Design of Gelled Fluid for Debris Removal in Subsea Pipeline

Chaitali Misra, Achala Danait, SPE, and **Lalit Salgaonkar,** SPE, Halliburton

Summary

Transportation of hydrocarbon through a pipeline may be hindered as a result of deposition of debris. The presence of debris within the pipeline leads to reduction in the effective flow area, thus reducing the efficiency of the transportation system. Some of the factors leading to formation of the debris are changes in temperature and/or pressure of the transported fluid and chemical reactions, which occur therein.

Pipeline-maintenance pigging is performed routinely to extend the operational life of pipelines. Recently, a combination of mechanical and chemical remedial measures has shown beneficial results in pipeline cleaning. Mechanical-brush pigs loosen the debris adhering to the walls, while chemical techniques, such as the use of gelled fluids, enhance the carrying capacity and help to transport the loosened debris out of the pipeline.

This paper presents the results of tests conducted to design a fast-breaking gelled fluid for a debris-removal operation in a long, large-diameter subsea pipeline in the Asia Pacific region. In addition to exhibiting good stability and debris-carrying capacity under the laboratory test and field conditions, the gel had to be compatible and demonstrate stability when mixed with other additives in the transported hydrocarbon. A highly viscous, aqueous-based linear polysaccharide gel was designed to satisfy these requirements. A key environmental and operational consideration was the easy and fast disposal of the gel after completion of the cleaning operation. With oxidizing breaker, gels prepared in potable water resulted in viscosity of <10 cp within 2 days, which was significantly shorter than when seawater-based gels were treated similarly. Preliminary field results indicate that the combined mechanical and gel system removed a significant amount of debris. Data from future trials will help evaluate the feasibility of such a technique for effective cleaning of the pipeline.

Introduction

Transport Pipelines and Issues. Pipelines are considered to be the most efficient means of transporting liquid or gaseous hydrocarbons across long distances. At various stages of a pipeline's life, the transportation of hydrocarbon is hindered as a result of deposition of debris formed as a result of several factors, such as changes in the temperature and/or pressure of the transported fluid as it is carried through the pipeline and the chemical reactions that occur therein. The type of debris present is usually a function of the conditions under which the pipeline operates, the property and chemistry of the transported fluid, and the metallurgy of the pipe (Abney and Browne 2006). Depending on the factors causing the formation of the debris, debris deposits can be composed of pipeline-corrosion products; rust; mechanical impurities, such as construction debris; silts; and deposition of organic and inorganic materials. Alteration of the physical and chemical characteristics of the crude oil while being transported can lead to precipitation of organic deposits consisting of paraffin wax and asphaltene. Inorganic scale deposits can be formed as a result of reactions of ions present in the formation water. Gas hydrates (commonly associated with deepwater drilling and production of oil and gas) can be formed during dewatering of gas pipelines, when water and natural gas combine under relatively high pressure and low temperature to form icelike compounds (Schreurs et al. 1994).

The presence of debris along the length of the pipeline leads to a reduction in the effective flow area of the pipeline, thus reducing its efficiency. To maximize the efficiency of the pipeline and lower operating costs, it is important to ensure that pipelines are cleared of such debris.

Pipeline Pigging. Pipeline pigging is a maintenance technique that is routinely used to treat pipelines and extend their operational life. The operational conditions and nature of the debris deposits dictate the types of pigs to be used for pipeline cleaning. Mechanical pigs are effective in removing the debris adhering to the walls of the pipe, but are prone to more wear and tear because they have firm contact with the pipeline wall, thereby allowing more fluid bypass. Gel-pigging technology was developed in the late 1970s as a chemical cleaning method. In addition to performing all the functions of conventional pigs, gel pigs have supplemental chemical capabilities (Uzu et al. 2000). They have been applied widely in pre-operational and operational pipelines to remove accumulated loose and adhering debris and solids, such as silts and formation sands, effectively from the walls of pipelines. Gel pigs have their limitations, and they are generally not suitable for long runs in dry pipelines or pipelines in which the propelling medium is gas because they tend to suffer from "gas cutting" or excessive bypass. "Debris-transport gels" are designed on the basis of the total debris volume in the pipeline; the pipeline diameter; existing flow rate through the pipe; transit time through the pipeline; and certain debris properties, such as mean particle size and specific gravity. Lately, a combination of mechanical and chemical remedial measures has shown beneficial results in pipeline cleaning. Mechanical-brush pigs help to loosen the debris adhering to the walls of the pipeline, while the gelled fluids in gel pigging help to transport this loosened debris.

Background

Mechanical-pigging operations performed on a 24-in. subsea pipeline in the Asia Pacific encountered problems that were attributed to the presence of high amounts of debris in the pipeline. The analysis of the debris revealed that the major portion of the debris was produced sand, which had settled in the pipeline as a result of the low flow velocity, high produced-water cut, and inefficient operational pigging. Foam pigs were launched as an option to try to redistribute the high debris deposits within the pipeline. During this

This paper (SPE 153157) was accepted for presentation at the SPE Oil and Gas India Conference and Exhibition, Mumbai, 28–30 March 2012, and revised for publication. Original manuscript received for review 20 June 2012. Paper peer approved 10 July 2012.

TABLE 1—SYNTHETIC SEAWATER RECIPE			
Order of Mixing	Function	Product	Amount Used
1	Tap water	—	To dissolve and dilute the system to 1 L
2	Sea salt	ASTM D 1141-52	41.953 g

TABLE 2—RECIPE DETAILS FOR GEL XA			
Order of Mixing	Function	Concentration	Amount Used
1	Synthetic seawater	—	1000 mL
2	Bacteria-control agent	0.15 lbm/1,000 gal	0.018 g
3	Iron-sequestering agent	7.8 lbm/1,000 gal	0.94 g
4	pH buffer	12.5 lbm/1,000 gal	1.5 g
5	Gelling agent	Variable (40, 60, and 80 lbm/1,000 gal)	Variable (4.8, 7.2, and 9.6 g)

TABLE 3—RECIPE DETAILS FOR GEL XB			
Order of Mixing	Function	Concentration	Amount Used
1	Synthetic seawater	—	1000 mL
2	Bacteria-control agent	0.15 lbm/1,000 gal	0.018 g
3	Gelling agent*	Variable (40, 60, and 80 lbm/1,000 gal)	Variable (12, 18, and 24 g)

*Gelling agent is an LGC and has 40% by weight of xanthan loading.

operation, various high-pressure spikes were recorded, which resulted in the rupture of the foam pigs.

It was proposed to carry out gel pigging in combination with mechanical pigging for the cleaning operation. It was decided to initiate a laboratory study to design a gel system for this application. Results of the laboratory tests would help the field personnel decide whether to proceed with field trials.

To minimize operational issues during the trials, the following requirements were provided by the field:

- The gel system should be stable enough to effectively suspend the debris while transporting it through the pipeline over the estimated pipeline-transit time of approximately 5 days at an operating temperature of approximately 15°C.
- The gel should have a minimum number of additives, and it should be compatible with additives, such as biocides and pour-point depressants (PPD), present in the pipeline.
- The gel system should be easy to mix or dilute on location with seawater as the base fluid.
- After completion of the cleaning operation, the gel should be broken in a shorter duration of less than 3 days to ensure safe and easy disposal.

Among the various polymers that could be used for the preparation of gelled fluids, xanthan was the preferred choice on the basis of past experience (Scott 1983) and considering its ready availability on location, which would help reduce the time needed to proceed with field trials. The present work details the laboratory studies directed toward optimizing a xanthan-based gel system for the proposed gel-pigging trials.

Experimental Methods

Gel Mixing. Synthetic seawater (ASTM D 1141-52 sea-salt formulation) **(Table 1)** was used as a base fluid for preparation of linear gels. Two different sources of xanthan polymer were used for preparation of the linear gel systems **(Table 2 and 3):**

- Gel XA was prepared using a high-grade xanthan-polymer powder as the gelling agent that could be gelled in a wide range of brines and completion and treatment fluids.
- Gel XB was prepared using an improved xanthan polymer in a liquid/gel concentrate (LGC) form as the gelling agent. The LGC form allowed easy dispersion and hydration of the polymer.

For Gel XA, the pH was adjusted to approximately 7 using an alkaline buffer, while pH adjustment by the addition of external buffer was not required for the hydration of Gel XB.

Bacterial presence in the gel system is known to degrade the polymer and adversely affect the gel integrity. Bacteria-control agents can slow down or mitigate the bacterial-reproduction process. Inclusion of this agent in the recipe was recommended to provide gels that are stable for extended periods of storage.

In the case of Gel XA, an iron-sequestering agent was added to sequester any free iron in the mixing water that could hamper the hydration of the gel. Addition of the iron-sequestering agent caused the pH of the system to drop to 3.5, and, hence, the addition of buffer was necessary to bring the pH back to a neutral value.

After the addition of all the additives, the contents were stirred for approximately 10 minutes in a Waring® blender. A 1-in. vortex was maintained during stirring, while ensuring no air entrapment. After 10 minutes, the gels were kept static for approximately 1 hour

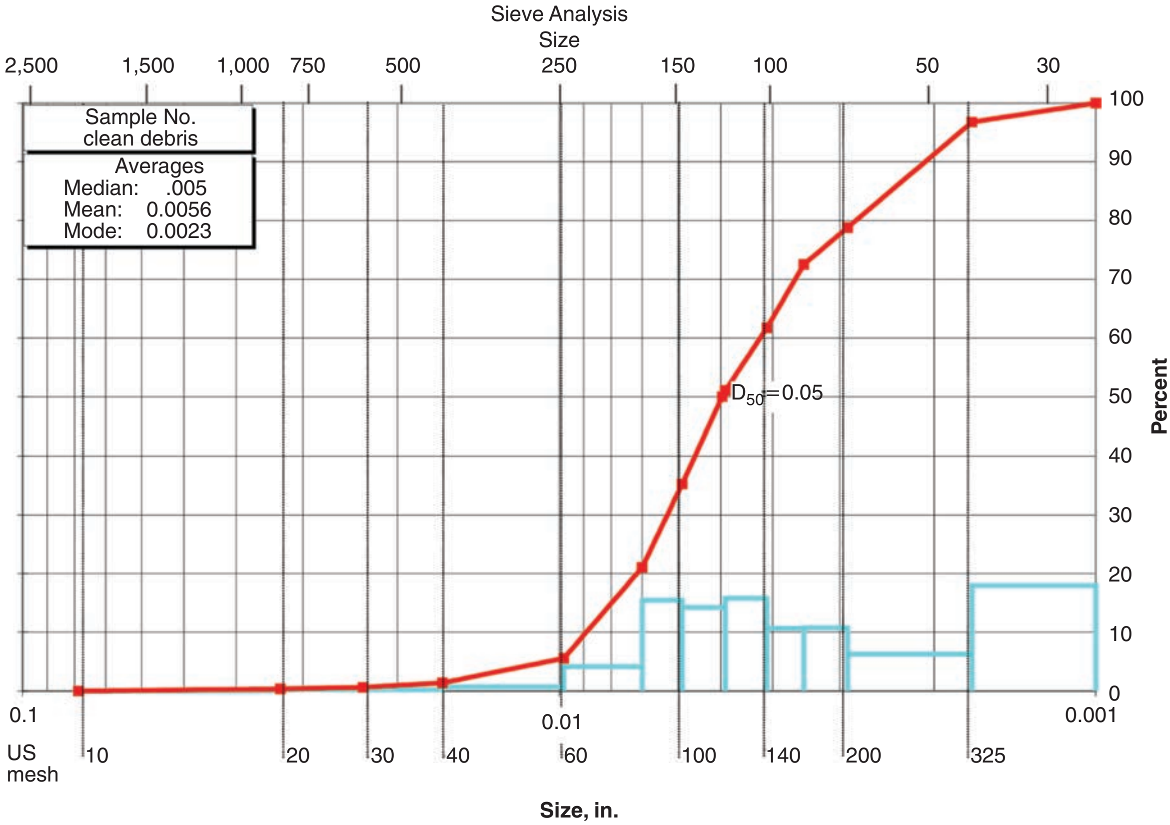

Fig. 1—Sieve analysis of the clean debris.

to ensure complete hydration and then stirred again for 2 minutes to ensure that the hydrated gel was homogeneous.

Debris-Suspension Test. The debris sample collected from the pipeline was a black-colored sludge material coated with an oily layer. The sample was washed with organic solvents to remove the oily layer and dried in an oven, resulting in brown-colored, cleaned debris sand. This brown sand could not be used for the debris-suspension tests because it imparted poor visibility to the gelled fluids. The suspension ability of a gelled fluid depends largely on the particle-size distribution of the debris solids. Hence, sieve analysis of the cleaned debris sand was performed, and it indicated a D_{50} value of 0.005 in. **(Fig. 1).** Therefore, 100-mesh white Oklahoma sand (sieve opening of 0.0058 in. and D_{50} of 0.006 in.) was used to simulate the debris solids in the debris-suspension tests.

The debris-suspension capacity of the individual xanthan gels was studied by suspending 1 lbm/gal of 100-mesh Oklahoma sand in the linear gel that was placed in a constant-temperature water bath maintained at 24°C. Sand settling under static conditions was monitored by visual observations every day for the estimated fluid-transit period of 5 days. Fluids exhibiting stability at 24°C would be expected to exhibit an increased stability at the lower subsea temperature of 15°C. Debris-suspension tests were performed by varying (1) polymer-gel loading and (2) sand loading. The plan was to conduct initial tests under static conditions. The diameter of the pipeline was very large (24 in.), with an expected very low shear rate up to 6 seconds^{-1}. The most-promising results obtained under static conditions would be repeated under dynamic conditions by subjecting the fluid to the expected pipeline shear rate.

TABLE 4—COMPARISON OF DEBRIS SUSPENSION FOR GELS XA AND XB AT VARIOUS GEL LOADINGS UNDER STATIC CONDITIONS AT 24°C

Gel System	Sand Loading Used (lbm/gal)	Gel Loading Used (lbm/1,000 gal)	Day 1	Day 2	Day 3	Day 4	Day 5
	1	40	P	F	F	F	F
XA	1	60	P	P	O	F	F
	1	80	P	P	P	P	P
	1	40	P	F	F	F	F
XB	1	60	P	P	P	P	P
	1	80	P	P	P	P	P

P=sand is suspended.
F=sand settled completely.
O=sand settling started or is partially suspended.

TABLE 5—MAXIMUM DEBRIS-CARRYING-CAPACITY TESTS FOR GEL XA UNDER STATIC CONDITIONS AT 24°C

Gel System	Gel Loading Used (lbm/1,000 gal)	Sand Loading Used (lbm/gal)	Day 1	Day 2	Day 3	Day 4	Day 5
XA	80	1.0	P	P	P	P	P
		2.0	P	P	P	O	O
		4.0	P	P	P	O	O
		6.0	P	P	F	F	F
		8.0	P	F	F	F	F
		10.0	P	F	F	F	F

P= sand is suspended.
F= sand settled completely.
O= sand settling started or is partially suspended.

Compatibility Test. Additives like PPD and biocides were being routinely injected into the pipeline. Hence, compatibility tests of the gelled fluids with these additives were conducted to ensure that the additives would not render the gel unstable during the pigging operation. Required amounts of the individual additives were mixed with the linear gel and observed for any signs of incompatibility.

Breaker Test. Various breaker systems were tested to break the gel during the post-pigging operation. The required amount of the individual breaker chemical was added to the optimized linear-gel system and placed in a constant-temperature water bath maintained at 24°C. After every 24 hours, the apparent viscosity of the recipe was measured at 511 sec^{-1} shear rate.

Results and Discussion

Debris-Suspension Test. Selection of a gel for gel-pigging operations depends on its ability to transport and suspend the debris solids. Therefore, it is essential to monitor the debris-suspension ability of any proposed gel-pigging fluid for the estimated transit time in the pipeline.

Debris-suspension tests under static conditions were carried out with varying concentrations (40, 60, and 80 lbm/1,000 gal, respectively) of the gelled fluids XA and XB. After adding 1.0 lbm/gal (120 kg/m^3) of 100-mesh Oklahoma sand, the sand-laden gelled fluids were monitored daily for 5 days **(Table 4).** A polymer loading of 40 lbm/1,000 gal exhibited poor suspension characteristics in both fluids, XA and XB (Table 4). A minimum of 80 lbm/1,000 gal polymer loading for gelled fluid XA and 60 lbm/1,000 gal polymer loading for gelled fluid XB was essential to suspend the sand effectively for 5 days under static conditions.

To be more cost effective, it is preferred to use a linear gel that can transport the maximum anticipated concentration of debris. Hence, debris-suspension tests were carried out using varying sand loadings from 1.0 lbm/gal (120 kg/m^3) to 10 lbm/gal (1200 kg/m^3) in both fluids XA and XB. On the basis of the results obtained in previous debris-suspension tests (Table 4), a polymer loading of

TABLE 6—MAXIMUM DEBRIS-CARRYING-CAPACITY TESTS FOR GEL XB UNDER STATIC CONDITIONS AT 24°C

Gel System	Gel Loading Used (lbm/1,000 gal)	Sand Loading Used (lbm/gal)	Day 1	Day 2	Day 3	Day 4	Day 5
XB	60	1.0	P	P	P	P	P
		2.0	P	P	P	P	O
		4.0	P	P	O	O	O
		6.0	P	P	F	F	F
		8.0	P	F	F	F	F
		10.0	P	F	F	F	F
	80	1.0	P	P	P	P	P
		2.0	P	P	P	P	P
		4.0	P	P	P	O	O
		6.0	P	P	P	F	F
		8.0	P	F	F	F	F
		10.0	P	F	F	F	F

P= sand is suspended.
F= sand settled completely.
O= sand settling started or is partially suspended.

(a) (b)

Fig. 2—(a) Static sand-suspension test after 5 days and (b) dynamic sand-suspension test under constant shear of 5.1 sec^{-1} after 5 days.

80 lbm/1,000 gal in the case of Gel XA and 60 and 80 lbm/1,000 gal, respectively, in the case of Gel XB was used for these tests **(Tables 5 and 6).**

From the preceding debris-suspension tests, linear-gel XB was the preferred choice because it demonstrated a higher degree of stability over five days. An optimum concentration of 80 lbm/1,000 gal was chosen on the basis of the ability of the fluid to suspend debris (at a maximum concentration of 2 lbm/gal) throughout the entire test duration.

Compatibility Test. PPDs are polymers that are designed to control paraffin-wax-crystal formation in oils and lubricants, resulting in a lower pour point and improved low-temperature flow performance. In subsea pipelines, there is a higher probability of wax deposition because of the low temperatures encountered. Hence, PPDs are typically injected into the pipeline to inhibit paraffin deposition. In the present case, PPD (P-1) was injected at a concentration of 75 to 120 ppm. Therefore, compatibility testing of the optimized linear-gel XB (80 lbm/1,000 gal) was carried out with P-1. The gel was mixed with 100- and 200-ppm concentrations of the PPD and observed over a period of 5 days. No incompatibility was observed during the entire test period.

Debris accumulated over a period of many years would be expected to have a large anaerobic bacterial population. Anaerobic bacteria do not pose a major problem to gelled fluids but lead to contamination in the wellbore or the producing formation, leading to hydrogen-sulfide-gas production. Linear-gel XB (80 lbm/1,000 gal) was mixed with a 500-ppm concentration of the biocide B-2 and observed for a period of 5 days. No incompatibility was observed during the entire period.

Feasibility Studies for Field Application. Gel-pigging operations require handling large volumes of gelled fluids on location. This task could be made easier if gel concentrates are prepared and diluted as per requirement. To investigate this, gel concentrates with 120 and 240 lbm/1,000 gal of Gel XB, respectively, were prepared. These highly viscous fluids could be diluted easily to the desired 80 lbm/1,000 gal fluid for gel-pigging operations.

The gel system was expected to encounter a very low shear of up to 6 seconds^{-1} when flowing through a large 24-in. diameter pipeline. Hence, it was important to ensure that the gel remained stable throughout the 5 days under the expected low-shear rate. To investigate this in the laboratory, 80 lbm/1,000 gal of linear-gel XB was prepared in seawater and 2.0 lbm/gal of 100-mesh Oklahoma sand was mixed. The slurry was stirred under continuous shear of 5.1 seconds^{-1} (which is the lowest shear achievable under the given laboratory conditions). To evaluate the effect of low shear on the debris-suspension properties of the gelled fluid, a visual comparison was made of the sand-laden fluid on day five under static and dynamic conditions **(Figs. 2a and 2b).** Even after 5 days, no settling of sand was observed at the bottom of the jar. This demonstrated the effectiveness of the gelled fluid to suspend debris for a period of 5 days under dynamic conditions.

Selection of Breaker Type and Concentration. After a successful pigging operation, the gel and the debris would be transported through the pipeline and, subsequently, collected in a tank at the other end of the pipeline. For effective and safe disposal of the gel in a very short time, it was necessary for the gel to be broken to an apparent viscosity of $<$10 cp. Xanthan gel has excellent stability over a wide pH and temperature range, and the polysaccharide is comparatively resistant to enzymatic degradation. The most commonly used breakers for polysaccharides are oxidizers. Hence, identifying a breaker that could break a high-polymer-loading xanthan gel in the short time span of 1 to 3 days at a low temperature of 24°C was an important task.

Various breaker options were tested with gels prepared in seawater **(Table 7).** Enzyme breaker ENZ-1 was unable to break the 80 lbm/1,000 gal Gel XB hydrated in seawater effectively. The minimum viscosity achieved was 62 cp at 300 rev/min after 3 days. Tests with OXD-1, an oxidizing breaker, also did not yield encouraging results. The lowest viscosity that could be obtained with 12.8% (v/v) OXD-1 was approximately 42 cp at 300 rev/min after 3 days.

The break tests with OXD-1 were repeated with gels prepared in tap water **(Table 8).** Compared with seawater, the gel prepared in tap water exhibited a much-lower viscosity of 31 cp with 12.8% (v/v) OXD-1 after 3 days. This demonstrated that faster break times could be obtained using tap water. Increasing the OXD-1 concentration to 25% (v/v) helped to achieve the desired break and a vis-

TABLE 7—BREAK-TEST DATA FOR 80 lbm/1,000 gal GEL XB HYDRATED IN SEAWATER AT 24°C

Breaker Recipe	Apparent Viscosity Measured at 300 rev/min on Fann-35 Viscometer, cp (hour)
5 ppt ENZ-1	64 (72)
10 ppt ENZ-1	62 (72)
6.4% (v/v) OXD-1	56 (72)
12.8% (v/v) OXD-1	42 (72)

TABLE 8—BREAK-TEST DATA FOR 80 lbm/1,000 gal XANTHAN GEL XB HYDRATED IN TAP WATER AT 24°C	
Breaker Recipe	Apparent Viscosity Measured at 300 rev/min on Fann-35 Viscometer, cp (hour)
12.8% (v/v) OXD-1	31 (72)
25% (v/v) OXD-1	5 (42)
AP-1 (Peroxide:TM:chelant ratio 1:1:1)	15 (72)
AP-2 (Peroxide:TM:chelant ratio 1:1:6)	9 (72)
Note: TM implies transition-metal source molecule.	

cosity of <10 cp in the short time of less than 2 days. Tests with a three-component-activated-peroxide system (AP-1 and AP-2) were also conducted. A viscosity of 9 cp was achieved in 3 days. However, the three-component-activated-peroxide system would be cumbersome to use in the field; therefore, the single-component OXD-1 was preferred.

Further, because desired short break times could not be achieved using seawater-based gelled fluids, it was proposed to dilute the debris-laden gelled fluids with tap water before injecting the breaker. Using a strong oxidizer, such as 25% (v/v) OXD-1, helped in breaking the xanthan gel completely (<10 cp) in a short time span of 42 hours. This fast break time would enable faster disposal of the broken fluid and, hence, would be more feasible onsite.

Field Trials

Field trials were conducted on the pipeline using Gel XB as a debris pick-up gel in conjunction with mechanical pigging. The removal of appreciable quantities of debris validated the effectiveness of the 80-lbm/1,000-gal xanthan as a debris pick-up gel. This further highlights the benefits of using a combination of mechanical- and gel-pigging techniques for pipeline cleaning.

Conclusions

From the extensive laboratory tests carried out, the following conclusions were made:

- Debris-suspension tests indicated that 80 lbm/1,000 gal of a xanthan fluid was effective as a debris pick-up gel for the present application.
- The gel system was effective in suspending 2 lbm/gal debris throughout the pipeline's transit time under an expected low shear of up to 6 seconds^{-1}.
- The gel system was compatible with additives, such as biocide and PPD, which were being injected routinely into the pipeline.
- The gel system was easy to mix on location. If required, a gel concentrate could be prepared and diluted as necessary, thus requiring minimum storage space and providing easy handling.
- Oxidizer breakers were effective in providing short break times when diluted with tap water compared with seawater, ensuring safe and easy disposal of collected debris-laden gelled fluids.

Acknowledgments

The authors would like to thank the management of Halliburton for permission to present this work. They also thank Giselle Braganza for her invaluable input.

References

Abney, L. and Browne, A. 2006. An Integrated Approach to Combating Flow Assurance Problems. Presented at the SPE Bergen One-Day Seminar, Bergen, Norway, 18 April.

Schreurs, G., Burman, P., Hamid, S. et al. 1994. Development Of Gel Systems For Pipeline Dewatering And Drying Applications. Presented at the Offshore Technology Conference, Houston, 2 May–5 May. OTC-7577-MS. http://dx.doi.org/10.4043/7577-MS.

Scott, P.R. 1983. System for removing debris from pipelines. US Patent No. 4,416,703.

Uzu, O., Napier, R., and Ngwuobia, K. 2000. Gel Pig Technology Applications in Pipeline Servicing. Presented at the Nigerian Annual International Conference and Exhibition, Abuja, Nigeria, 7–9 August. SPE-66068-MS. http://dx.doi.org/10.2118/66068-MS.

Chaitali Misra began her career as an application engineer in production enhancement at the Halliburton Technology Center, Pune, India in June 2007, and then became the Technical Professional for the Production Enhancement Team, providing technical services to the Eastern Hemisphere, before moving to her current position. Misra holds an MS degree in environmental and water resources engineering from the Indian Institute of Technology, Madras, Chennai, India.

Achala Danait is the Technology Leader for the Production Enhancement team at the Halliburton Technology Center in Pune, India, where she has been since 2007. She began her career in academics as an assistant professor in polymer chemistry and also worked on government-sponsored research projects. After 9 years in academics, she moved to Sudarshan Chemical Industries Ltd. and worked as a senior manager (R&D) for 5 yrs, during which time she was involved in conducting research on phthalocyanine pigments. Danait holds a PhD degree in polymer chemistry from the Indian Institute of Technology, Mumbai.

Lalit Salgaonkar is a Principal Scientist at the Halliburton Technology Center in Pune, India, having worked on various projects in the fracturing/acidizing/sand-control side of the Production Enhancement service line. He began his career in research and development (R&D) in the field of hard-core synthetic organic chemistry. After working for 2 years in the R&D setting, he moved to Halliburton in 2007 and, since then, has been a part of the Technical Services team, which provides expertise and technical solutions to various Halliburton locations in the Eastern Hemisphere. Salgaonkar holds a PhD degree in organic chemistry from the Institute of Chemical Technology, Mumbai.