predominant Streamline Fields (PSF) and Weak Streamline Fields (WSF) can be identified. The PSF can be classified into different levels based on statistically analyzing Strength Index of Streamline Field (SISF), which is a function of both allocation factor and the swept volume of the specific well pair at a given time step. Generally speaking, areas with strong PSF most likely indicate where reservoir channeling occurred at this specific time period, and this channeling is likely to persist until enough change is done. The relative stable WSF zones, with reasonable formation thickness have good potential to be bypassed pay.

To verify the findings above, a dozen conceptual models have been built and tested, and consistent results were found. This dynamic reservoir study processes provided an extra tool for reservoir scale waterflood optimization, well selection for profile modification/water shutoff, and infill drilling.

The Gudong case study indicated that PSF behavior began about 4~6 years from the start of water injection. That time period was consistent with a lot of other history data. The findings helped EOR and infill drilling in Gudong field.

Conclusions from this study have led to a better understanding of the displacement mechanisms and the nature-and-man-made dynamic-heterogeneity in the field, which may not be able to obtain otherwise.

Introduction

A key issue for mature water-flooded reservoir management is to have a sustainable oil production with a systematic working procedure to improve long term water injection efficiency. To achieve sustainable oil production with a cost-effective approach for a mature reservoir with 95% or more water-cut, like W7 reservoir of Gudong field, is highly desirable, but can be a very challenging task. A lot of efforts have been made for many years, but in fact we still see a lot of room for improving in this area. Identifying predominant channeling zone (PCZ) which may be called with close terms “channeling” or “thief zone” for a mature reservoir is a crucial step. This paper presents an innovated and practical working procedure for identifying PCZ vertically and laterally or areally utilizing predominant streamline fields (PSF) analysis methods. A case study has been presented utilizing the proposal approach.

The study field, W7 reservoir at Gudong field, located on-shore Bohai Bay of China, which covers about 11.7 km² with 83 production wells and 58 injection wells, has about 25-year production history. The pay named Ng 63+64, one of the major pays in W7, with impermeable overlying and underlying stratum, is a typical fluvial associated facies sandstone, late Tertiary in age, porosity about 34%, 2-10 m in thickness at most place, and permeability ranging 620 md to 2510 md roughly. The reservoir has produced about 33.5% of the initial oil in place and reserves with over 98% of water-cut to 2009.
Waterflooding commenced in 1987 prior to the field average reservoir pressure falling below the bubble point. Excessive unproductive water production has become a major concern in this field since 1996 when water-cut reached 95% \(^2\). The reservoir has good physical boundaries- impermeable boundaries provided by a few major faults all around the northern, eastern, and southern boundaries of the reservoir, and the west boundary with formation dipping toward the west to an open and deeper boundary as an aquifer. Therefore, it is an idea reservoir to conduct some a field-wide simulation and analysis study about the reservoir. A 3D flow-based computer model has been used in this simulation with 890,000 grids partitioning the 11.7 km\(^2\) domain, Ng63+64 pay W7 reservoir.

Three-dimension PSF identification and characterization quantitatively are the main focus of this study. By introducing the strength index of streamline field (SISF), which is a function of both well-pair flux and the swept volume of the specific well-pair at a given time step, and the SISF ratio, which is a ratio SISF at time T and SISF at T+1 for the same well-pair, we can get a better idea when the SISF becomes stable. Of course, when the value of SISF ratio versus time approaches to 1 (Figure 9) or close to 1 for a well-pair, more often than not, the PSF there has existed there for certain period of time. The corresponding time when SISF ratio approaches to 1 is time PCZ formed. As you can see that we can estimate when PCZ was formed by using the relationship between SISF ratio and production time.

Based on the SISF value, the PSF can be classified into different categories. Generally speaking, areas with strong PSF most likely will become PCZ, and the PCZ is likely to persist until enough change is done. Therefore, the results of this study can be applied to assist improving reservoir waterflooding efficiency. The W7 of Gudong case presented here is not a special case; rather it is a very common case for many reservoirs in eastern China basins.

In summary, the PSF analysis technique can be a useful tool for the second or third oil recovery in a mature field. And the PSF study plays an irreplaceable role in identifying and forecasting the PCZ or channeling. Based on PCZ distribution in a reservoir, we will have more leverage to play with such as, adjusting injection-production ratio, optimizing profile modification design, deploying infilling wells, achieving healthy and sustainable oil production cost effective manner for a longer term. The ROI (Return on Investment) will be unbelievable high for this study.

**PSF Concept**

Flow field in a reservoir can be defined as the swept range of fluid flow through certain porous medium volume three-dimension-wise where representative element volume (REV)\(^3\) exist. The fluid flow driving force is pressure gradient, and keeps in mind that that the true reservoir pressure gradient is much more complicated than what we may think of, which may come from results of a coarse-grid simulation. PSF generally can be referred to as the flow strength in certain volume of porous medium is stronger significantly than that of the adjacent porous medium with the same size in volume. One of its obvious characteristics is the significant larger fluid flowing between the injector-producer pairs than average, and of course higher than average flow velocity too. For those zones where PSF developed, we normally can observe that streamlines are denser, higher water injection PV numbers, lower oil saturation normally and etc. One of the major advantages for using PSF in reservoir characterization and management is that we can understand the reservoir changes better by considering the static geological information, and production history that actually changes the static geological parameters. We all know that we will never have a full picture of "a true geological model, of course a static one ", which means the static geological information has a great deal of uncertainty. For a medium-high permeability reservoir, initial reservoir properties could be modified significantly through the production history unsurprisingly. The production data, in contrast to the static geological data, is much more accurate and has much less uncertainty. Then the streamline field is the common results of the multiple-factor including static geological data, production history data and the modification to the static geo-model due to production. Our sensitivity studies have shown that production history data contributes more to PSF in terms of the shape and the strength than any other single parameter can do. That matches an old proverb called “water dropping wears the stone”. The flow-based simulation gives us more dynamic reservoir information by comparing the field history in streamline fields format rather than pressure gradient. We know that pressure gradient is tremendously simplified in our mind for so long especially when coarse-grid simulation results come to us. Therefore, analyzing streamline field, especially analyzing PSF will give engineers a lot more reservoir information that other methods may not be able to provide. By introducing the Strength Index of Streamline Field (SISF) and SISF ratio, which is SISF at time T and SISF at next time level T+1, we can better understand when the SISF becomes stable. Further more, we can estimate when predominant channeling zones (PCZ) was formed by analyzing the value of SISF versus time (Fig. 9-11), which will be discussed further in next sections.

As a matter of fact, we used to understand a reservoir mainly from the "static-to-static" point of view, which means that by taking the "static geological data" and build a "static model", and do the rest works based on the static model even though the data used to build model were 30 or 50 years old. By introducing the PSF approach, we have to use the "static + dynamic" to "dynamic + modified static due to the dynamic" working format to characterize reservoir dynamically rather
than statically. Using reservoir W7 as an example, with millions and millions tons of water injected, tons and tons of sands produced, and millions tons of oil produced during last 25-year development and production, the reservoir has been modified very much. Years of lab studies and other related research focusing on how the reservoir properties may change during the long time reservoir production history have indicated that the formation becoming much more heterogeneous than it initially was. The reservoir from a "Youth reservoir" at early days becomes a “middle-aged reservoir” now after years of production and development. Some important properties of the reservoir might have changed at certain degree. With all those changes made for the reservoir, have the flow patterns changed accordingly? What we have found out from our study to this question is a YES. A field PSF analysis approach leads us to reach this conclusion quantitatively.

Using PSF analysis approach, advantages may be listed as follows:

First of all, the PSF strength can be quantified through the unit flow rate between each injection-production well pair, and both of the flow pathway and orientation can be characterized through streamline simulation method with 3D visualization showing the flow pathways three-dimensionally. And the density of the streamline distribution reflects the flow rate distribution and each streamline represents almost the certain amount of flow flux.

Secondly, streamline moving back and forth in 3D can be visualized, recorded, replayed and/or rotated so that the streamlines, the travel time and etc. can be reviewed again and again in a computer screen. All important information about flow pathway related information can be studied in detail.

Thirdly, even a localized streamline field may change because the rates change or temporally shut-in of the wells, but that does not impact much for our field scale and long-term flow pattern or streamline fields’ studies. Contrary, a local streamline field change in short period of time will help us to understand and characterize the reservoir better. What we addressed will be that the field-scale streamlines field or flow pattern and local PSF pattern trend versus time. When we carefully compare and analyze all streamline fields at the time interval of each month or quarter for a 20 or 30 years of the production history, a lot of information will show up. This is very important for mature reservoir management, especially for those fields in Eastern China fields, like field W7.

Field W7, a typical fluvial deposit reservoir in eastern China basins, has very strong general heterogeneity and anisotropy due to the fluvial constantly migration, and lateral deposition. Most well deployment was in uniform spacing like most fields. When we look at back the operation practice in this field, the homogeneous field property concepts have been used such as, “radius” of well treatment, or “radius” of drainage areas and so on. Now the question raised is why do we use homogeneous concepts to do engineering works while we know it is not true? How can we shift our engineering practice from the homogeneous concept to non-homogeneous one so that the strong heterogeneous/ anisotropic reservoir nature can be addressed without contradictory ourselves?

It is time to move on. The PSF studies can provide some good solutions.

In general, by introducing the PSF concept and its analysis working procedure, we will have extra tool to look at the reservoir channeling problems caused by the original and secondary heterogeneity/ anisotropy of the reservoir. The secondary heterogeneity/ anisotropy could be caused by dynamic force of the fluid flow and oil properties changes due to long time production-injection and intense pumping. The flow-based simulation and powerful 3D visualization allows us to implement the PSF analysis working procedure to get what we want the most for a mature reservoir—which portions of the reservoir had been washed badly, and which parts had not, where is the bypassed oil remained.

**Methodology**

Basis of streamline simulation: For facilitating the discussion together, let’s look at a simple case, a two phase flow of oil and water, both fluid and rock are incompressible or compressibility could be ignored at this point; the mathematical model of streamline tracking in three-dimensional space and time along the streamline by introducing time of flight, \( t(\Psi_x) \), can be in the following format:

\[
\phi \frac{\partial S_j}{\partial \tau} + \bar{u}_i \cdot \nabla F_j = 0 = \sum_{\text{streamline}} \left( \frac{\partial S_j}{\partial t} + \frac{\partial F_j}{\partial \tau} \right)
\]  

(1)
In equation (1), the left is a typical 3D flow equation, while the equation on the right, a 1D flow equation, shows that at each streamline's flow direction the saturation and time fulfill the equation on the right, therefore, to solve saturation along streamline is a 1D problem that solve a number of time as a unit. This numerical scheme is not only fast and never introduce numerical divergence or artificial diffusion etc, which avoid the typical mass conservation problems as finite difference methods has. A good mass conservation scheme is very important for solving saturation, especially for a mature reservoir simulation with long production history. The direction of a streamline and the total flux, orientation can be graphically expressed as in Figure 1. By taken the gravity as a factor in the flow simulation, Equation 2, also graphically as expressed in Figure 2 is the split form which can be directly applied to numerical solution.

\[
\frac{\partial S_w}{\partial t} \approx \frac{\partial S_w}{\partial t_C} + \frac{\partial S_w}{\partial t_G} \quad (2)
\]

Convention time step  gravity time step

In figure 2, the left diagram shows streamline mobile under the effect of mobile pressure gradient, while the right one is under gravitation. A split of factor is introduced to solve the pressure gradient and gravity simultaneously as shown in Equation (2) (Datta-Gupta et al, 2001).  

Quantification of PSF

Strength of streamline can be quantitatively characterized as the volumetric flux between an injector producer pair and its swept volumes for that amount of fluid to flow through. Therefore, strength index of streamline field (SISF) can be defined as the volumetric flow rate between an injector producer pair compare with the swept volume in the injection well, the expression is below:

\[
Q_{i,P} = \iint (q_{w-i}) \, dxdy \quad (3)
\]

and

\[
SISF = Q_{i,P} / V_{swept} \quad (4)
\]

Where, SISF is strength index streamline field, \(q_{w-i}\) is the flux from the injector \(w\) to a specific producer \(i\) or to a boundary. \(Q_{i,p}\) is an integration of the flux over the area that fluid (tracer) flows through from a injector to a specific producer. And \(V_{swept}\) is swept volume for that specific injector producer pair. Write the interwell sum of the flow rate in a bi-stream-functions format as: (Datta-Gupta, 2001).
\[ Q_{I,P} = \int_{t_p} d\Psi d\chi \]  

(5)

Swept volume of the injector producer pair:

\[ V_{\text{swept}}^{(t)} = \int_{t_p} d\Psi d\chi \theta(t - \tau(\Psi, \chi)) \tau(\Psi, \chi) \]  

(6)

In fact, this relationship may be extended to finite times and see (6). If one well nearby a boundary is studied, and similarly \( Q_{I,P} \) also can cause exchange between this well and a boundary (flow out or flow in boundary).

**PSF Analysis Procedure and Classification**

After completed a reservoir simulation with a flow-based model, we will have a complete set of field scale streamline mapping for every time step. Just by reviewing and comparing all streamline distribution at field-scale and local-scale levels for every time step through the reservoir production history, we can certainly get some general ideas about flow pattern of the reservoir that we can not get otherwise. If one follows the systemic working procedure proposed in the paper, significant quantitative information can be obtained, which may not be able to obtain otherwise.

For a given field, the PSF analysis procedure can be as follows:

1. Conduct a flow-based numerical simulation and HM;
2. Review, compare and identify some trend and possible rapid streamline field changes between different time steps;
3. Do some statistic works for most injector-producer well pairs including the flux and the mean values of the flux for all well-pair in the field;
4. Calculate the mean value of the swept volume for all well-pair in the field;
5. Compare strength index of streamline filed (SISF) values for all well pair in the field and select those well pair with the larger SISF values;
6. Use SISF values as criteria to determine where PSF may exist and how many they are over there;
7. Create some conceptual models to verify what you have found from the real reservoir modeling works and do some sensitivity studies with the actual model and conceptual models if time allows.

PSF can be classified into three categories based on SISF value:

- Mild PSF
- Medium PSF
- Intense PSF

What we also have found out through our 3-year PSF study is that the isolated PSF zones have a tendency to connect each other while production is on-going unless major change is done. And this tendency really starts when SISF ratio approaches to 1. This is the turning point that we can see the general flow pattern may change significantly. It is also the point that PCZ starts to form, water injection efficiency becomes significant lower than before. This is also the point that water shut-off and/or reservoir profile modification must kick off.

By using the similar procedure, one can easily get the weak streamline field (WSF), which can be used for locating the potential zones of remaining bypass oil in-place.

**Case Study and Application**

As presented in this paper, reservoir W7 has 25 years production history. The reservoir has been modified very much due to the long time production activities. To name a few of those modification or changes, permeability has increased 14-16% at some wells comparing with those in 15 years ago according to the core analysis; oil becomes denser, much less oil remaining oil in place at some portions of the reservoir, and higher water-cut are also realized.
For a high permeability and good mobility reservoir like W7, only 33% oil-in-place recovered while water cut reaches over 98% is not a satisfactory number. Most likely, some wells must have been recycling a lot of water for a long time. We see the reservoir W7, a "middle-aged reservoir" comparing with the reservoir 20 years ago then, a very "youth reservoir". The reservoir has changed, and we know something can be improved if we understand what have changed and where the changes might take place. A powerful way to position ourselves for a better understanding the changes is to use them as opportunities to learn the reservoir in the correct way. Conducting dynamic reservoir characterization and description through flow-pattern-based approach as presented above is what we have elected to do.

Following the working procedure presented above, we have completed the history matching (HM) with all key indicator matched at 95% or better (Figure 3) and both HM errors of field oil and water production are less than 0.5%.

By taking the production history reservoir modification into the HM account, we spent much less time to get the good HM results as shown in Fig.3. During the HM process, PSF concepts helped a lot because we got some ideas where and which grid properties may change and to what degree it may change to (up or down) by reviewing the possible PSF zones. With a good HM, we then start to select our initial PSF candidates, and at the same time to conduct the full-wide well pair flux statistic study so that we can have a decent ideas how many zones fit into our PSF criteria so that a list of PSF with well pair name can be created.

Figure 4 is field-wide well-pair flux distribution chart, which indicates the mean values of well-pair flux is only 35.5 m³/day, and about 12% of well-pairs in the field have flux at over 80 m³/day. As we can see from the chart, some well-pairs have flux over 200 m³/day. We certainly should examine those well-pairs that have very large flux. A large number of flux between well-pair is always a worrisome situation. We used the well-pair flux of 80 m³/day as the cut off value for PSF well-pair candidates selection at first, and examined the sweep volume accordingly. Then certainly we got a short list of well-pairs with relative high SISF values over certain production history.
After a short list of well-pairs with relative high SISF values is created, a cross-checking with 2D and 3D streamline field is a necessary procedure. Figure 5 and figure 7 are two local streamline fields with PSF highlighted and those zones associated well-pairs are on the short list we had created using SISF selecting procedures. The PSF zones (Fig. 5 and Fig. 7) were coloured blue-like which indicates the fluid flow at a relative higher speed. The WSF zones can be selected in the similar way but using just relative smaller SISF value and pick the gray or light red/yellow colors in this case as marked in Figure 5. Figure 6 is the corresponding remaining oil distribution to Fig. 5. The remaining oil in place is expressed as in the unit of cubic meters per the unit bulk reservoir volume which is the grid area times the thickness of the pay at that particale grid, and the red to green areas indicate the oil rich spots (Fig 6). We do see the WSF (Fig.5) and oil-rich spots (Fig.6) match quite well.

As showing in Fig. 7, PSF zones and WSF zones occurred nearby each other, which indicate the areal dynamic-heterogeneity is quite severe. Dynamic-heterogeneity was caused by the initial formation heterogeneity and modification to the pay due to long time production history.
There are total over twenty locations like in Figure 5 and 7 for W7 reservoir. Figure 8 gives us some ideas what a single well-pair PSF may look like in 2D and 3D and a lot other information such as: there is over 83% of the injected water into the single producer, which yields 107.4 m³/day flux for this single well-pair, and the injected water took about 13 days to reached the front line (marked as 13.6 days front in red) as marked in figure 8. There are about 25 well-pair in this reservoir like this with a long history. It may be due to the superimposed multiple wells and multi-layers production practice, make this type channeling zones were hard to identify without using some new approaches, like PSF analysis methods present here. This is a very common problem that many fields in Eastern China are facing now. The combination effect of the areal heterogeneity initially plus long history intense waterflooding make what we can see in Figure 5 and Figure 7, PSF and WSF nearby each other in zones—the nature-and-man-made dynamic-heterogeneity.

General speaking, PSF will become stable after a few years waterflood production as we have seen from the field W7. A very good way to characterize the PSF stability is to use SISF ratio, which has been discussed previously in this paper. In this field, the average oil production had been relatively stable since 1992 after a batch of infill wells were deployed during 1991. This allows us to apply the PSF analysis procedure easily. Figure 9 and 10 clearly indicate that the SISF ratio of almost each well-pair changes decrease significantly after four to five years of the well-pair communication in general. This is the period time when the PSF starts to form and become stable, and it is also the time when PSF becomes PCZ. Relative stable oil production with gradually natural declining and water production rapidly increasing from 1992 to 1997 as shown in Figure 3 exactly matches above finding very well. In other words, in this case a significant number of well-pair transfer a lot of more fluid then before and keep high after those wells in operation.

In general, a relative steady PSF zone leads to a static concept called predominant channeling zone (PCZ). The term PCZ has some similarity to the terms that have been used for a number of years called “channeling” zone, which can be understood as dynamic-heterogeneity induced by-product.

![Figure 9 - SISF Ratio Of Some Well Pair-Actual Base Model( )](image)

![Figure 10 – SISF Ratio Of Some Well Pair-Actual Base Model( )](image)

Even though we have got the similar results from other basins of Eastern China, we still constructed 16 conceptual models based on the geological feature in W7 to verify this finding regarding SISF ratio changes over production time, and sensitivity study of single parameter impact for various model parameters. The conceptual models simulation results
consistently confirmed the 4-6 years SISF ratio curves osculation reduction and finally approaching to 1 or close to 1 as shown in Figure 11.

The fact of SISF ratio changes over time reflects and confirmed that massive information including lab testing data that the reservoir properties do changes over time. We can define the initial reservoir heterogeneity and secondary or modified reservoir heterogeneity as dynamic-heterogeneity. Reservoir dynamic-heterogeneity is a very useful concept for medium-high permeability sandstone reservoir seems. Using PSF and its associated concepts is the best way to characterize the dynamic-heterogeneity because PSF has strong finger print of all static (geological) information and production (dynamic) information.

As we have seen that PSF analysis approach has allowed us to be able to estimate bypass oil in place by combining the WSF, oil saturation distribution and dynamic-heterogeneity concept.

After this study, a new reservoir management plan including infill drilling, injection and production adjustments has been proposed field wide. Of course local adjustment has been made and very promising results have been achieved. More works need to be done in order to make this method more efficient and to find some possible limitations even though the general methodology is applicable to other fields.

Conclusions and Acknowledgments

One comprehensive dynamic reservoir characterization methodology with a very practical working procedure has been presented using a 25-year old reservoir W7 and sixteen conceptual models. By introducing the concept of predominant streamline fields (PSF) with its classification using strength index of streamline field (SISF) and applying the PSF analytical procedure, we can locate the highly desired spots “predominant channeling zone (PCZ)” three-dimensionally in a reservoir. Utilizing the relationship between the SISF ratio and production time, we also quantitatively estimate the time when PCZ may form. A lot of costs can be saved when some measurements are taken before PCZs are developed. PSF and WSF occur side-by-side in many cases, and therefore by locating PSF and WSF, bypass remaining oil can be better characterized.

Conclusions from this study are very beneficial for reservoir management as a whole.

More works need to be done in order to make this method more efficient and to examine some possible limitations that this method may have even though the general methodology is applicable to all sandstone or even some natural fracture fields with waterflooding.

Nomenclature

\[ \chi = \text{Bi-streamline function (L)} \]
\[ \Psi = \text{Bi-streamline function (L}^2/\text{T)} \]
\[ \Delta \tau = \text{Time of flight} \]
\[ q = \text{Flow rate at } \Delta \tau \text{ time} \]
\[ S_w = \text{Water Saturation} \]
\[ F_w = \text{Fractional Flow of water phase} \]
\[ U_t = \text{Total Velocity (L/T)} \]
\[ U_o = \text{Velocity of oil (L/T)} \]
\[ U_w = \text{Velocity of water (L/T)} \]
\[ q_{r-u} = \text{Fluid conduction of rock volume} \]
\[ Q_{SP} = \text{Interwell fluid flow} \]
\[ V_{sweep} = \text{Swept Volume between injector producer pair} \]
\[ M = \text{Amount of tracer} \]

**Reference**

3. Wang, Y. Z et al :“Analysis on Fine Reservoir Description and Remaining Oil Pattern in the West Part of the 7~(th) Block in Gudong Oilfield( Reservoir Engineering)”, Internal Report, Shengli Oil Administration, Gudong Production Company, Geoscience Research Institute. May, 2000, China.