Abstract

A completion-fluid displacement is an important well operation that can be complicated by various physical conditions and constraints. As such, this dynamic process can be difficult to plan without practical means to manage and synchronize key parameters. Described in this paper is an innovative displacement-design tool known as “rainbow” charts, so-called because of their distinctive graphical look. The charts are used in conjunction with standard graphs to display and analyze on a single sheet of paper the hydrodynamic aspects of a completion-fluid displacement. For comparison purposes, the method is applied to a Gulf of Mexico displacement that was originally designed using an effective, but more conventional spreadsheet approach.

A rainbow chart is a continuous plot of the position of each fluid in the annulus and work string throughout the displacement. Pressure and flow-rate curves positioned directly above or superimposed on a rainbow chart permit a vertical line drawn though all the graphs to precisely define key parameters at any specific time. Also, design overlays drawn on a rainbow chart assist in detailed analysis of certain parameters (such as flow regime) in any part of the well during any part of the displacement.

Perhaps the most important benefit of rainbow charts is that their framework makes it possible to address other pressing issues, such as the combined hydrodynamic and chemical effects related to wellbore cleaning. Comments on these issues and enhancement opportunities also are included in this paper.

Introduction

The first, and one of the critical steps in the completion process, is the displacement from drilling mud to clear-brine completion fluid. The objective of this operation is to provide a clean brine in a water-wet wellbore devoid of whole mud and mud film. This requires a properly designed and executed plan of hydrodynamic parameters, as well as chemical factors, particularly if synthetic or oil-based fluid are involved.

Displacement design can be complicated by various physical conditions and constraints. Among these are multiple spacers and washes, persistent and tenacious synthetic-based mud films, wide differences in fluid density and viscosity, directional profiles, complex geometry configurations, and pressure, horsepower, and flow-rate limitations. Analysis of this dynamic process is particularly difficult without practical means to manage and coordinate key parameters. Conventional graphical techniques using computer spreadsheets have provided a step improvement in the displacement design process. However, this approach has inherent limitations.

The subject of this paper is an innovative tool that works in conjunction with standard graphics to optimize completion-fluid displacements. Known as “rainbow” charts because of their distinctive graphical appearance, their purpose is to synchronize key parameters on a single sheet of paper or static computer display. Currently, the charts are linked to basic hydrodynamic factors, including flow rates, volumes, and pressures (surface and downhole). Chemical factors also can be addressed; but this is under development and discussion in this paper is limited.

Engineered displacements using rainbow-chart examples are presented to show how the design process can be improved, simplified, and clarified. Much of this paper is based around a Gulf of Mexico displacement case history. Illustrative examples generated by a fit-for-purpose computer program also are included to demonstrate the flexibility of the overall rainbow-chart concept. However, the intended focus here is on the rainbow-chart concept and not the details of the software.

Displacement Design Using Conventional Graphics

A 10,770-ft (10,020-ft TVD) well from Vermilion 363 completed in 1997 was selected to illustrate use of the rainbow charts. Table 1, captured from the original spreadsheet, summarizes pertinent well data. The completion operation involved displacing 17.0-lb/gal water-based mud to 17.0-lb/gal ZnBr₂ completion brine in a wellbore having open perforations within the target sand interval. The spacer package consisted of (a) 50 bbl of 17.5-lb/gal viscosified, barite-weighted spacer followed by (b) 25 bbl of 8.6-lb/gal surfactant wash and (c) 50 bbl of 11.6-lb/gal viscosified CaCl₂. A 4.5-in. by 3.5-in. work string was installed inside 7.625-in. casing.
Pore pressure in the target BN-1 sand at 10,020 ft was 8,720 psi (16.74-lb/gal equivalent). Maximum allowable bottomhole pressure was estimated at 9,275 psi (17.8-lb/gal equivalent). Because of the dynamic hydrostatic-pressure profiles created by fluids of different density, the well had to be circulated on choke to keep the bottomhole pressure within the 555-psi operating window. Concurrently, the flow rate had to be as high as possible to promote proper wellbore cleaning by the wash spacer, without exceeding the bottomhole-pressure limit.

Two areas of particular concern are identified in Table 1. As seen in Fig. 1, the first one occurs at about 183 bbl when the low-density wash spacer reaches TD. The flow rate reduction from 2.25 to 1.5 bbl/min is required to keep the bottomhole pressure within range. Also at that point, the annular hydrostatic pressure begins to decrease rapidly as the wash spacer enters the annulus. Back pressure is required to keep the bottomhole pressure above the pore pressure from there forward. The second concern is from 422-497 bbl, the period over which the heavier, viscous spacer first reaches the surface until the wash spacer is circulated completely out of the well. It is during this period that the choke pressure is at its highest values.

Actual displacement followed the plan; however, the operation was somewhat difficult and lengthy, complicated by the low flow rates and narrow operating window.

The Rainbow-Chart Concept

The displacement plan described in the previous section would be easier to follow if it were possible to quickly visualize the downhole fluid locations and accurately coordinate them with flow rates and resulting pressures. These are precisely the primary advantages of rainbow charts.

A rainbow chart is a continuous plot that shows the position of each fluid involved in the displacement as it circulates through the annulus and work string. The independent axis can be pump strokes or cumulative fluid volume pumped. When used with flow-rate and pressure curves, either superimposed or positioned directly above, a vertical line drawn through all the graphs at any specific fluid-volume value can precisely define key parameters, including:

1. Position and length of each fluid in the annulus and work string
2. Hydrostatic pressures in the annulus and work string
3. Hydrostatic pressure differential at TD
4. Bottomhole pressure
5. Flow rate
6. Pump pressure and hydraulic horsepower
7. Choke or Back pressure (if required to maintain bottomhole pressure within specified limits).

Clearly, other data curves can be added, space permitting on the hardcopy or computer screen. However, the focus in this paper is on the hydrodynamic variables listed above.

The rainbow-chart method is illustrated by the computer-screen capture in Fig. 2 for the Vermilion example. The two multi-colored rainbow charts are synchronized vertically with the volume of fluid pumped and laterally with the well geometry. The upper geometry and rainbow-chart pair applies to the work string. The lower pair for the annulus has been “unfolded” downwards to prevent overlapping the work-string chart. (Note: This figure and others like it are computer screen captures. This accounts for the crowded, “flat” look. These charts are designed to be printed in portrait mode.)

Fig. 2 might look somewhat daunting at first glance; however, the red vertical line placed at 170 bbl helps put all into focus. In a real setting, the vertical line can be moved interactively using a mouse on a computer screen or a straight edge on a hardcopy printout. The data set in the upper left-hand corner of Fig. 2 matches conditions after pumping the 170 bbl. Additional data at selected fluid-volume points from a more detailed matrix are listed in Table 2. Clearly, the graphics make it easier to review and evaluate the displacement.

The basic construction of a rainbow chart is best explained by first visualizing the red vertical line as a very narrow, fluid-filled slot. Each fluid (identified under “Displacement Design”) is represented by a different color within that slot, as shown in Fig. 3. A multitude of the slots placed side-by-side and blended together would then become a rainbow chart.

Design Overlays

“Design overlays” add another level of usefulness to the combined graphics in Fig. 2. These overlays act as templates that when superimposed over rainbow charts permit evaluation of various design parameters. For example, the wash spacer ideally should be in turbulent flow to maximize wellbore cleaning and help achieve water-wet surfaces. Even for wells with complex geometry and a variable flow-rate schedule, the overlay method allows immediate inspection of the flow regime for each fluid throughout the displacement.

A design overlay essentially is a large matrix or data grid. As expected, rows are depth-based and columns are pump-strokes or volume-based. Fig. 4 illustrates a single-column overlay superimposed over a schematic of a fluid-filled slot like those shown in Fig. 3. Grid mesh size can be 50-500 ft by 1-5 bbl depending on the application.

Each cell in the data grid can contain records of valuable information such as those listed in Fig. 4. Some of the records already are considered, while others are reserved for future enhancements. The most promising of these are related to more detailed hydrodynamic
analyses and chemically related issues, of which wellbore-cleaning analysis is perhaps the most critical.

The significance of the records in the data grid is that each can be compared to a pre-set condition. A flag (true or false) is set depending on the result of the comparison defined by a single or complex SQL-type interrogation. An example condition might be "turbulent flow and velocity < 100 fpm". If the comparison flag is set in a particular cell, a thin vertical line is drawn corresponding to the position of the cell in the data grid. The collection of thin lines constitutes the final overlay template.

Fig. 5 shows a design overlay applied to Fig. 2. The selected design criterion is flow regime. Cross-hatching is indicated wherever the regime is not laminar (turbulent or transitional flow). Note that the wash spacer (Fluid B) is turbulent throughout the displacement (work string and annulus). Recall that the flow-rate schedule was 2.25 bbl/min for 183 bbl and 1.5 bbl/min for 25 bbl before returning to 2.25 bbl/min. The viscosified 11.6-lb/gal CaCl₂ (Fluid C) is turbulent in the work string except for the small period (indicated by the arrow in Fig. 5) where the flow rate was lower and the pipe diameter was larger. The overlay indicates that the ZnBr₂ completion fluid is turbulent throughout the work string and laminar throughout the annulus. Maximum hydrodynamic values for the entire displacement are listed in the upper left-hand corner of the figure.

Design Options
Several design options are available to help optimize certain dis placements. Some of these are software features and are not discussed here. However, two options that are central to the rainbow charts concept are illustrated in Figs. 6-8.

The screen capture in Fig. 6 shows the Vermilion example design if displaced using reverse circulation. On close inspection, the design, as is, would impose a higher-than-desired bottomhole pressure after pumping around 335 bbl when the wash spacer enters the work string. Clearly, a correction is possible, but this is not pertinent to this paper.

The second design option is related to staged displacements. A different 19,472-ft (16,010-ft TVD) well was selected to illustrate how rainbow charts could be effectively used to evaluate and design an indirect displacement. For simplicity, displacement to seawater is planned for two stages (whereas a three-stage displacement probably would be more appropriate). Fig. 7 gives stage-one results with the tapered work string at 9,250 ft; for stage two the work string is at TD in Fig. 8. Additional design criteria include maximum pump pressure of 4,500 psi, and maximum and minimum flow rates of 4.0 and 0.5 bbl/min, respectively. The ability to set practical boundary conditions such as these is an important time-saver for design engineers. The final displacement to ZnBr₂ is not illustrated.

Enhancements and Opportunities
The rainbow-chart framework is such that finite-difference methods are available for advanced applications. Among these are detailed hydrodynamic analyses and chemically related issues such as wellbore cleaning. Generally speaking, these opportunities can be realized by enhancing existing data grids, or superimposing additional grids that focus on particular technologies. The following are some opportunities for hydrodynamic-related issues:

1. Adjustments for temperature and pressure effects on downhole rheology and density. The framework already is in place and tools are available, but considerable uncertainties and complexities can be involved. For one, additional information required on the drilling mud formulation is sometimes not available to the completion operation. Also, circulating temperature profiles are not easily defined.

2. Allowances for fluid-fluid interfaces and their effects on localized density, viscosity, and chemical makeup (surfactants). Some research already has been conducted in this area, and results are promising. Validation with field data will be critical.

3. Advanced displacement mechanics. This is very computer-processing intensive, but numerical methods fit within the rainbow-chart scheme. The impact of eccentricity on pressure loss and wall shear stress is an area of special interest. Also, improved techniques for predicting flow regime (especially in eccentric annuli) are critical for evaluating hydrodynamic effects on mud-film removal.

Perhaps the greatest opportunities exist when combining hydrodynamic and chemical factors to accurately predict wellbore cleaning, especially when a synthetic-based mud is involved. Model developments are in progress, and, as before, implementation lends itself to the rainbow-chart framework already in place.

Conclusions
1. The design and execution of complex displacements from drilling mud to clear-brine completion fluid can be improved, simplified, and clarified using an innovative tool known as "rainbow" charts. The technology is applied to the displacement plan of a Gulf of Mexico Vermilion 363 well that was originally designed using conventional spreadsheet analysis.

2. Static rainbow charts, when combined with conventional pressure and flow-rate graphics, provide a complete view of a dynamic completion-fluid displacement on a single sheet of paper or static computer screen.

3. The process allows design engineers to quickly
visualize downhole fluid positions, accurately coordinate them with pressures and flow rates, and evaluate options.

4. Superimposed "overlays" turn rainbow charts into powerful design tools by indicating when and where given parameters fall within specified ranges.

5. The rainbow-chart framework has application for more advanced uses, including detailed hydrodynamic analyses and critical chemically related issues such as wellbore cleaning.

Nomenclature

A, B, C… – spacer fluids
BHP – bottomhole pressure, psi
dHP – delta hydrostatic pressure, psi
HHP – pump hydraulic horsepower, hhp
Pann – annular pressure loss, psi
Pchoke – choke pressure loss, psi
PhAnn – annular hydrostatic pressure, psi
PhWS – work-string hydrostatic pressure, psi
Ppump – pump pressure, psi
Pws – work-string pressure loss, psi
SQL – structured query language
ZnBr₂ – zinc bromide completion fluid

Acknowledgements

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References


Vermilion 363 Mud Displacement with spacers and ZnBr₂

Table 1 – Displacement-data matrix for Vermilion example showing position of each fluid and pressures at selected values for volume pumped.

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Fig. 1 – Pressure curves for Vermilion 363 displacement example summarized in Table 1.

Fig. 2 – Rainbow charts application for the example shown in Fig. 1.
Fig. 3 – Schematic illustrating rainbow chart construction using a multitude of individual fluid-filled slots placed side-by-side.

Fig. 4 – Overlay grid showing parameters defined for each element at a given volume or stroke.

Fig. 5 – Design overlay applied to Fig. 2. Cross-hatched areas indicating where flow regime is not laminar. The arrow points to an area where Fluid C is in laminar flow in the work string.
Fig. 6 – Vermilion 363 example design if displaced using reverse circulation.

Fig. 7 – First part of a two-stage indirect displacement for a well with complex geometry. Work string is at 9,250 ft.
Fig. 8 – Second part of a two-stage displacement for a well with complex geometry. Work string is at TD (19,472 ft).