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A Cross Flow Filtration Process to Manage Fines in Non-Aqueous Drilling Fluids

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Abstract

High concentrations of fines in non-aqueous drilling fluids can adversely impact drilling performance by reducing drilling rates, increasing the equivalent circulating density, and impairing filtration control. When fines concentration increases to the point where the fluid properties are out of specification, the only viable option is dilution, which is expensive and results in buildup of inventory.

A cross flow filtration process for the control of fines in non-aqueous drilling fluids has been developed and tested. The process provided successful results in field trials with used drilling fluids from the Eagle Ford and Haynesville shale plays, recovering up to 70% of the available base fluid. In Canada, the process has also shown reliable and consistent results, with recoveries between 50-60%. Recovered base fluid is completely free of solids and has virgin like quality to be restocked in the base fluid tank.

In the filtration process, the drilling fluid is preheated and fed into a recirculation loop containing the membrane modules. A circulation pump is utilized to achieve the required cross flow velocity, allowing the base fluid to permeate through the membranes. The process is fully automated and requires only minimal operator intervention.

This filtration technology can be used for oil-base (OBM) and synthetic-base (SBM) drilling fluid inventory reduction or as a fluid management practice to maintain the drilling fluid within specifications. When used for inventory reduction, it reduces costs by recovering the maximum volume of base fluid for reuse in the drilling fluid while minimizing environmental impact by decreasing the volume hauled off for disposal.

Introduction

One of the most significant waste streams from oil and gas exploration and development is spent drilling fluids. Existing solids control strategies for removing low gravity solids (LGS) have limitations. One of the challenges is that particles below 5 microns, common cut for a centrifuge, become progressively more difficult to remove. These small particles require an inordinate amount of time and energy to separate from the drilling fluid, and over time, the concentration of LGS increases until mud quality suffers. The most common way to reduce the LGS to levels where they are no longer detrimental to drilling fluid performance is through dilution. Dilution may not be efficient, as the cost of the continuous phase of the fluid (i.e. base oil) is substantial and it results in an increased in inventory.

There is limited data to quantify the costs and benefits associated with strict control of LGS, even though it is well-known that drilling fluids highly contaminated with drilled solids or poor solids control, tend to increase non-productive time (NPT) due to lost circulation, stuck pipe, and other wellbore instability events.

Paiaman et al. (2009) discussed the complications related to a rigorous analysis of drilling rate due to the difficulty of completely isolating the variable under study. Although their study lists several factors affecting rate of penetration (ROP) such as personnel efficiency, rig efficiency, formation characteristics, mechanical factors, and hydraulic factor, their focus was on drilling fluid properties. The evaluation determined that an increase in plastic viscosity (PV), will result in a decreased ROP. In the same manner, the ROP decreased with an increase in mud weight. At constant PV, the penetration rate is decreased by increasing solids content.

Guo et al (2014) analyzed drilling data of around 1,000 wells in the Eagle Ford. The study confirmed the detrimental effects of LGS on drilling operations by comparing OBM with high and low LGS concentrations. Drilling data analysis showed that wells drilled with a high drilled solids concentration (LGS >10%) caused more NPT events and reported three times more stuck pipe and hole pack-off events, compared with wells drilled with a LGS concentration below 10%. The results measured in number of drilling days and drilling fluids cost showed that higher LGS content reduced the drilling efficiency (feet drilled per day) between 14 and 18% and increased the drilling fluids cost per foot up to 23%.

Background

Filtration is a well-studied separation technique where a medium is used to retain undesired material from a flow stream. It can be broadly identified into two classes, dead-end filtration and tangential-flow filtration. The cross flow filtration technology is of the latter class. It utilizes a tubular style membrane module in which feed flows through the tubes, the filtered fluid (permeate) flows perpendicular through the tube membrane walls; the rejected material (retentate) continues to flow out the exit of the membrane module. There are also two broad styles of membrane material in industry, polymeric or organic and inorganic materials of construction. Inorganic membranes can be of ceramic or metallic material and in this application due to oilfield conditions, the membranes are inorganic being comprised of titanium dioxide and stainless steel.

Physical mechanisms of bulk flow filtration are a well-studied phenomena dating back to 1855 with Darcy's Law which describes fluid flow through a semi-permeable barrier. Darcy's Law proportionally relates instantaneous filtration rate $dV(t)/dt$ and permeate flux J (Lmh) of a fluid of apparent viscosity μ through a semi-permeable media which has cross sectional area A_M of and permeability k, to constant differential pressure drop ΔP through differential thickness dz:

$$J = \frac{1}{A_M}\frac{dV(t)}{dt} = -\frac{k}{\mu}\frac{dP}{dz}$$

Flux J, is directly related to superficial velocity u, and Darcy's Law can further be related to tangential flow filtration of fluids with the introduction of characteristic resistances $Ri = \Delta z_i/k_i$ of media in series such as filter cake Rc, membrane media Rm, and substrate media Rs:

$$J = \frac{1}{A_M}\frac{dV(t)}{dt} = \frac{\Delta P}{\mu\,(R_c + R_m + R_s)}$$

In addition to Darcy's Law, the Hagen-Poiseuille Law also applies, directly relating flow velocity v through the pores to transmembrane pressure (TMP) drop when flow is laminar or Reynold's number ($Re=Dv\rho/\mu$) is less than 2,100. This is true in most cases and especially for viscous flow through small pores.

$$v = \frac{D^2}{32\mu L}\,(P_o - P_L)$$

Although the mentioned equations can be used to describe the fluid mechanics of the process, there are additional considerations when examining the boundary layers near the membrane wall. The critical properties driving the filtration process with respect to invert drilling fluids are cross flow velocity and the TMP. The importance of the cross flow velocity is in preventing the drilling fluid from behaving as it does downhole. In downhole conditions, the drilling fluid deposits a filter cake with thickness proportional to the volume of base oil de-fluidized into the formation. This is highly dependent on the permeability of the formation, which is much more permeable in most instances than the permeability of the membranes. The high cross flow velocity of 10-30 ft/sec prevents the static cake from depositing on the membrane surface and instead creates a region off all dynamic filter cake in this boundary layer. Further, the driving force in this region, the TMP can be simplified due to negligible sweep velocity of the permeate fluid (relative to the tube side velocity) and expressed as below:

$$TMP = \frac{P_{in} - P_{out}}{2} - P_{perm}$$

In the expression P_{in} is pressure at the inlet, P_{out} is pressure at the outlet and P_{perm} is the pressure at the permeate outlet of the membrane module.

With respect to the resistances encountered by the base oil in this boundary layer environment containing drilling fluid solids, formation solids, and emulsion brine droplets, the prevailing theory may have been most accurately described by Albert Einstein in his 1905 paper on the theory of Brownian movement. In the publishing, he describes a theory of the diffusion of small spheres in suspension wherein, he states the diffusion coefficient depends primarily on the coefficient of viscosity of the liquid and the particle size. The implications on this theory on the process are profound, as the brine droplets and fine solids are both rejected by the membrane. Thus the smaller size fine solids and brine droplets concentrate near the membrane within the boundary layer and contribute greatly, along with the characteristic resistance of the membrane, to the overall flux defined by Darcy.

Development

A cross flow filtration pilot unit was built to determine the technical feasibility and scale-up potential of the membrane systems to provide a viable technology to treat OBM/SBM spent drilling fluids or reservoir drill-in fluids contaminated with LGS/fines.

The pilot scale studies aimed to identify the temperatures, pressure drops, cross flow velocities, and membrane flux optimization for high recovery of permeate and reduced concentrate volumes.

The design of the pilot unit (Figure 1) was compact, self-contained and included pumps, tanks, piping, fittings, gauges, and controls. Titanium dioxide membranes on sintered stainless steel substrate having a nominal pore size of <0.5 micron were used in the system.

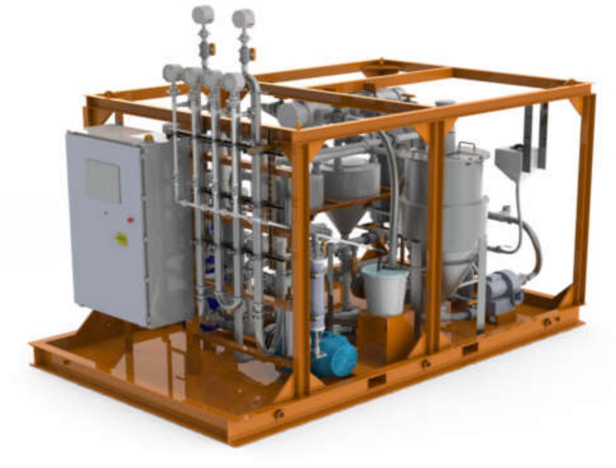


Figure 1. Cross flow filtration pilot unit

Each pilot batch consists of approximately 40 gal of drilling fluid and it is processed between 3 to 4 hours, taking permeate (base fluid recovered) flow measurements every 10 min. The batch is heated to a temperature of 170-190 ˚F and is then processed through the system at a cross flow velocity of <30 ft/sec. Figure 2 shows a simplified process diagram.

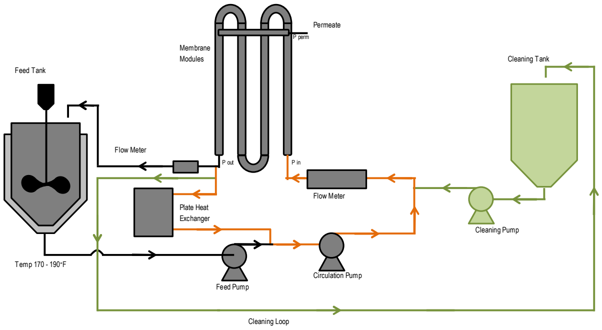


Figure 2. Pilot unit simplified process diagram

Extensive pilot testing with several types of OBM and SBM proved consistency of the treatment process by providing recovered base fluid greater than 50% of available oil in the feed with solids content below 1%.

Figure 3. Feed and recovered base oil sample

Membrane literature discusses the importance of the differential pressure between the inside and outside of the tubular membrane or TMP. Pilot tests were run at controlled high, low, and uncontrolled TMP. Comparing performance, it became evident that processing at unrestricted TMP proved superior due to the dense, viscous, non-Newtonian nature of the feed material.

Early during pilot testing, there was a great deal of effort spent on investigating potential membrane fouling and clean-in-place procedures. It was thought based on literature that the drilling fluid solids could potentially plug the membrane. Over time, it became empirically evident that the membranes reached a steady and repeatable performance level after an initial processing period. By allowing the filtration to proceed to minimal permeation rates, or until a desired recovery was achieved and then changing the feed fluid over to an unprocessed material, permeation rates returned to high levels. The lack of penetrative fouling was additionally proven by membrane autopsy and scanning electron microscopy (SEM).

Presented below are typical permeate flux and oil recovery curves which demonstrate the above lesson learned. Early in processing, permeation rates are high and exponentially decay to what is referred to as an asymptotic flow rate. Processing can continue at this low flow rate until concentration of the feed fluid increases the viscosity to an upper pump limitation. Simply by changing the batch volume to unprocessed fluid, permeation rates return to the previous high level.

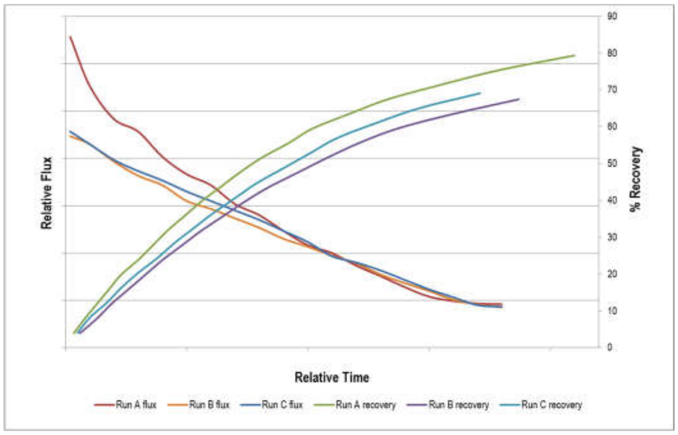


Figure 4. Pilot scale permeation rates and recovery curves

Although initially designed and fabricated to prove the feasibility of the technology, the pilot unit can be utilized as a tool to forecast the performance of the full scale prototype unit on equivalent feed drilling fluid.

Process Description of the Cross Flow Prototype

The cross flow full scale unit consists of two 40 ft ISO skids (feed skid and process skid), with equipment classified as Class I Div 2 and CSA certified. The process runs in a semi-batch mode, with each batch measuring approximately 500 gal. The process is fully automated with each skid containing all required instrumentation to properly monitor and control the process.

The feed skid contains two feed tanks that receive the spent drilling fluid from the storage tank via an auxiliary pump. Two positive displacement feed pumps are used to deliver the heated feed to the process skid at a specified flow rate and pressure. The feed skid is also fitted with a centrifugal pump, used to circulate a mixture of propylene glycol/water through a heater. A plate heat exchanger is also installed in the heating loop. Actuator valves change position according to the corresponding process step.

The process skid contains the main circulation pump providing the required flow rate to achieve the specified cross flow velocity. Permeate is collected on the shell side of the membranes and directed to a temporary storage tank located in the skid, before it is pumped to the corresponding product storage tank.

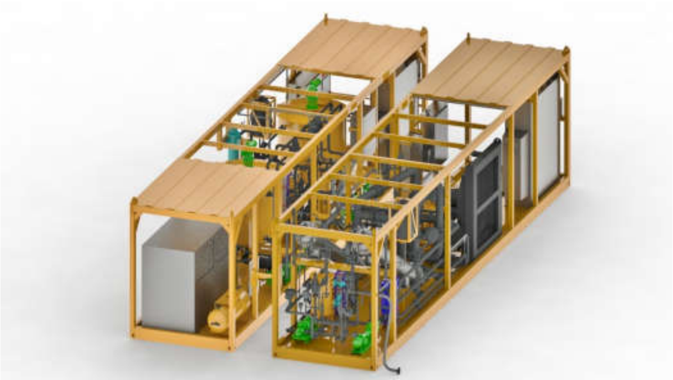


Figure 5. Cross flow filtration prototype unit

The process requires temperature to be efficient, but it also requires temperature control to ensure it operates at temperatures lower than the flash point of the drilling fluid. To achieve this, the process skid is fitted with heat exchangers and a cooling pump. An air cooled radiator rejects system heat to the environment. A chiller further decreases the permeate temperature to a temperature below the base oil’s flash point.

An auxiliary centrifugal pump feeds 500 gal of fluid into the system tanks. Once the first tank fills, the fluid moves through the heat exchanger where it is heated up to a temperature (set in the heater configuration panel) of around 170-190 ˚F. Once reaching the temperature set point, the actuated valves route the fluid in the feed tank to the process skid, which allows the second tank to start filling and heating. The fluid that enters the process skid is pumped to the recirculation loop at the optimum cross flow velocity (given by the circulation pump set point) and the process continues under the specified conditions while producing permeate. As this step continues, the fluid becomes more concentrated with solids and water.

The system now uses the preheated feed in the other tank to displace the retentate in the recirculation loop and membrane modules and route into the tank which was just processed. This is achieved via a volumetric totalizer. A volume equal to the process skid piping and tube side volume of the membrane is pumped as displacement volume.

When the displacement step is completed, the actuated valves direct the fluid from the second feed tank to the process skid and route the remaining retentate from the first tank to the corresponding storage tank. All fluid is drained from this tank. The end of this step, enables the actuated valves to begin filling this tank with fresh feed and the process continues as described above.

Throughout the process, drilling fluid temperature is controlled by an air cooled radiator with a variable frequency drive. The speed of the air cooled radiator depends on ambient temperature conditions. Permeate discharge temperature is also controlled using a motorized refrigeration unit.

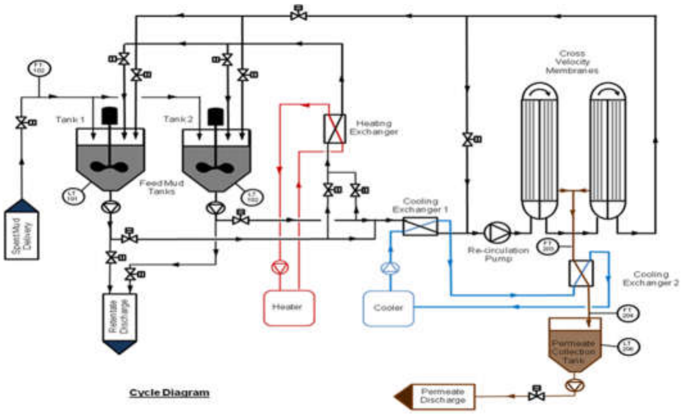


Figure 6. Full scale simplified process flow diagram

Applications

The applications identified for the use of this technology are inventory reduction and fluid and waste management. With regard to inventory reduction, many locations must reduce the drilling fluid inventory due to lack of storage capacity or because the drilling fluid is considered spent due to a high concentration of fines. In most cases, the disposal cost is high, and clients are looking for alternatives to reduce costs while minimizing environmental impact. The goal of inventory reduction is to reduce the drilling fluid inventory using a more economical method than disposal. The cross flow process achieves this by recovering the maximum volume of base fluid for reuse in the drilling fluid, thereby minimizing the inventory write off and the volume hauled off for disposal. Treatment for inventory reduction generally occurs at a drilling fluids processing or storage facility.

The other application is fluid management where the goal is to reduce the concentration of fine LGS without increasing the drilling fluid inventory, thereby ensuring that each hole section can begin with a drilling fluid well within the LGS specification without incurring the added expense of dilution and inventory management. Fluid management can be achieved on weighted drilling fluid systems where viscosity control is a priority and where it is difficult to maintain the required LGS concentration without reverting to dilution. Treatment for fluid management would be at a drilling fluids processing facility or at a drilling pad.

Performance

Performance data collected from field trials in Texas and Oklahoma has shown excellent agreement between pilot and prototype unit – a scale up factor of approximately 40X – when operating with seven different OBM from ongoing drilling operations. No fouling or plugging of membranes was observed over the entire course of testing. Automated control of the batch process was fully demonstrated by the end of the trials.

During trials in Texas, several batches with different properties (oil/water ratio, weight, % solids) of diesel-base drilling fluid were used to evaluate and tune the system and establish the equipment performance by verifying processing rates and base oil recovery. Figure 7 contains information on the properties of the feed drilling fluid and the retentate obtained during this trial.

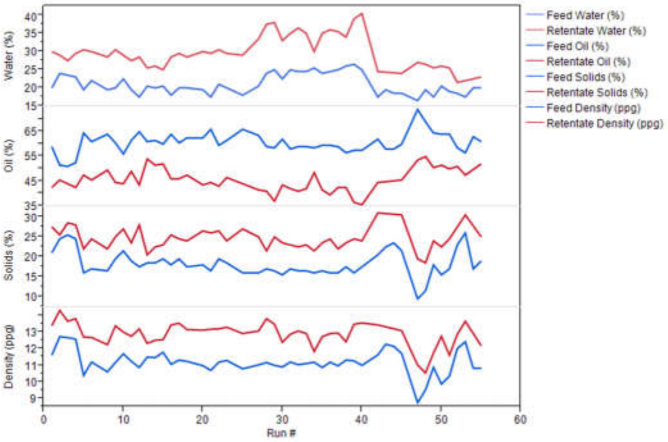


Figure 7. Feed and retentate composition in Texas

The processing rate was determined by the time a batch of 12 bbl will take, depending on the required/expected recovery. The base oil recovery was determined by:

$$R = 100\ \frac{V_p}{F_f V_f}$$

Results obtained from Texas testing (Figure 8) showed repeatable base oil recovery between 50 and 60%.

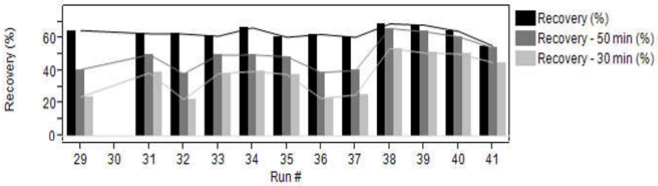


Figure 8. Example of Texas field trial results

To validate the inventory reduction model, fines contaminated diesel-base drilling fluid from the Haynesville shale play was transported to a drilling fluids processing facility in Oklahoma. The feed stock for this inventory reduction was 478 bbl of a 15.2 ppg fluid containing 17% LGS concentration with an oil water ratio of 86:14. Centrifugation was used to reduce the fluid density to 10.2 ppg, removing 100% of the HGS, leaving 272 bbl for processing by the cross flow unit. The centrifuge underflow volume of 206 bbl was returned to the plant as barite slurry to be reused as weight material. Average recovery of diesel in the cross flow feed was 55%, corresponding to 93 bbl. All recovered diesel was returned to the plant for fluid reconstitution and the rejected material was sent for disposal.

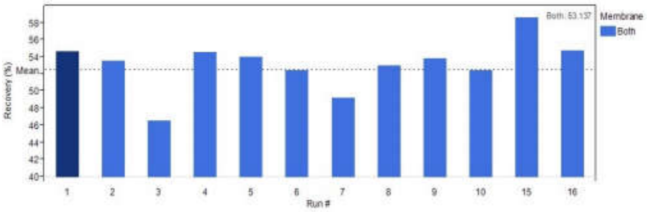


Figure 9. System performance in Oklahoma

There are currently several locations with excess inventory as a result of dilution to control fines, and there is no storage capacity to accommodate the additional volume. In many of these locations the disposal cost is high; not only due to the method used but also to the excessive transportation cost. An example of this situation is in Eastern Canada where disposal costs are high. The cross flow filtration system was used to treat some of this spent mud volume, recovering valuable synthetic base fluid. Waste was reduced by around 30%. Table 1 shows treatment volumes and fluid properties. System performance can be seen in Figure 10 in m^3.

Table 1. Canada fluid properties

Fluid Properties	Unit	Batch 1	Batch 2	Batch 3
Treatment Volume	m^3	220	148	184
Mud Weight	kg/m^3	1,490	1,500	1,370
Oil Content	%v/v	63%	56%	57.5%
HGS Content	%v/v	13%	11%	8.5%
LGS Content	%v/v	9%	12%	10%

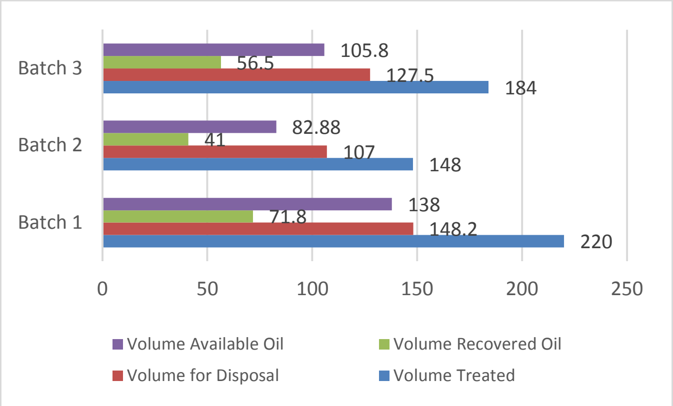
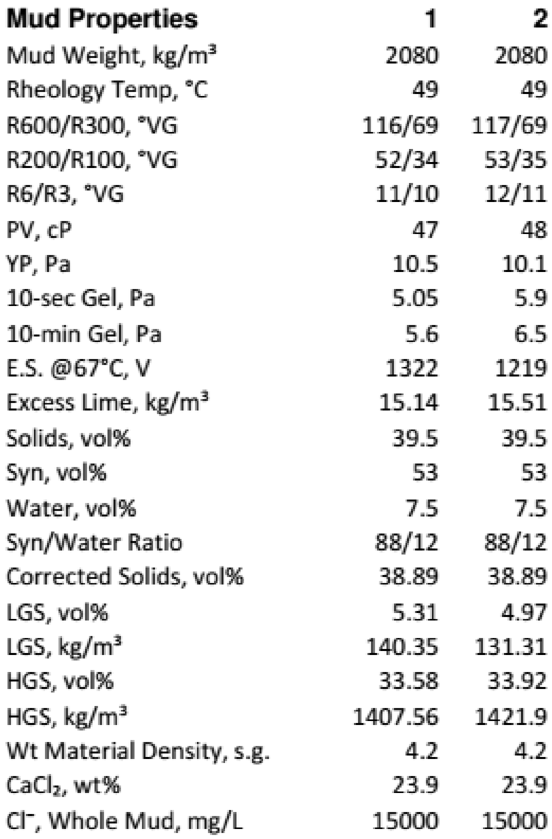


Figure 10. System performance in Canada

The base oil recovered was analyzed using gas chromatography mass spectrometry (GC-MS) and presented the same fingerprint as the one of virgin base fluid. The table below confirms that an SBM built with recovered base oil presents the same properties as one built using virgin base fluid.

Table 2. Drilling fluids properties comparison



Mud Properties	1	2
Mud Weight, kg/m³	2080	2080
Rheology Temp, °C	49	49
R600/R300, °VG	116/69	117/69
R200/R100, °VG	52/34	53/35
R6/R3, °VG	11/10	12/11
PV, cP	47	48
YP, Pa	10.5	10.1
10-sec Gel, Pa	5.05	5.9
10-min Gel, Pa	5.6	6.5
E.S. @67°C, V	1322	1219
Excess Lime, kg/m³	15.14	15.51
Solids, vol%	39.5	39.5
Syn, vol%	53	53
Water, vol%	7.5	7.5
Syn/Water Ratio	88/12	88/12
Corrected Solids, vol%	38.89	38.89
LGS, vol%	5.31	4.97
LGS, kg/m³	140.35	131.31
HGS, vol%	33.58	33.92
HGS, kg/m³	1407.56	1421.9
Wt Material Density, s.g.	4.2	4.2
$CaCl_2$, wt%	23.9	23.9
Cl^-, Whole Mud, mg/L	15000	15000

Conclusions

Cross flow filtration was successfully tested on the treatment of OBM and SBM drilling fluids, obtaining base fluid with no solids or water.

Recovered oil presents the same characteristics as virgin base oil and proves to be suitable for use in new drilling fluid reconstitution.

The cross flow filtration in OBM and SBM is a viable technology to be used for inventory reduction by recovering valuable base fluid and reducing disposal volume or for fluid management by maintaining the fluid under the required LGS specifications.

Processing rates and amount of base oil recovered varies depending on the feed drilling fluid properties. Case studies performed have shown processing rates of approximately 150 bbl/day and base oil recoveries between 50% and 60% of the oil available in the feed fluid.

TMP and the size distribution of fine solids and brine droplets contribute to the resistance to permeate flux and thus the overall filtration performance.

With experience gained through the technology's development, a clean-in-place procedure is not required. Changing the concentrated retentate out for fresh, unprocessed feed, returns system performance to expected permeation rates.

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Nomenclature

F_f = *Concentration of oil in the feed mud volume (%v/v)*
HGS = High Gravity Solids (%v/v)
ISO = International Organization for Standardization
LGS = Low Gravity Solids (%v/v)
NPT = Non-Productive Time
OBM = Oil based mud
SBM = Synthetic based mud
TMP =Transmembrane Pressure (psi)
V_f = *Initial mud (feed) volume (gal)*
V_p = *Volume of permeate recovered (gal)*

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