AADE-19-NTCE-025

Predicting Downhole Spacer Contamination in Wellbore Displacements

Vítor Lopes Pereira and Dale E. Jamison, Halliburton

This paper was prepared for presentation at the 2019 AADE National Technical Conference and Exhibition held at the Hilton Denver City Center, Denver, Colorado, April 9-10, 2019. This conference is sponsored by the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individual(s) listed as author(s) of this work.

Abstract

Spacer contamination can significantly affect cleanup efficiency during wellbore displacements. A method is presented to accurately and timely estimate the interface growth between fluids during displacement operations.

As the fluids particular to a displacement train are flowing through the wellbore, interface mixing and/or channeling invariably occur, generating pockets of blended fluids of unknown characteristics.

Understanding the degree and rate at which spacer contamination can occur is key for determining the associated impacts on the overall wellbore cleanup efficiency during the design phase. Any undesired material left in the wellbore could potentially compromise the execution of subsequent planned operations and, eventually, the reservoir's expected return rates and life span.

An analytical methodology was developed to capture the effects of spacer mixing and/or channeling during wellbore displacements. The approach was developed and validated against actual data for a wide range of wellbore geometries, operational conditions, and spacer train configurations.

Results indicate good agreement between measured and predicted return spacer properties (such as density) as a consequence of the estimated spacer interface contamination. Simultaneously, the entire time span of each displacement operation is simulated instantaneously, enabling optimization exercises otherwise impractical.

Accurately assessing the impact of several displacement setups with regards to possible spacer contamination and consequent overall displacement cleanup efficiency in a timely manner is of significant value to designers needing to optimize spacer volumes and properties to be pumped in such industry-crucial operations.

Introduction

Wellbore fluid displacement is performed by circulating a second fluid through the wellbore. At some stage after drilling to target depth and before completing a well for production, a cleanup displacement operation is performed to remove the original drilling fluids as well as residual solids from the wellbore. Proper removal of these materials is vital to the longevity of a wellbore because residue can hinder completion operations and ultimately impair the ability of the reservoir to produce. A cleanup displacement operation is performed using a series of wellbore servicing fluids—namely "pills," "spacers," or both—which provide both chemical and mechanical cleaning actions. When circulated through the wellbore in a defined sequence, this collection of fluids is commonly known as a displacement train (**Fig 1**).

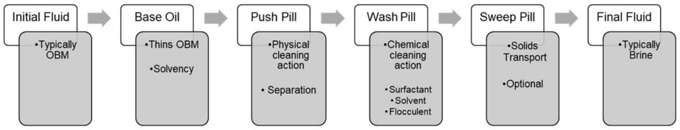

Fig. 1—"Typical" fluids displacement train.

A cleanup displacement operation is constrained by various factors, including, but not limited to, environmental regulations, operational restrictions, and the risk of reservoir damage. Therefore, the planning, designing, and execution requires rigorous adherence to detailed steps and best practices to achieve thorough cleaning efficiency.

During the planning phase of a cleanup displacement operation, fluids' properties, volumes, chemical additives, concentrations, and flow regimes are carefully selected to fit the individual purpose of each spacer as well as the overall displacement purpose of maximizing cleanup efficiency.

Mixing and channeling effects that occur at the interface between two or more fluids can detrimentally impact the overall cleaning efficiency of a displacement train. Many factors dictate the level of interaction between the fluid interfaces, such as

- Flow path geometry: varying lengths, annular gaps, and drillpipe diameters and positions (eccentricity and angle)
- Operational conditions: varying flow rates, pressures, temperatures, and drillpipe rotations
- Fluids' configurations: varying volumes, miscibilities, densities, rheologies, and surface tensions

Attempting to completely avoid mixing and/or channeling during displacements is desirable but not always feasible. Understanding the degree to which it might occur at different times and wellbore positions is key for determining their associated impacts on the overall cleaning efficiency performance.

Many distinct numerical approaches to predict fluid interface interaction have been the object of study in the industry[1-3], providing insightful information to displacement train design professionals. However, despite advances in high-performance computing, these methods are computationally intense and often impractical for displacement train design optimization exercises.

In this context, opportunities exist to explore accurate yet less computationally demanding methodologies.

The development and validation of analytical algorithms to model the effects of mixing and channeling on spacer integrity during wellbore displacements is presented here.

Theory

Building on existing empirical approaches for fluid interface mixing within pipeline flows[4-6] and the Rayleigh-Taylor instability method for interface channeling[7-9], this work proposes an analytical methodology to model and simulate fluid interface growth within eccentric-annulus wellbores.[10-14]

Interface Mixing

In the proposed methodology, the interface volume between fluids, $\boldsymbol{I}$, is calculated and incremented as the fluids move through the wellbore using the empirical pipeline flow mixing model, as described in **Eq. 1**.

$$\boldsymbol{I} = \boldsymbol{f}(\boldsymbol{d}, \boldsymbol{L}, \boldsymbol{U}, \boldsymbol{v}) \qquad \text{Eq. 1}$$

The interface kinematic viscosity, $\boldsymbol{v}$, is calculated using established mixing rules involving fluids' densities and apparent viscosities, both estimated at experienced downhole pressures, temperatures, and shear rates during the simulated displacement.

Interface Channeling

The potential channeling effects are incorporated in **Eq. 1** by modifying the interface velocity term, $\boldsymbol{U}$, according to the fluid interface stability rules proposed by Rayleigh-Taylor (**Fig. 2**), where the interface channeling velocity, $\boldsymbol{U_c}$, is described in **Eq. 2.**

$$\boldsymbol{U_c} = \boldsymbol{f}(\boldsymbol{A}, \boldsymbol{g}, ^\circ, \boldsymbol{S}) \qquad \text{Eq. 2}$$

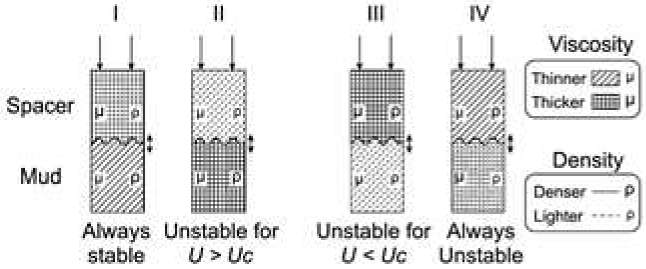

Fig. 2—Rayleigh-Taylor fluid interface stability rules.

Eccentric-Annular Flow

Finally, a schema is developed to extend the functionality of the pipeline flow mixing model to annular flows, particularly eccentric ones.

Fundamentally, the three-dimensional *(3D) flow profile for a given eccentric-annular section is calculated and split into a given number of segments, n. Based on the profile, each segment is treated as a pipe with a hydraulic diameter of an equivalent cross-sectional area and with its own fluid interface velocity (**Fig. 3**).

By implementing this methodology, it was possible to obtain the interface volumes between different fluids flowing through an eccentric wellbore at any given depth in any given time during the simulated displacement.

It is relevant to mention that pipe rotation effects are being considered when estimating the experienced shear rate in the annulus, as well as the distance traveled by the interface and its velocity within a given annular section.

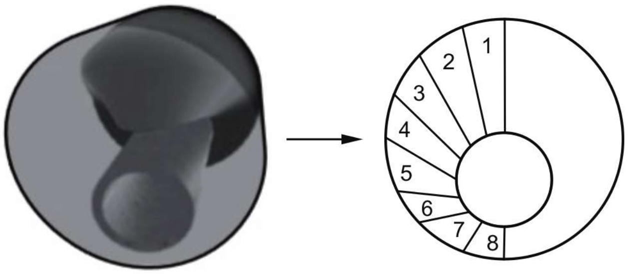

Fig. 3—Eccentric annular flow profile [3D and two-dimensional (2D)].

Results

The predictions from the proposed spacer contamination models are demonstrated in simplistic single-annular-section scenarios.

Fig. 4 shows predictions from the spacer contamination model for an 8.5-in. hole with a 5.87-in. drillpipe having varying drillpipe eccentricities.

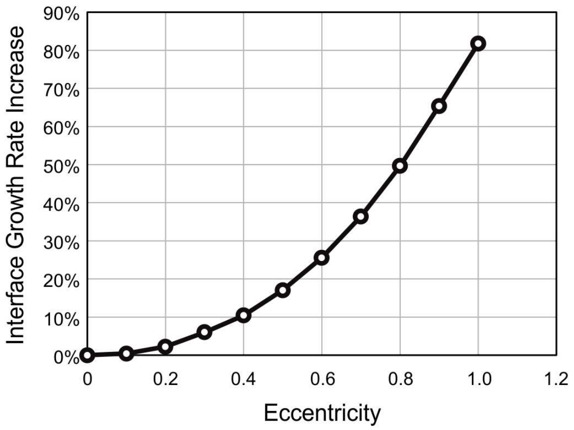

Fig. 4—Interface growth rate increase as a function of eccentricity.

The leading fluid is a 12.5-lbm/gal oil-based mud (OBM) having a 49-cp apparent viscosity. The trailing fluid is a 13.5-lbm/gal push pill [water-based mud (WBM)] having a 118-cp apparent viscosity.

The fluids were circulated at an axial flow rate of 800 gal/min at a vertical angle against gravity. Drillpipe rotation was 60 rev/min. The model results show that the interface growth rate is considerably higher for an eccentric annulus compared to a concentric annulus; interface growth rate increments up to 82% were predicted for fully eccentric scenarios (compared to the baseline non-eccentric case). Thus, the relevance of using centralizers during displacement operations is demonstrated.

Fig. 5 shows predictions from the spacer contamination model for the same conditions presented previously but, varying the axial flow rates and keeping eccentricity constant. The model results show that the interface growth rate is considerably lower for higher axial flow rates; interface growth rate reductions up to 87% were predicted for the highest axial flow rate scenario tested of 1,000 gal/min. Thus, the relevance of maintaining the highest possible flow rates within pressure limits during displacement operations is apparent.

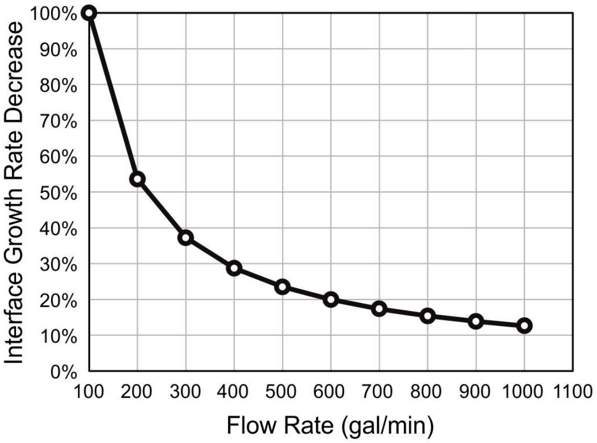

Fig. 5—Interface growth rate decrease as a function of flow rate.

Fig. 6 shows predictions from the spacer contamination model for an 8.5-in. hole with a concentric 5.87-in. drillpipe having a varying fluids' delta density (1.0 lbm/gal) and delta apparent viscosity (69 cp) alignment with the gravitational direction. The fluids were circulated at an axial flow rate of 800 gal/min at a vertical angle. Drillpipe rotation was 60 rev/min.

- Case 1 (Baseline): both delta density and delta apparent viscosity aligned with the gravitational direction.
- Case 2: both delta density and delta apparent viscosity aligned against the gravitational direction.
- Case 3: delta density aligned with the gravitational direction while delta apparent viscosity aligned against it.
- Case 4: delta apparent viscosity aligned with the gravitational direction while delta density aligned against it.

The model results show that the interface growth rate is higher for cases where the delta density is aligned against the gravitational direction, more so if the delta apparent viscosity is also aligned against gravity. Additionally, the order of magnitude for this change is proportional to the delta's order of magnitude. This behavior is in agreement with the Rayleigh-Taylor interface stability rules. Thus, using a push pill (higher density and apparent viscosity) as a barrier fluid is necessary to help minimize the interaction between the initial fluid and the spacers' train, particularly in the annulus, where the interface growth rates are expected to be higher because of the lower fluid velocities.

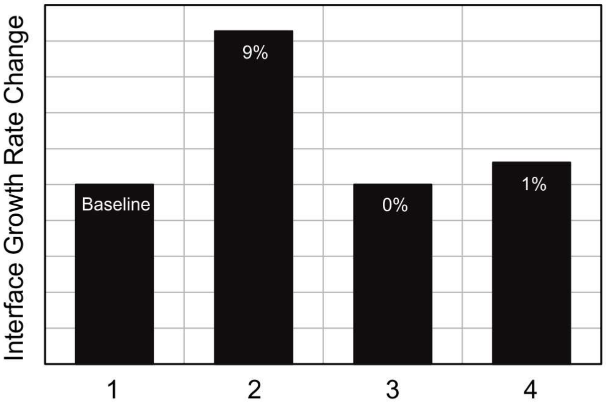

Fig. 6—Interface growth rate change as a function of delta density and delta apparent viscosity alignment with the gravitational direction.

By applying the analytical methodology described in conjunction with using a wellbore hydraulics simulator, it is possible to predict the expected levels of interaction between the fluids' interfaces for a given displacement operation in a timely manner.

Fig. 7 shows the predicted composition of the fluids returning back to surface vs. the pumped volume throughout a given displacement.

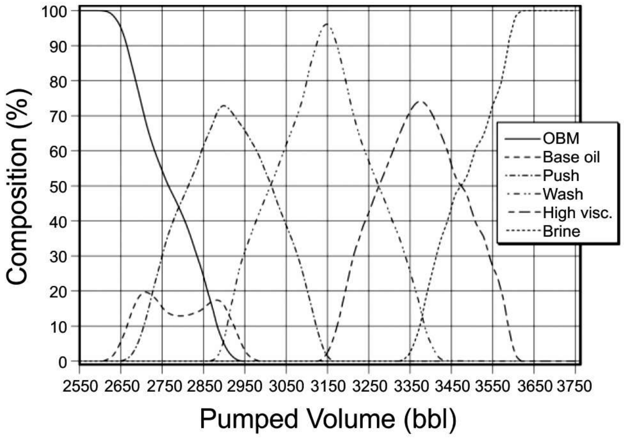

Fig. 7—Return fluids composition as a function of pumped volume.

In this particular case, a displacement train is circulated in the following sequence: OBM, base oil, push pill, wash pill, high-viscosity pill, and brine. The calculated cumulative interface lengths were used to simulate the locations of composite fluids formed throughout the simulated displacement operation. For example, the cumulative interface lengths are used to determine that OBM, base oil, push pill, and the respective interfaces coexist as they are leaving the wellbore (back to the surface) after 2,800 bbl was circulated in the displacement operation. Note that at any point of time in the displacement operation, the concentration of wellbore servicing fluids in **Fig. 7** equals 100% (e.g., 42% OBM, 12% base oil, and 46% push pill equates to 100% at approximately 2,800 bbl pumped).

Finally, when evaluating the results illustrated in **Fig. 7**, a displacement design engineer might observe that a maximum of 70% spacer integrity for the push pill returning back to surface is insufficient to ensure sufficient separation between fluids to prevent compromising the displacement goal.

Because of the analytical nature of the proposed modeling approach, results such as those displayed in **Fig. 7** are obtained instantaneously, enabling displacement design engineers to perform optimization exercises using varying flow path geometries, operational conditions, and fluids' configurations toward the desired thresholds. In this particular case, re-performing the simulation with an increment of 125 bbl on the push pill original volume would have resulted in a 70% return composition peak to move toward 90% integrity, a value that would typically agree well with the barrier function proposed for this particular spacer.

Field Validation

During wellbore fluids displacements, fluid samples are often collected at the return lines to further assess the actual degree of fluids' interaction while circulated through the wellbore. This is achieved by evaluating the physical and chemical properties of the collected samples, as well as the elapsed time in which they were obtained, and comparing to those of the individual fluids at the expected times if no interaction was to occur during the displacement. This procedure is commonly referred to as flow back analysis.

Results from this type of analysis were used to validate the proposed methodology. A total of 16 wellbore fluid displacements with varying flow path geometries, operational conditions, and fluids' configurations was validated.

Based on the predicted degree of fluids' interaction and the consequent return fluids composition over time (such as those indicated in **Fig. 7**), in conjunction with the individual fluid properties (such as density), it is possible to also estimate the expected fluid properties at the returns over time. This process is shown in **Fig. 8**.

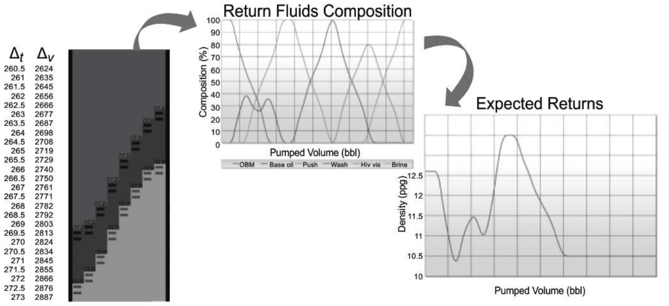

Fig. 8—Predicted return fluids' properties process.

Fig. 9 compares the actual (dots) vs. predicted (solid line) return fluid density curves for one of the 16 wellbore fluid displacements validated. Results indicate good agreement between actual and predicted profiles. The same behavior is exhibited for all 16 displacements assessed.

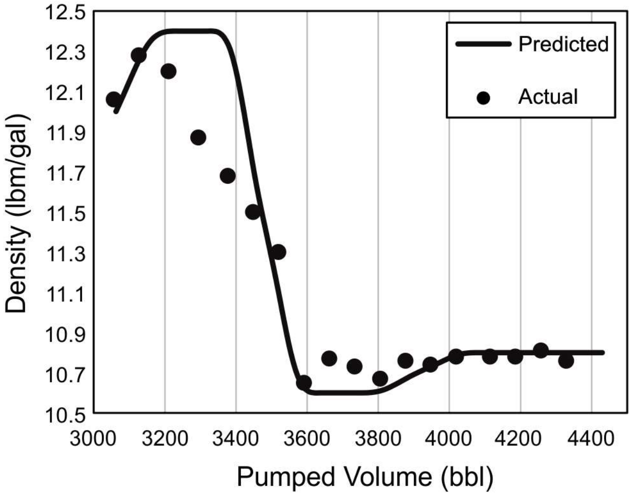

Fig. 9—Predicted vs. actual return fluids' density.

When running the validation analysis against the 16 wellbore fluids displacements, an interesting case was observed, where the integral of the measured density values (dots) indicated more mass coming out of the system than was originally pumped. **Fig. 10** illustrates this particular case, where the second slope in the dots (approximately 3,500 bbl pumped volume) is not observed (nor expected) in the predictions. As the pill returning to the surface around this time is the high-viscosity pill, and integrating the dots generated more fluid mass than pumped, a hypothesis was formulated that materials already present in the wellbore before the displacement began were transported out. This led to a surprising finding that the proposed methodology could also help facilitate an easier assessment of cleanup efficiency for wellbore fluids displacements.

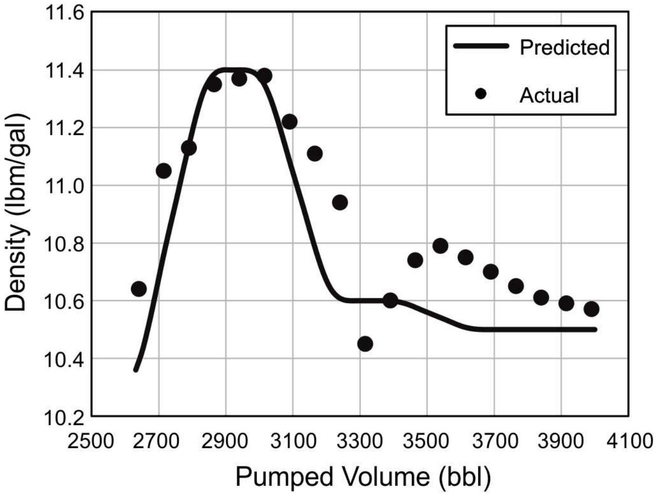

Fig. 10—Predicted return fluids' properties process.

Conclusions

The following conclusions are a result of this work:

- A new, accurate, and time-effective analytical model was developed to predict interface mixing and channeling during wellbore fluids displacement in an eccentric annulus at downhole conditions.
- Drillpipe eccentricity leads to increased fluids' interface interaction; increments up to 82% were predicted for fully eccentric scenarios.
- Increased flow rates lead to decreased fluids' interface interaction; reductions up to 87% were predicted for higher flow rates.
- Delta density aligned against the gravitational direction leads to increased fluid interface interaction; this behavior is augmented if the delta apparent viscosity is also aligned against the gravitational direction. Increments are proportional to the deltas' order of magnitude.
- Based on comparison with the flow back data obtained in the field for several displacement configurations, it was validated that the proposed analytical methodology is capable of timely and accurately predicting the fluids' interface interaction during a displacement operation.
- Displacement design engineers desiring to understand and optimize the effect of flow path geometry, operational conditions, and fluids' configuration over the overall displacement train interaction can effectively achieve this goal by using the proposed methodology.
- When combined with the samples' data collected for flow back analysis, the proposed methodology can also help facilitate an easier assessment of cleanup efficiency for wellbore fluids displacements.

Acknowledgments

The authors thank Halliburton for providing the appropriate support and permissions to develop and present this work.

Nomenclature

Δ_t = *delta time (elapsed time)*
Δ_V = *delta volume (pumped volume)*
° = *angle*
μ = *interface viscosity*
v =*interface kinematic viscosity*
% = *percentage*
A = *interface Attwood number*
bbl = *barrels*
cp = *centipoise*
d = *hydraulic diameter*
g = *gravity constant*
gal/min = *gallons per minute*
I = *interface volume*
in. = *inches*
L = *interface distance travelled*
lbm/gal = *pounds per gallon*
OBM = *oil-based mud*
rev/min = *revolutions per minute*
S = *interface area*
U = *interface velocity*
U_c = *interface channeling velocity*
WBM = *water-based mud*

References

1. Wu, H ., Madasu, S., Lin, A.: "Modeling fluid displacement in a well system environment", US9416631B2, (2016).
2. Karbasforoushan, H., Ozbayoglu, E. M., Miska, S. Z., Yu, M., Takach, N.: "On the instability of Cement-Fluid Interface and Fluid Mixing", SPE-180322-MS, (2016).
3. Van Oort, E., Enayatpour, S.: "Advanced Modeling of Cement Displacement Complexities", SPE-184702-MS, (2017).
4. Patrachari, A. R.: "Deterministic models to explain the phenomenon of interfacial mixing in refined product pipelines", PhD Thesis, School of Chemical Engineering, Oklahoma State University, (2012).
5. Ekambara, K., Joshi, J. B.: "Axial mixing in pipe flows: turbulent and transition regions", Chemical Engineering Science No. **58**, (2003) 2715–2724.
6. Tichacek , L. J., Barkelew, C. H., Baron, T.: "Axial mixing in pipes", AIChE Journal No. **3**, (1957), 439–442.
7. Piriz, A. R., Cortazar, O.D., López Cela, J. J., "The Rayleigh-Taylor instability", American Journal of Physics No. **74**, (2006) 1095–1098.
8. Taylor, G. I.: "The instability of liquid surfaces when accelerated in a direction perpendicular to their planes," Proc. R. Soc. London, Ser. A1364-5021, No. **201**, (1950) 192–196.
9. Lord Rayleigh: Scientific Papers, Cambridge, U. P., Cambridge (1900), Vol. II, 200–207.

10. Guckes, T. L.: “Laminar Flow of Non-Newtonian Fluids in an Eccentric Annulus”, ASME Paper No. **74**, (1974) 57–62.
11. Nouri, J. M., Umur, H., Whitelaw, J. H.: “Flow of Newtonian and Non-Newtonian Fluids in Concentric and Eccentric Annuli”, J. Fluid. Mech. No. **253**, (1993) 617–641.
12. Caenn, R., Darley, H. C. H., Gray, G. R. M.: “Composition and Properties of Drilling and Completion Fluids”, Elsevier Inc. (2011), ISBN: 978-0-12-383858-2.
13. Riberio, P. R., Podio, A. L., Sepehrnoori, K.: “The Effect of Rotational Speed and Eccentricity on Annular Flows with Application to Slim Hole Drilling Hydraulics”, SPE-26958-MS, (1994) 669–677.
14. Kulkarni S., Singh, J., Lopes Pereira, V, Porter, A.: “Real-Time ECD Management by Accounting for Effects of Drillpipe Rotation and Eccentricity in the Wellbore”, AADE-17-NTCE-097, (2017).