DISPLACEMENT DEMYSTIFIED

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During the process of clean-up and cement operations, a wellbore contains multiple fluids that displace each other. During a typical cement operation, a spacer or chemical wash is first pumped down and displaces the native mud before the cement slurry is pushed through the well to a desired depth. Centralisers are set at certain optimal intervals on the casing to maintain a good standoff. Fluids are

Pegasus Vertex, Inc.
Drilling Software

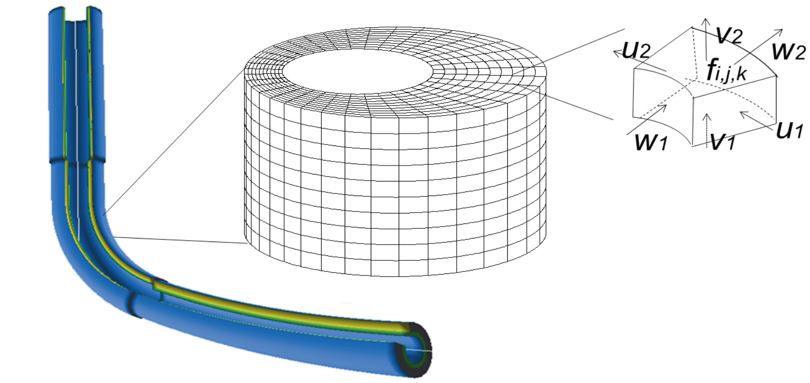

Figure 1. *3D grid.*

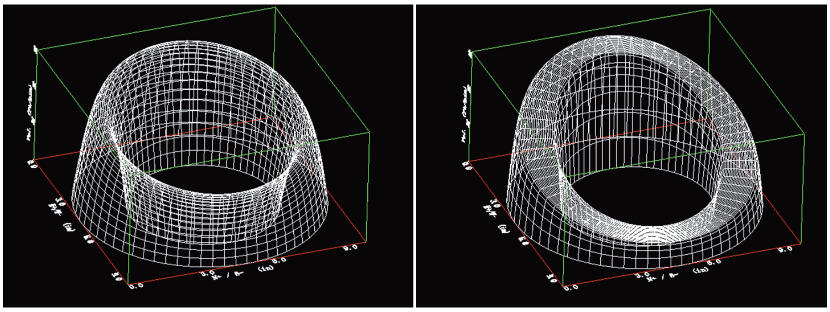

Figure 2. *Velocity profile in an eccentric annulus.*

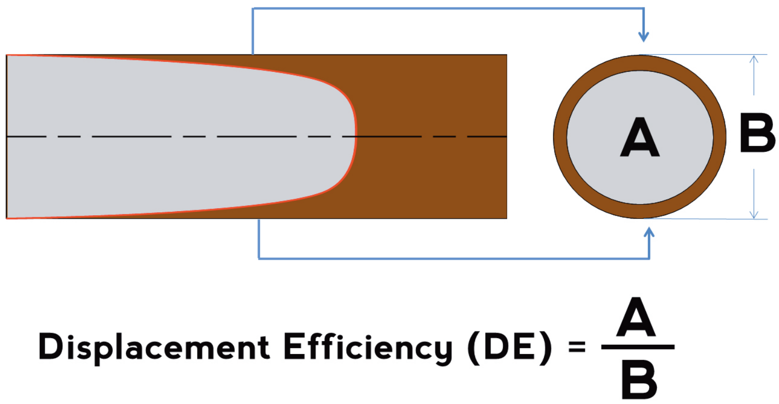

Figure 3. *Definition of displacement efficiency.*

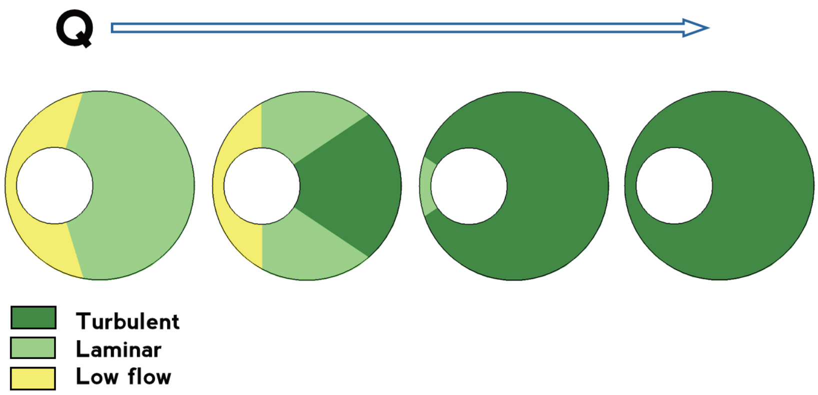

Figure 4. *Flow patterns in an eccentric annulus.*

specially designed and pumping rates are carefully selected to control the bottom hole pressure and to achieve a high displacement efficiency. Mud channelling and mud cakes on the wall are the first things to avoid in order to achieve a successful cement job. Evaluations on displacement efficiency for a cement job should include, but not be limited to the following aspects:

- Final mud/cement volumetric fraction.
- Final cement top position.
- Mud channelling.
- Mud cake severity.
- Cement slurry contamination.

Poor centralisation is one of the most detrimental factors in limiting the efficiency of displacement. Without using centralisers, sections of the pipe string in a directional well could touch the wall. Annular flow speed in the narrow side can be distinct from the wide side. Sometimes, the flow speed in the narrow side can be blocked, forming a mud channel. Compatibility is another necessary consideration. Rheological characteristics of the mixture of mud-spacer and cement-spacer at various ratios could be tested following certain recommended procedures, to predict viscous interface behaviours, and avoid unfavourable velocity profiles at the interface. Slurry contamination can also be examined through a compatibility test. In addition, density and rheology of each fluid alone could result in certain shear patterns in the annular clearance and possibly leave mud cakes on the wall, thus reducing the efficiency of mud displacement.

Good displacement efficiency brings in a strong cement bond around the pipe and along the whole cement column. A strong cement bond between pipe and formation is the purpose of the whole job, which provides pressure isolation, prevents leakoff and helps pipe support and protection. Mud channelling and mud cakes must be predicted in time to prevent severe situations that can be expensive to deal with. Generally speaking, the total cost of cementing can reach up to 17% when a squeezing job is needed, compared to 5% when a better job was done in the first place thus squeezing is not required. When real time monitoring and control of fluid displacement under the ground is essentially impossible, prediction based on a reliable modelling is crucial for cost reduction and safety purposes.

Modelling

Producing a theoretical solution of fluid flow and transport in the annulus of variable geometric sections of a directional well is a challenging problem. A finite volume method is used to solve the equations of momentum, continuity and concentration transport. Mud, spacer and cement slurries or others are all modelled as non-Newtonian Hershey-Buckley fluids. Flow path is the eccentric annulus with sections of variable sizes and inclination angles. Flow domain is then discretised into a 3D structured grid as shown in Figure 1.

In the calculation, a velocity profile at each annular cross section is first obtained through a pressure-flow

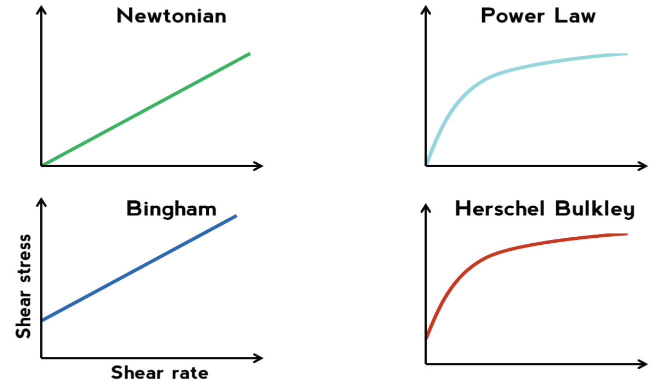

Figure 5. *Rheology models.*

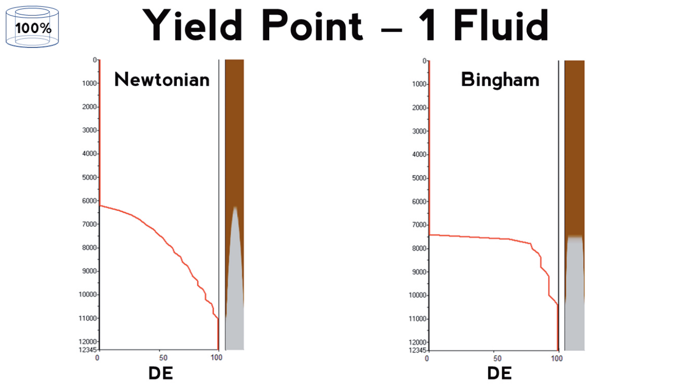

Figure 6. *Single fluid displacement.*

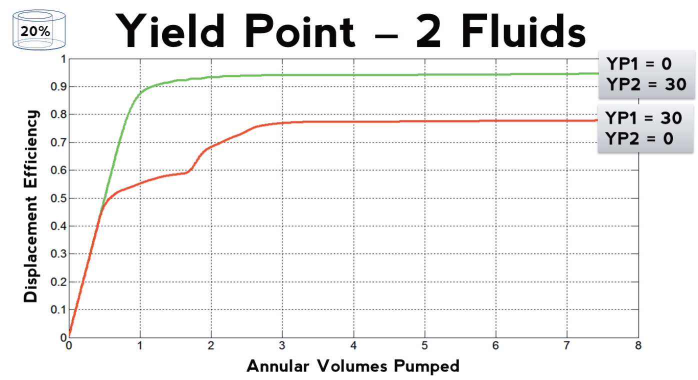

Figure 7. *Displacement efficiency history with different YP.*

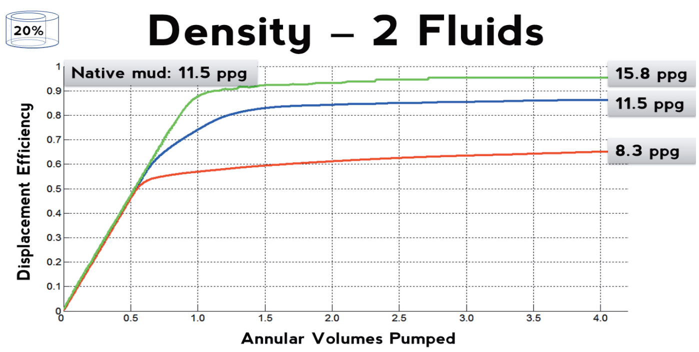

Figure 8. *Effects of density on displacement efficiency.*

rate iterative method. Based on narrow gap flow assumption (parallel slot analogy), the cross section is treated as an unwrapped slot with various widths in the azimuthal dimension, where pressure is uniformly distributed.

Figure 2 shows two examples of velocity profiles computed from this model for an eccentric annulus, which is defined by a 6 in. pipe in a 10 in. hole, with a standoff of 85%. The image on the left is for a Newtonian fluid with viscosity of 24 cP, while the image on the right is for a Bingham plastic fluid with a plastic viscosity (PV) of 24 cp and a yield point (YP) of 4 lb/100ft^2. When the flow rate is at 3 bpm, a faster flow can be observed for both cases. Bingham plastic fluid has a more flat velocity profile.

The azimuthal flow is calculated based on mass conservation. Fluids transport and mixing are considered with a concentration function defined at each cell and for each fluid. Then a volume of fluids (VOF) based method is used to solve fluid species transport. A virtual interface reconstruction is introduced in the solution to suppress axial numerical diffusion.

A common parameter defining the ability of one fluid displacing another is the displacement efficiency, which is the fraction of annular volume occupied by the displacing fluid.

Numerical simulation and experiments have been carried out to examine various factors affecting fluid displacement efficiency in order to determine optimal fluid designs and operating conditions and to guide the field practice.

Displacement efficiency is dramatically affected by flow patterns. After its successful application on real cement jobs, turbulent displacement became widely accepted and a rule called ‘contact time’ was applied, meaning the annular wall requires sufficient time to come into contact with the turbulent displacing fluid. One of the benefits of turbulent flow is that the enhanced mixing and erosion help remove the viscous residue remaining on the wall, especially on the narrow side. Plug flow is also often desired because its solid-like central portion of fluids largely reduces the interface length. It is, therefore, critical to correctly determine the flow regime and solve its velocity profiles respectively.

In this model, flow regime is determined at each depth and each azimuthal location independently by calculating the critical Reynolds number using local rheology, velocity and channel width. For an eccentric annulus, three flow regimes – low flow, laminar and turbulent – can co-exist, which means that mud may be removed effectively on the wide side, while static mud remains on the narrow side, resulting in a channel. It also takes a high flow rate to make all the flow in the annulus turbulent.

Fluid rheology

Rheological properties determine the velocity profile and pressure drop. Figure 5 shows the four models that are commonly used by the oil industry and these are: Newtonian, Bingham plastic, power law, and Hershey Buckley.

Bingham plastic or Hershey Buckley fluids have a YP, which is responsible for the fluid plug when the shear force is not sufficient to cause a velocity gradient with it. Compared to Newtonian fluids this velocity region is usually beneficial for efficient displacement due to the relatively uniform fluid front. As shown in Figure 6, using a fluid with a YP of 32 lb/100 ft^2 makes a relatively flat fluid front compared to the Newtonian fluid, which has a YP of zero.

Simulation tests are run to examine the displacement efficiency of two fluids with different YP values in an annulus of 9.625 in. pipe in 12.25 in. hole for a section of 1000 ft. The first case uses the fluid with YP of 30 lb/100 ft^2 to displace a Newtonian fluid. The second case uses Newtonian fluid to displace Bingham fluid with a YP of 30 lb/100 ft^2. Up to eight times the annular volume of the displacing fluid is pumped in and the history of volumetric displacement efficiency is drawn in Figure 7. The displacement efficiency runs to steady as around two annular volumes are pumped in. The first case is very efficient, reaching over 90% efficiency. The second case is less than 80% efficient.

Effects of density

As shown in Figure 8, using a low density fluid (8.3 ppg) to displace a 11.5 ppg fluid gives a roughly 60% efficiency, while replacing it with a 15.8 ppg fluid causes the efficiency to reach as high as 95%. This simulated result is consistent with previous experience.

Effects of standoff

A well-centralised pipe in a wellbore will lead to a more uniform axial velocity profile and a shorter interface between the displacing and displaced fluids. With poor standoffs in an eccentric annulus, the wall shear stress and frictional pressure drop are lower, which further exacerbates mud removal problems.

Simulating the displacement of four fluids in the annulus (mud, spacer, lead and tail slurry), Figure 9 reveals the 2D unwrapped annular fluid concentration plots for a vertical well under identical fluids and operating conditions, except with different standoffs. Mud channel becomes more severe as the standoff lowers to 50%, when spacer basically flows in the wide side only. Only when the heavy cement slurry enters into the annulus, is the mud channel partially removed. The relationship between displacement efficiency and standoff is generally acknowledged and poor standoff is avoided in practice by installing centralisers.

The fluid interface is uneven not only along azimuthal direction but also across the clearance. The fluid near the wall moves slowly and causes drag on the fast moving centre fluid and induces shears between layers. This velocity profile is parabolic for Newtonian fluid in flat slot and becomes complex in the annulus for non-Newtonian fluids. The process gets further complicated when using fluids with different rheology properties. As shown in Figure 10 the leading edges of the fluids at narrow side fall behind those at wide side. For cases with 70% and 50% standoffs, no spacer is seen at the narrow side since it flows to the wide side, while stronger mixing between fluids is observed.

Effect of hole deviation

High-density fluids are prone to move downward under gravitational force and replace the bottom fluids due to Rayleigh-Taylor instability; thus, they form an elongated interface. A reverse order of fluid density in the annulus (heavy fluid on top of light fluid) will cause poor displacement efficiency. As the incline of the angle increases, the axial component of gravity gets weaker and the transverse component is more likely to cause noticeable effects. Thus the hole deviation could be an important factor in changing the displacement efficiency.

As shown in Figure 11, in an annulus of standoff of 100%, the fluid interfaces are quite flat and smooth for both vertical and horizontal wells. As the standoff gets lower (Figure 12), the efficiencies between the vertical and horizontal wells are more differentiable. In other words, the advantage of a heavy fluid displacing a light fluid is lost in the horizontal well.

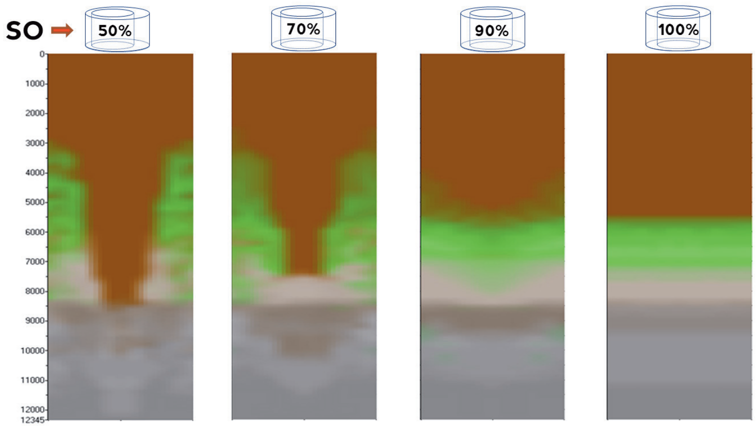

Figure 9. *Fluid distribution in annulus.*

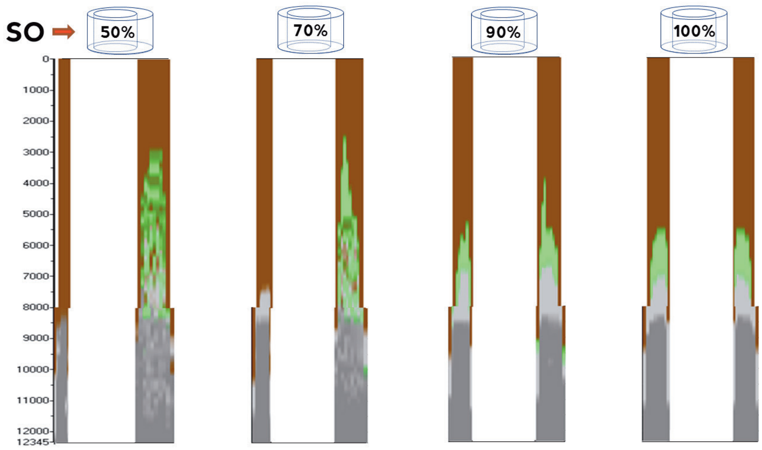

Figure 10. *Fluid distribution at narrow side and wide side.*

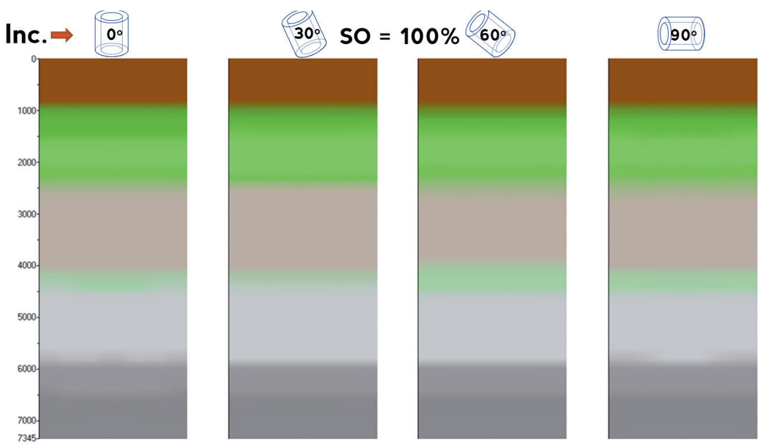

Figure 11. *Mud channelling at various inclination angles (standoff = 100%).*

Casing rotation

Applying a rotation or reciprocation to the casing during displacement is a very efficient way to improve the job quality. Casing movement breaks up areas of stagnant mud, which can cause cement channelling.

Figure 13 gives a comparison of four cases with different rotational speeds. Standoff is 70%. From the simulation result, a slight rotation of 1 rpm clears the mud channel considerably and pulls back the spacer top. Increasing the rotational speed to 10 rpm, the unevenness between narrow and wide side is almost removed, leaving only a slightly wavy interface. A 30 rpm rotation allows for

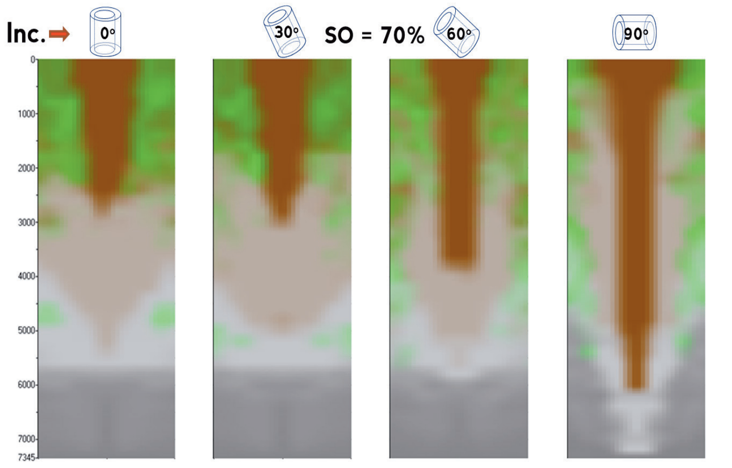

Figure 12. *Mud channelling at various inclination angles (SO = 70%).*

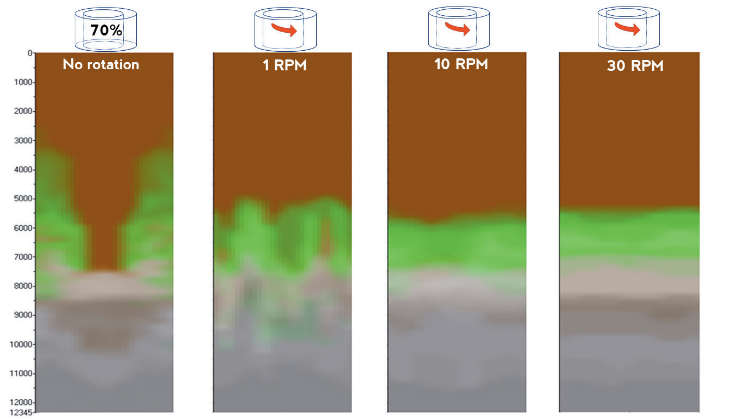

Figure 13. *Effects of casing rotation.*

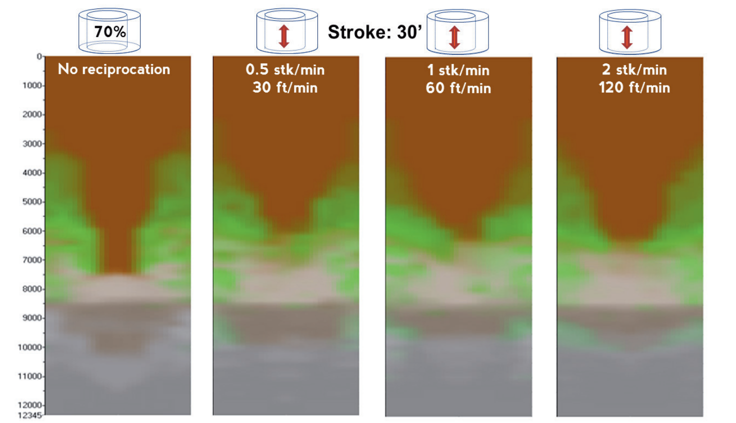

Figure 14. *Effects of casing reciprocation.*

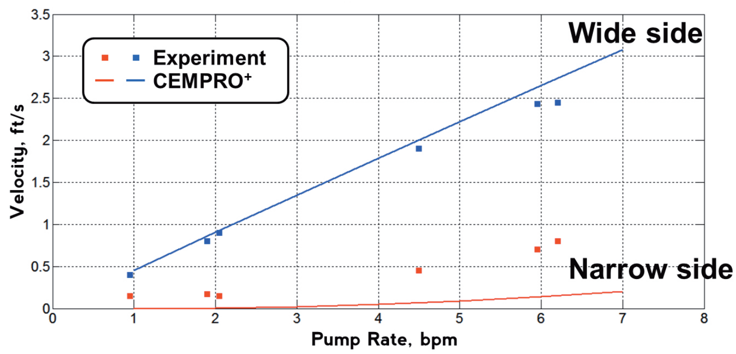

Figure 15. *Comparison of annular velocities in narrow and wide side.*

perfect displacement, nearly as good as achieved with a 100% standoff case.

Movement compensates partially for poorly centralised casing by changing the flow path and allowing the slurry to circulate completely around the pipe.

Mechanical scratchers attached to the casing further enhance the benefits of the pipe movement.

Casing reciprocation

Casing reciprocation produces similar beneficial effects, though not as much as those of rotation. In Figure 14, the stroke length of reciprocation is fixed and the frequency is increased. The improvements are gradual, yet significant enough to implement.

However, reciprocating pipe can induce surge and swab pressures that promote pipe sticking and surface casing-head pressure. This is particularly true when equivalent circulating density (ECD) and fracture pressures are very close, or when shallow gas or water influx is critical.

Validation

The axial velocity profile across the annulus at a given depth is usually the first thing that needs to be found before further details can be uncovered. Even for single fluid flow, this could not be easily addressed with a mathematic approach for an eccentric annulus, due to the complexity of non-Newtonian fluid behaviours. Experiments (SPE 109563) have been carried out to verify the apparent dominance of the wide side flow for a high viscosity fluid (symbols), while the narrow side flow comes at a low speed or even blocked. Numerical simulation was carried out using the same lab data: an annulus of 9.625 in. OD pipe inside a 12.25 in. ID pipe with a standoff of 55%. Fluid is Bingham plastic with a plastic viscosity of 74.5 cP and a YP of 33 lb/100 ft^2.

Figure 15 shows close agreements that are found with current computer modelling. However, current numerical methods are likely to underestimate the narrow side flow velocity (lines).

Conclusion

A computer modelling program designed for a displacement job was developed and produced reasonable results that agree with previous research work and field practice. The program is also further used as a tool to investigate the factors that play important roles in the displacement process through a series of case studies. The 3D model makes it possible to see the condition of the whole wellbore including fluid concentration, velocity profile, flow pattern and more. A quantitative estimate of displacement efficiency is also achievable.

Current studies suggest some field rules. For example, it is almost always worthwhile to employ centralisers to maintain a well centralised casing. One normally uses a high density fluid to displace a low density fluid, utilise turbulent displacement, and apply a viscous fluid with a large YP. This study also uncovered the relation of displacement efficiency to pumping rate, considering the flow transition.

In practice, each job is different and should be carefully designed. Computer modelling prior to the execution could be one of the key elements that contribute to the success of the cementing job. A reliable computer program could save an individual time and money, increase the success rate and reduce non-productive time (NPT).