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CEMENT-LINED PIPES FOR WATER LUBRICATED TRANSPORT OF HEAVY OIL

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Abstract—This paper presents different strategies for preventing oil from fouling the walls of core–annular flow pipelines and also for restart from an unexpected pipeline shut-down. The most promising of these strategies is to use cement-lined pipes. Experiments presented here show that hydrated cement-lined pipes are highly oleophobic and therefore resist fouling for long term. A pilot scale cement-lined core–annular flow pipeline using No. 6 fuel oil never fouled in over 1000 h of operation. Repeated and determined attempts to soil properly hydrated cement-lined pipes with heavy Venezuelan crudes always failed.

Key Words: core–annular flow, oil fouling, cement-lined pipes, heavy crude oils.

1. INTRODUCTION

Water-lubricated transport of heavy viscous oils is a technology based on a gift of nature in which the water migrates into the region of high shear at the wall of the pipe where it lubricates the flow. Since the pumping pressures are balanced by wall shear stresses in the water, the lubricated flows require pressures comparable to pumping water alone at the same throughput, independent of the viscosity of the oil (if it is large enough). Hence savings of the order of the viscosity ratio can be achieved in lubricated flows. Oil companies have had an intermittent interest in the technology of water-lubricated transport of heavy oil since 1906 (Isaacs & Speed 1904). Heavy crudes are very viscous and somewhat lighter than water, though crudes heavier than water do exist. Typical crudes might have a viscosity of 100 Pa·s and a density of 990 kg/m^3 at 25°C. Light oils with viscosities of less than 0.5 Pa·s do not give rise to stable lubricated flows, unless they are processed into water–oil emulsions and stiffened. Stable lubricated flows are usually called core–annular flow or CAF for short.

The science behind the technology of CAF has given rise to a large literature which has been reviewed recently by Joseph & Renardy (1992) and Ho & Li (1994). This literature has many facets which include different models for levitation (see Oliemans & Ooms 1986 and Bai *et al.* 1996) empirical correlations giving the pressure drop versus mass flux in laminar and turbulent flows (Arney *et al.* 1993; Huang *et al.* 1994), classification of flow types (Charles *et al.* 1961; Bai *et al.* 1992), stability studies (see Joseph & Renardy 1992 for a review of all studies) and reports of industrial experience.

The most important commercial line to date was the 15 cm diameter, 38 km long Shell line from the North Midway Sunset Reservoir near Bakersfield, California, to central facilities at Ten Section. The line was run under the supervision of Veet Kruka for 12 years from 1970 until the Ten Section facility was closed. When lubricated with water at a volume flow rate 30% of the total, the pressure drop varied between 6200 and 7600 kPa at a flow rate of 5000 m^3/day with the larger pressure at a threshold of unacceptability which called for pigging. In the sixth year of operation the fresh water was replaced with water produced at the well site which contained various natural chemicals leached from the reservoir, including 0.6 wt% sodium *m*-silicate. After that, the pressure

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drop never varied much from the acceptable 6200 kPa value and the CAF was stable as long as the flow velocity was at least 0.9 m/s.

Even though lubricated flows are hydrodynamically stable, oil can foul the wall. This is an adhesion rather than a hydrodynamic effect and is not taken into account in the equations used to study stability. The hydrodynamic stability of lubricated flow is very robust even when oil wets the wall. A water annulus can lubricate an oil core even in a pipe whose walls are completely dirty with oil. Sometimes, however, the fouling builds up leading to rapidly increasing pressure drops and even blocks the flow. For example, figure 1 shows an experiment with Zuata crude oil (density = 996 kg/m^3, viscosity = 115 Pa·s at 25°C) from the Orinoco belt being pumped through a 20 cm i.d., 1 km pipeline operated by INTEVEP S.A. and located in San Tome, Venezuela. When the input fraction was 4% water and the superficial oil velocity was 1.5 m/s the pressure gradient increased monotonically from 200 up to 1200 kPa due to the gradual fouling of the pipes. If allowed to continue, the Zuata would have completely fouled and blocked the pipeline.

The experiments in Venezuela also showed that oil fouled some places more than others, near pumping stations where the pressure is highest and the holdup and core wave structure are developing and around line irregularities such as unions, bends, flanges and curves. Another major problem is an unexpected shut-down in the line; the oil and water stratify, causing the oil to stick to the pipe wall, making it harder to restart the line.

It is desirable to lubricate the oil core with as little water as possible because a small water input alleviates the problem of dewatering. On the other hand, oil is more likely to foul the pipe wall when a small amount of water is used, so it is desirable to suppress fouling.

2. REMEDIAL STRATEGIES

Remedial strategies to prevent fouling naturally alter the adhesive properties of the wall which depend on the solid surface and the oil used. The different strategies that have been tried were

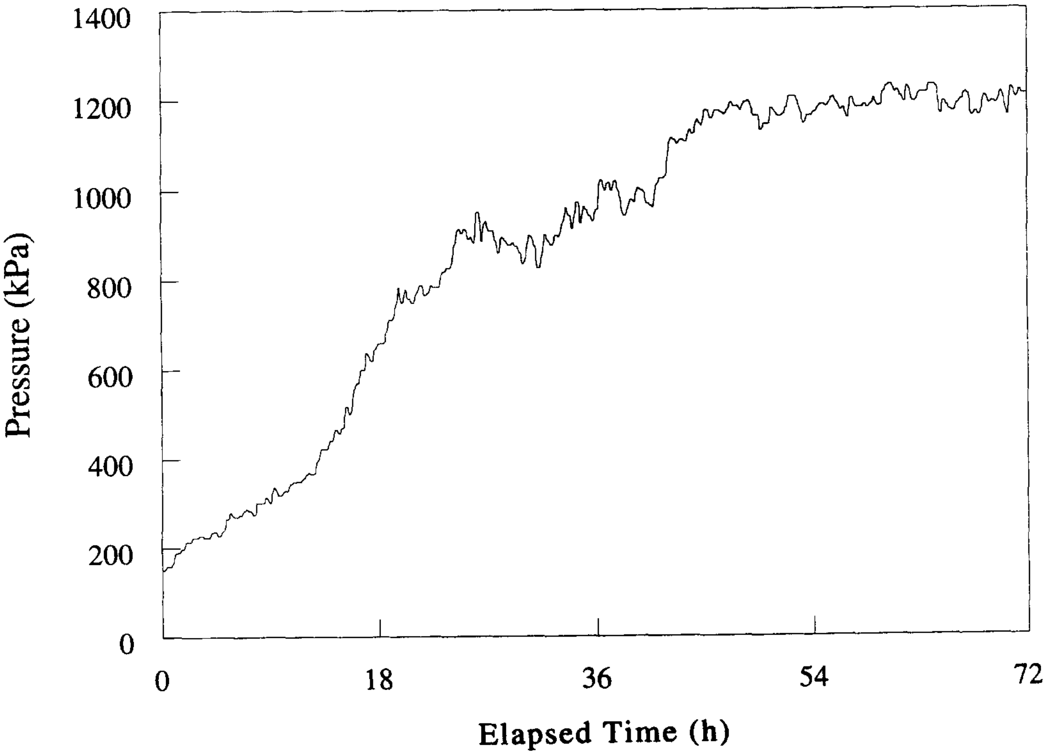

Figure 1. Fouling of the INTEVEP test loop with Zuata crude. Water input fraction = 4%, superficial oil velocity = 1.5 m/s. Pressure losses increase monotonically as the pipeline fouls. High blockage was experienced after 2.5 days of operation.

discussed by Arney (1994), Ribeiro (1994) and Ribeiro *et al.* (1996) and only the most relevant will be mentioned below.

It is well known that the addition of sodium *m*-silicate in the water will inhibit fouling of carbon steel pipes. It does so by increasing the negative charge density of the steel surface through the adsorption of SiO_3^{-2} ions. But the flowing water constantly washes the silicate ions from the steel pipe walls, so a continuous supply is needed. The continuous addition of sodium *m*-silicate did not completely suppress the fouling of Maraven's 54 km San Diego–Budare line by Zuata crude. Sodium *m*-silicate also helps to make normally hydrophobic quartz glass surfaces hydrophilic. Although the effect lasts longer on glass than carbon steel, it does not appear to be permanent. A very substantial increase in the hydrophilicity of quartz can be achieved by hydration in sodium *m*-silicate and a surface gel may actually form there. Desirable aggregates in mortars of portland cement are mainly quartz or silicates so that these treatments should be studied further.

Other chemical treatments which were studied and made normally hydrophobic walls hydrophilic either lead to undesirable emulsification (polymers) or do not prevent fouling by Zuata. Hydration in sodium *o*-silicate promotes rather than prevents fouling.

Excellent, and apparently permanent, oleophobicity can be obtained in materials that can be processed to form strongly hydrophilic gels at the surface. Two such gelling materials were found: a sulfonated ABS plastic (say, Cycolac®) and some ordinary mortars of portland cement hydrated in a low concentration of sodium *m*-silicate solution (say 0.5–1%). The oleophobic and hydrophilic properties of the sulfonated plastics are remarkable (the plastic becomes durably wet after immersion in water and oil will not stick) but the use of such plastics in lubricated lines is problematic because they are too expensive and probably too fragile for pipeline applications.

It is well known that mortars of portland cement form strongly hydrophilic calcium silicate hydrate gels (C–S–H) naturally while curing. The addition of small amounts of sodium *m*-silicate appears to promote the calcium–silicate composition that renders the gel more hydrophilic. The oleophobic properties of the C–S–H gels are persistent but may slowly degrade due to slow changes in composition when immersed in fresh water. The hydrophilic properties of a degraded gel can be restored by recharging the mortar in a sodium *m*-silicate solution.

The idea of using cement-lined pipes to remediate the fouling of pipes in water-lubricated lines of heavy oil is due to D. D. Joseph and is specified in a list of claims by Rivero *et al.* (1994). Though the hydrophilic properties of C–S–H gels in cements are well known (but not well understood) the oleophobic and anti-fouling properties of wet cements seem to have been first studied in the recent experiments in Minnesota and INTEVEP S.A. to which we have just alluded. We are searching for compositions and treatments for optimal anti-fouling cements.

At present, it appears that cement linings offer a practical solution to the problem of fouling because they not only have good oleophobic properties but are commercially available at prices not greatly in excess of unlined pipes. The results given below show that, in any event, lined pipes work perfectly in test situations and that even the restart problem may be remediated by wet cement linings.

3. EMPTYING TESTS FOLLOWING STRATIFICATION (STARTUP)

The most severe fouling occurs when the pipeline is unexpectedly shut down for a period of time. These shut-downs can occur for a variety of reasons (for example, the power service to one or more of the pumping stations can be interrupted). In this case, lighter than water–oil rises and sticks to the top of the pipe. If the pipeline is horizontal, the oil rises leaving the bottom of the pipe free of oil. In this case restart is not a severe problem; as the pressure is increased, a single bump or wave forms at the pipe entrance where the pressure is highest. This bump partially blocks the flow increasing the local pressure at the front face. This local high pressure moves the bump forward and forces the water to move circumferentially, peeling the oil off the wall in an unzipping operation as the bump is pushed forward. Restart is accomplished by this kind of natural pigging. But, if the pipe is on an incline, the oil rises to the crest and completely blocks the flow (figure 2). In this case, the only way to remove the oil is to apply pressurized water and wait for it to finger through and remove the clog. All restart procedures are greatly benefited by remedies which reduce adhesion.

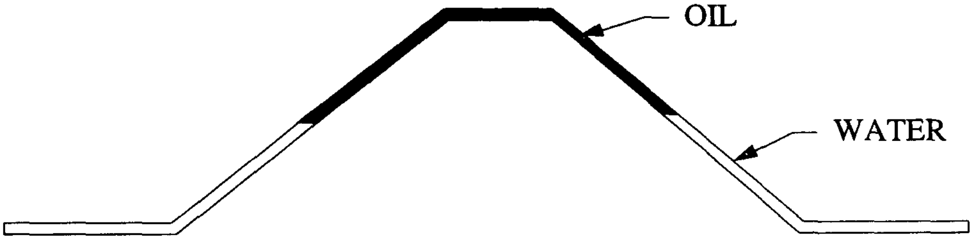

Figure 2. Oil–water stratification in a stopped pipeline going up and down a hill. The viscous crude oil rises to the crest completely blocking the flow.

In this section we report results of experiments designed to test anti-fouling in the situation where the oil and water stratify. Emptying tests were performed in both vertical and horizontal pipes. Two heavy crude oils from Venezuela were used for these tests: Cerro Negro Despojado (CND) and Zuata. At 25°C, the viscosity and density of CND and Zuata are 1290 Pa·s and 1009 kg/m^3 and 115 Pa·s and 996 kg/m^3, respectively.

3.1. *Preliminary tests*

We performed a number of preliminary tests in which commercial surfactants were applied to steel surfaces, both at ambient and warm (65°C) temperatures. In addition, oil emptying tests were performed on short horizontal cement tubes. Commercial surfactants successfully prevented CND from fouling steel plates at ambient temperatures. Otherwise, carbon steel always fouled with oil. In addition, surfactants had no apparent effect on Zuata crude oil. By contrast, short cement tubes never fouled. These preliminary tests motivated the present work and an entire line of investigation into the optimal composition of cement to prevent fouling (Ribeiro *et al.* 1996) and the investigations reported below.

3.2. *Emptying tests of crude oil in short pipes*

In these tests, we observed how strongly the oil adhered to a pipe wall. Different pipes were first hydrated and then filled with equal amounts of Zuata crude oil and water. The filled pipes were stored in a vertical position for a long time before emptying. These tests simulate the conditions after an emergency pipeline shut-down, followed by a prolonged down-time. In such situations, the water (heavier than oil) drains to the bottom of the pipe and the oil floats to the top as shown in figure 3.

We performed these tests on carbon steel, galvanized steel and cement-lined pipes. The cement pipes (Cement Lining Co., Houston, TX) were lined by spin-coating following the ANSI-AWWA C205-89 standards. The carbon steel and galvanized steel pipes are standard commercial pipes. Each pipe had a 5 cm i.d. and was cut into three sections of 60 cm length.

For each material, one piece was soaked in water and two pieces were soaked in 1 wt% aqueous sodium *m*-silicate for 1 week, so that the inner walls of each pipe were thoroughly hydrated. After this, the pipes which were soaked in water were filled with a 50% oil–water mixture. The pipes which were soaked in sodium *m*-silicate were filled with either a 50% oil–water mixture or with a 50% oil–49.5% water–0.5% sodium *m*-silicate mixture, according to table 1. The pipes were filled by adding successively small amounts of water (or sodium silicate solution, if the case) and oil. The pipes were capped at the ends and placed in the vertical position (figure 3). The oil rose and completely filled the upper half of the pipes. After standing for 6 days, we opened the pipes by removing the top cap, inclining the pipes about 20° from the horizontal and opening the bottom cap. The results are described below, and summarized in table 1.

3.2.1. Cement-lined pipes. Although the oil completely filled the top half of the pipe, we could see that the cement walls were still wet with water. When the pipes were emptied into a beaker, the oil discharged as a plug lubricated by water. All three cement-lined pipes emptied in the same way. All cement surfaces appeared to be generally clean [see figure 4(a)] after emptying. However, the final results were different for each pipe.

The pipe which was soaked in water was clean with the exception of one spot about 1 cm^2 in

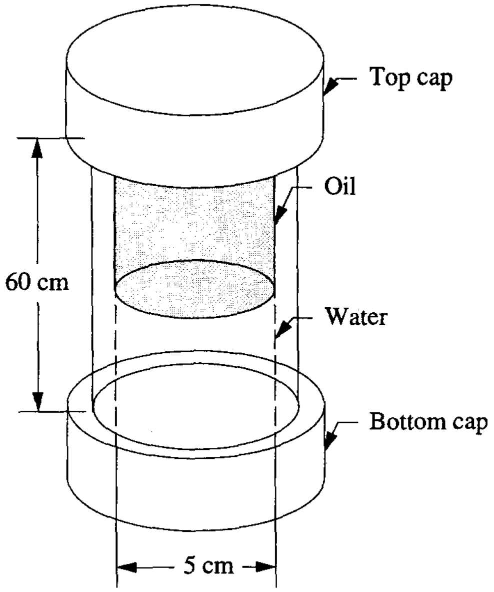

Figure 3. In this emptying test, the pipe is hydrated for a week. Then, over 50% of the pipe is filled with oil, the rest water. The pipe is covered with its axis aligned with gravity for 6 days. Then it is opened, emptied and inspected. This test simulates an unexpected pipeline shut-down in inclined pipes.

size, close to the top edge of the pipe. This oil spot could not be completely removed by running tap water.

The pipes hydrated in sodium *m*-silicate were easily cleaned. Spots which were not removed by gravity were rinsed away with slowly running tap water. However, oil which penetrated a crack in the cement surface could not be completely removed with rapidly running tap water [see figure 4(b)].

3.2.2. Galvanized steel pipes. Unlike the cement pipes, none of these pipes emptied immediately; at first the oil slowly trickled out, followed by a rapid discharge of water, which penetrated through the oil mass. In all cases, some spotting occurred in the region close to the top of the pipe, with spot sizes typically 10–40 cm^2. We were not able, in any case, to completely remove all the oil spots with running tap water. However, pipes which were hydrated and treated with sodium *m*-silicate could be partially rinsed. Galvanized pipes did not resist fouling as well as the cement-lined pipes, but were decidedly less fouled than carbon steel pipes (see figure 5).

3.2.3. Carbon steel pipes. Carbon steel pipes emptied in the same way as galvanized steel pipes. Heavy fouling of carbon steel pipes occurred in nearly every place touched by oil. Figure 6 shows

Table 1. Results of emptying tests in short pipes. Cement-lined pipes fouled less than steel pipe and carbon steel fouled more than galvanized steel sodium *m*-silicate reduced fouling in all cases

Pipe material	Hydrating solution	Testing solution	Results after emptying†	Results after rinsing†	Comments
Cement-lined	water	Zuata + water	LF	NF	one small oil spot
	1% sodium silicate	Zuata + water	LF	NF	some oil inside a crack
	1% sodium silicate	Zuata + 1% sodium silicate	LF	NF	perfectly clean after rinsing
Galvanized steel	water	Zuata + water	MF	MF	large oil spots
	1% sodium silicate	Zuata + water	MF	MF	large oil spots
	1% sodium silicate	Zuata + 1% sodium silicate	MF	LF	imperfectly clean
Carbon steel	water	Zuata + water	HF	HF	completely fouled
	1% sodium silicate	Zuata + water	HF	HF	completely fouled
	1% sodium silicate	Zuata + 1% sodium silicate	HF	HF	heavily fouled. Clean channel on bottom of pipe

†NF = no fouling; LF = light fouling; MF = moderate fouling; HF = heavy fouling.

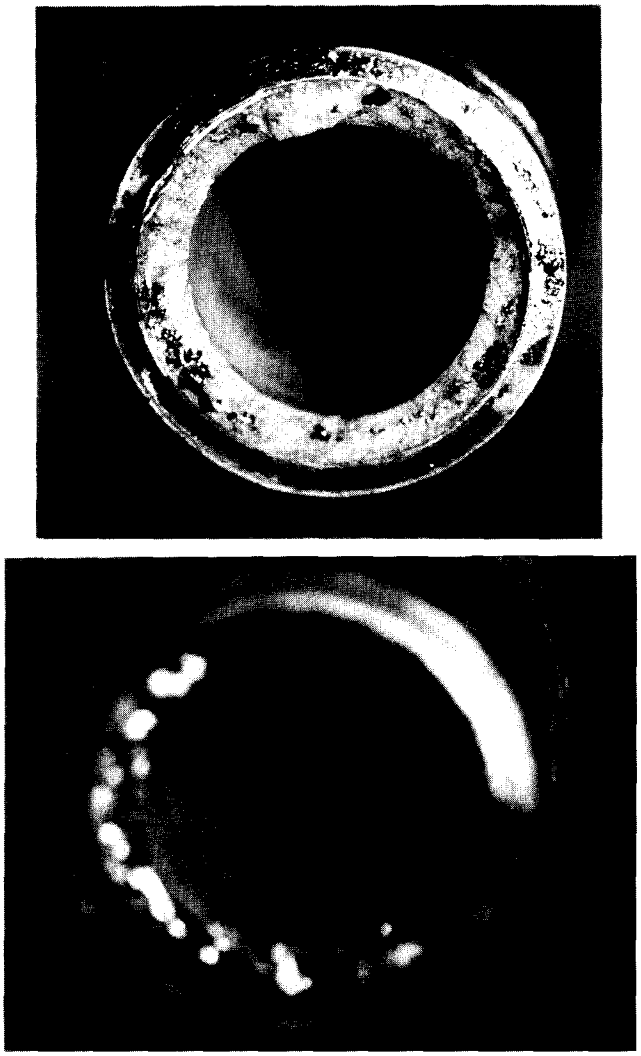

Figure 4. (a, b). Results from emptying tests on vertical cement pipes. Crude oil fills a crack in the pipe wall. Otherwise, the pipe is completely clean.

the oil dripping from the fouled pipe after all water was gone. Oil fouling the carbon steel pipe walls could not be rinsed.

Table 1 summarizes the overall results of the emptying tests using pipes of different materials. Aside from these findings, it is important to acknowledge that the oil spots in the galvanized pipes were confined to the top edges of the pipes where the pipe wall may have dried due to drainage. The spots at the top edge of the pipes might also be a consequence of the mechanisms by which galvanized pipes interact with a water–oil system.

3.3. Emptying tests in longer vertical pipes

We did the emptying tests in longer pipes to learn something about scale-up and the effects on fouling of oil over water under slightly heavier static pressure. Five centimeter diameter cement-lined pipe, 4.8 m long was selected from the same stock as the previously mentioned 60 cm long pipe. It was placed in a vertical position and hydrated with aqueous 1% sodium *m*-silicate solution for 6 days. The pipe was loaded with water and Zuata crude at a ratio of about 1:1. After 6 days, the pipe was emptied, following the procedure of section 3.2.

Unlike the experiments in short pipes the oil did not discharge as a lubricated plug; a thin streak of oil fouled the length of pipe previously occupied by oil, the pipe walls were moderately fouled, with most of the fouling concentrated along the oil streak. Some of the oil spots could be rinsed

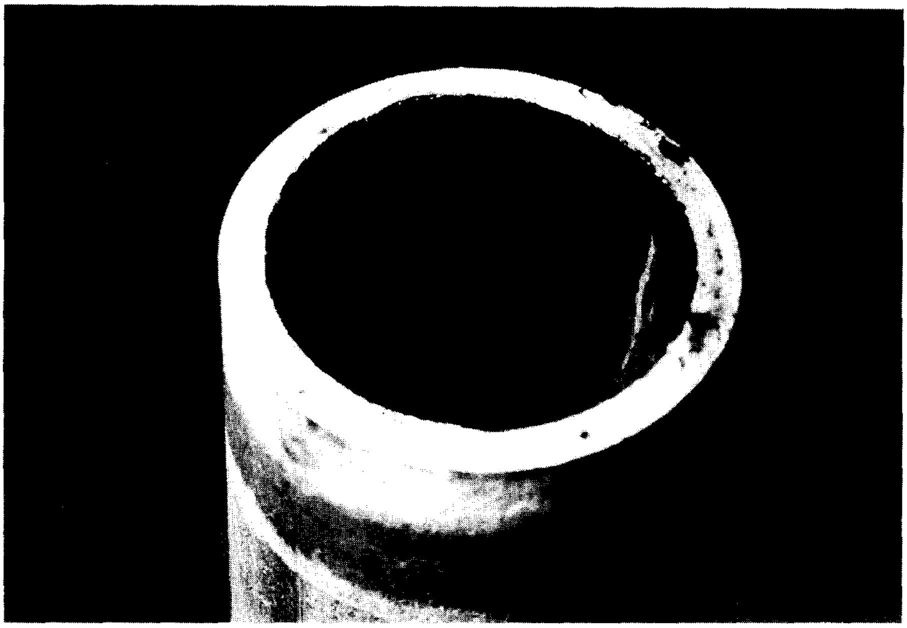

Figure 5. Galvanized steel partly fouled with oil. Large portions of pipe are clean.

from the pipe walls, but the streak could not be cleaned. To explain this fouling, we observe that the filling process consumed 2 h, during which time the pipe wall may have dried. Also, the pipe was tilted while being loaded so that the oil sheared against one side of the pipe and possibly caused the streak. We think that the pipe fouled because of our pipe loading procedure. Nevertheless, the results are mentioned here to alert future workers of the need to keep the cement pipe walls wet.

The previous experiment was repeated and expanded. Two more 3.6 m long test sections were cut from a similar 5 cm i.d. cement-lined pipe. The filling procedure was redesigned to better simulate the conditions of an actual pipeline shut-down in which the pipe walls are always wet. This time, after the pipes were chemically hydrated (as discussed below), they were completely filled with water. Then, the water was slowly drained from the bottom cap while oil was simultaneously

Figure 6. Carbon and steel pipe. The entire pipe is heavily fouled.

added through the top, until both pipes were filled with a 1:1 ratio of water and Zuata. By using this procedure, we are certain that the pipe wall never dried.

We repeated the previous experiment with one of the pipe sections. It was hydrated in sodium *m*-silicate for 10 days, then filled using the above procedure, and stratified under gravity for an additional 10 days. Then, the pipe was placed in the inclined position to be emptied. The cap at the oil end was removed, while the water-side end cap was kept in place. At first, the oil trickled out as if sticking to the wall. When the water-side end cap was removed, the oil discharged as a lubricated plug followed by the water, as in the short pipe experiment. Some spots of oil were on the pipe wall, but they were readily washed away with running tap water. A video showing this experiment is available from the authors upon request.

A new hydration method was tried on the second section. Ribeiro *et al.* (1996), have shown that the calcium silicate hydrate gel at a cement surface absorbs water and prevents fouling. This gel can be enhanced by soaking the cement pipe first in an aqueous calcium chloride solution, then in a sodium *m*-silicate solution. The pipe was soaked with a 2% calcium chloride solution for 5 days, and then refilled and soaked with a 1% sodium *m*-silicate solution for 5 more days. After the 10 days the pipe was loaded following the previously mentioned procedure, and left to stratify under gravity for 10 more days. The pipe then emptied as before with the oil rapidly discharging as a lubricated plug and after rinsing, the pipe walls were completely free of oil.

4. PIPELINE TESTS

In emptying experiments, the forces which promote adhesion operate for a long time. Pipeline tests of fouling were carried out in a pilot-scale core–annular flow pipeline for extended periods of time. The aim of these experiments was to study fouling under operating conditions and also to compare the performance of steel and cement-lined pipes.

In each experiment, the flow rate was controlled and the pressure drops measured. The pipes' performance was evaluated by following the friction factor as a function of time. The friction factor is defined in Arney *et al.* (1993) as:

$$f = \frac{2\Delta P D_2}{\rho_c L V^2}$$

where ΔP is the pressure drop over length L, D_2 is the pipe diameter, $\rho_c = \eta^2\rho_o + (1 - \eta^2)\rho_w$ is the composite density, ρ_o and ρ_w are the oil and water densities, $\eta = D_1/D_2$, $D_1$is the average core diameter, $V = 4(Q_o + Q_w)/\pi D_2^2$ is the average velocity, Q_o and Q_w are the oil and water volume flow rates, respectively. η can be obtained from the hold-up correlations given in Arney *et al.* (1993). The Reynolds number was defined as $\mathrm{Re} = \rho_c V D_2[1 - \eta^4(m - 1)]/\mu_w$, where $m = \mu_w/\mu_o$ and μ_w and μ_o are the water and oil viscosities.

4.1. Apparatus

We constructed a closed-loop continuous operation horizontal core–annular flow pipeline shown in figure 7. The oil and water are both stored in the 900 l tank and are separated by gravity. A positive displacement (Moyno) pump draws the oil from the upper part of the tank, passes it through a micro motion direct mass flow meter, to the injection nozzle and into the test pipes. The oil flow rate is controlled either by varying the pump speed or by manipulating the bypass valves. The water is drawn from the bottom of the tank, filtered, pressurized with a centrifugal pump and then passed through a rotameter and into the injection nozzle. The oil and water then flow in a core–annular configuration through the two test sections. With this serial design feature, different pipes can be simultaneously compared, if desired. A glass J-tube is placed after test section 1 and serves to return the flow without oil fouling at the 180° turn and also provides a means for visualization. Similarly, a short glass pipe is placed after test section 2 for flow visualization. Pressure measurements were done with inverted water manometers. The pressure taps were drilled into the bottom of each pipe so as to avoid their fouling for as long as possible. In this manner, the overall system pressure can be monitored, as well as the hydraulic head loss through the whole pipeline. Both the oil and water are returned to the supply tank where they are separated and

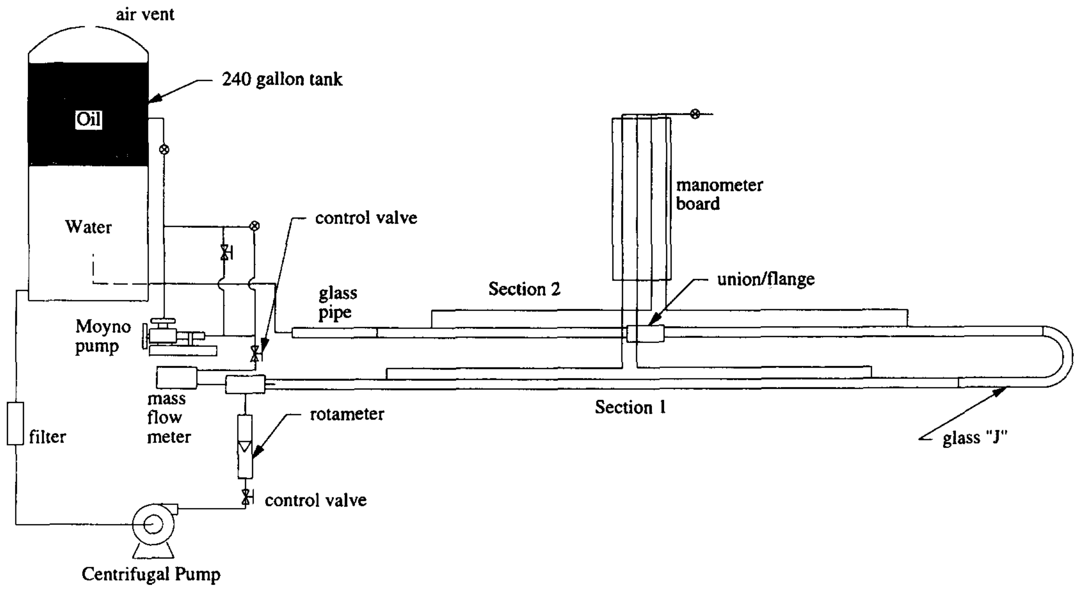

Figure 7. Diagram of the pilot pipeline featuring continuous operation and changeåble test sections.

reused. Critical dimensions for the different pipes are shown in table 2. The cement-lined pipe was always filled with a 1% sodium silicate–water solution when it was in storage and washed before installed. Fuel oil No. 6 (density = 900 kg/m^3, viscosity = 2 Pa·s) and water were used in all experiments. Fuel oil No. 6 does not adhere to steel surfaces as much as Zuata, but Zuata and water have nearly the same density and are not easily separated under gravity. In this sense, the pipeline tests are not as severe as the emptying tests.

4.2. *Galvanized steel versus cement-lined pipes*

In our first experiment, we put the cement-lined pipe in test section 1 and placed two new galvanized steel pipes connected with a union in test section 2. Both test sections were then filled with water and allowed to stand for more than a day. We ran the pipeline using an input fraction of 65% oil, with an overall average Reynolds number of 5800, and recorded the pressure for more than 24 h. No big changes in pressure were observed in either pipe. After the test, the pipeline was flushed with water and disassembled. Neither the galvanized steel nor the cement pipes were fouled by No. 6 fuel oil. However, galvanized pipes were fouled by Zuata in emptying tests, even when hydrated in sodium silicate. Galvanized steel pipes are not fouled by some oils and therefore can be used in some situations.

4.3. *Carbon steel versus cement-lined*

Two carbon steel pipes were placed in test section 1 which is just after the injection nozzle, and a cement-lined pipe was placed in test section 2. The steel pipes were connected with a union. As

Table 2. Dimensions of the different pipes used in pipeline experiments

Pipe material	Diameter (cm)	Length of the section (m)	Distance between pressure taps (m)	Pipe connection
Cement-lined	2.45	6.31	3.47 or 4.00†	none
Galvanized steel	2.43	2 pieces @ 3.07	3.28	union
Carbon steel I	2.65	2 pieces @ 3.19	3.47	union or flange
Carbon steel II	2.64	6.27	4.00	none

†We used 3.47 m in the tests against galvanized steel and carbon steel pipe I and 4.00 m in the tests against carbon steel II.

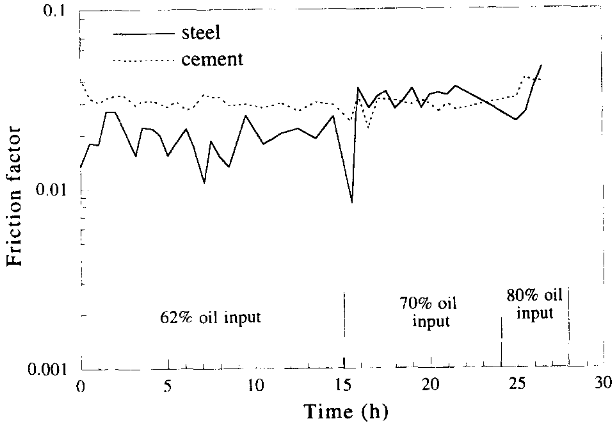

Figure 8. Friction factor vs cumulative time for cement-lined and steel pipes. Frictional losses are steady for the cement-lined pipe, but are erratic and increasing in the carbon steel pipe, indicating the accumulation of oil on the steel surface.

in the previous experiment, both pipes were filled with water and allowed to stand for more than 24 h before running the experiment with a 90% oil input at an average Reynolds number of 2800. Fifteen minutes later, the oil completely clogged the pressure taps on the steel pipe. After flushing the pipeline with water and dismantling, we found that the steel pipes were heavily fouled, but the cement-lined pipe was clean.

The carbon steel pipe was scrubbed with detergent and water until visibly clean, then thoroughly flushed with water and dried. In the next experiment we reversed the position of the test sections, putting the cement-lined pipe into test section 1 just after the nozzle where the tendency to foul is greatest. Again, both pipes were hydrated with water for more than 24 h. Then, we started the flow and measured pressure gradients for an input fraction of 65% and a Reynolds number of 5500. No appreciable change in the pressure gradient was observed for 15 h. The input fraction was then changed to 70% oil and the flow was maintained at Reynolds number of 4600 for 9 h. We noticed a gradual rise in the pressure gradient for the steel pipeline and a marked rise in the static pressure of the system. The rise in the static pressure is due to the formation of clots in the steel pipe after the last pressure tap. We finally increased the input fraction to 80% oil and measured pressure as a function of time for 2 more hours, when heavy fouling of the pressure taps in the steel pipe forced us to stop the line.

The results for this last test can be seen in figure 8, which shows the friction factor versus cumulative time. It clearly displays the difference between the steel and cement-lined pipes. Generally, the friction factor for the steel pipe is always rising and is very scattered. The most dramatic change is the steep rise of the friction factor when operating at 80% oil input. On the other hand, the friction factor in the cement-lined pipe was steady.

After the test was finished, we disassembled the pipes and photographed the inside walls. These are shown in figure 9. The steel pipe is completely fouled on all of its surface, with particularly heavy fouling just after the union. The cement-lined pipe was not fouled; the few oil spots that appeared were at the very end of the pipe around the connection between the pipe and the glass J-tube. These spots could be readily washed away with running water. Comparing this experiment to the previous one, it seems that the steel pipe fouls much more slowly when placed away from the nozzle. However, we must note that for the previous experiment, where the steel pipe was adjacent to the injection nozzle, we started right away with a 90% oil input, and the steel line fouled in 15 min. In the present case, where the cement-lined pipe came after the nozzle, we started with 65% oil input, increased to 70% and then to 80%. Two hours after the final increase, pressure taps fouled in the steel pipes.

It is important to mention that the friction factor for cement is generally larger because the cement walls are rough. In single fluid flow systems, cement-lined pipes exhibit a friction factor which is twice that for smooth pipes. When using pipes with larger diameters the effects of roughness will be significantly diminished.

4.4. A brief experiment with a flanged pipe

In the previous experiment, heavy fouling was observed around the threaded union in the steel pipes. The union creates a gap between the two pipe sections, which actively promotes fouling. In an attempt to eliminate this gap, we instead placed a flange between the two sections. The flange allowed the two pipe sections to be closer, but not perfectly butted together, since it requires a 2 mm thick gasket. The two carbon steel sections were thoroughly cleaned with detergent and water; the pipeline was reassembled and hydrated in water for a day.

We started the experiment with 80% oil input ratio and after 5 h we stopped the line and disassembled the pipes. We discovered that the flanges had initiated fouling. In fact, heavy fouling was observed for about 30 cm after the flange. The rest of the steel pipe was spotted with oil (the cement-lined pipe was clean).

We learn from this experiment that junctions between pipe sections can create bad fouling

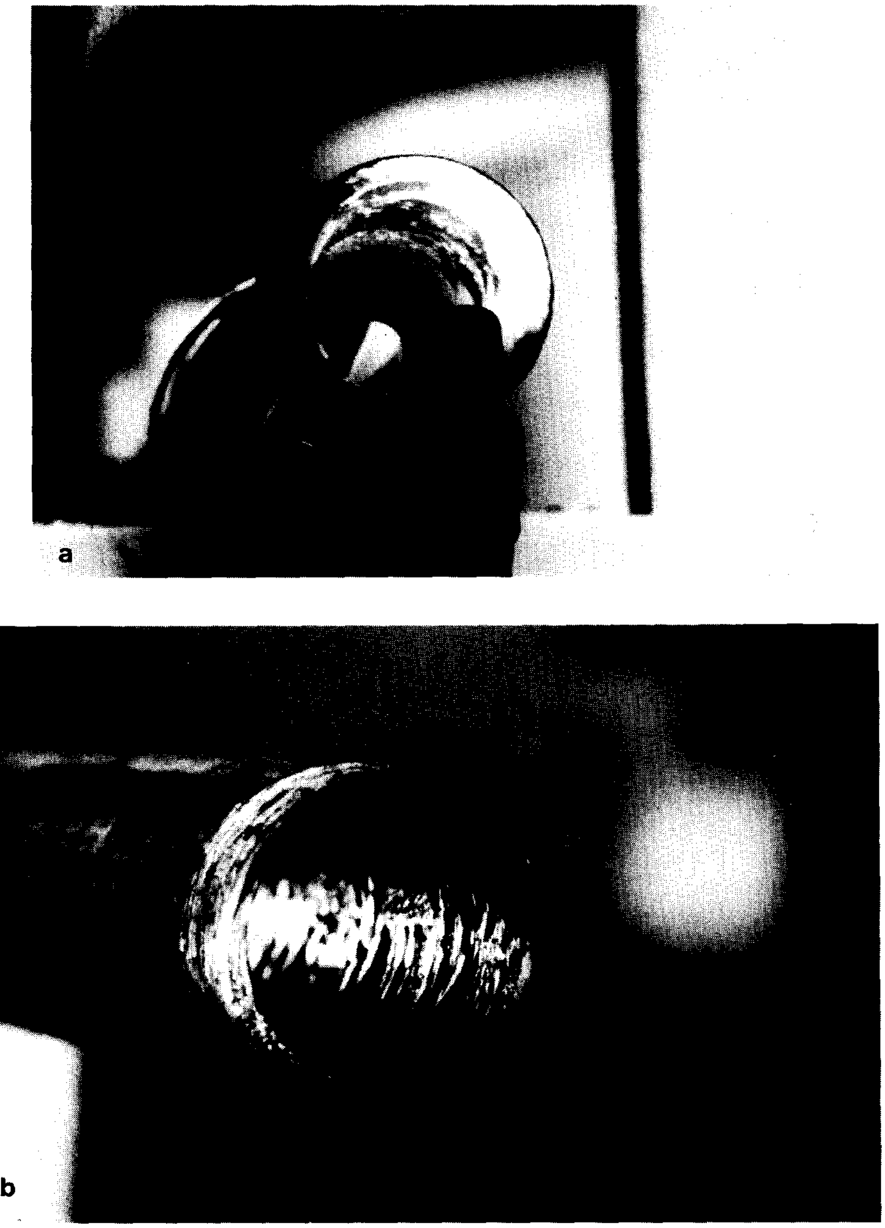

Figure 9. Inner surface of the cement (a) and steel pipe (b) pipes after the 24 h test. The cement pipe was fouled by the oil around the edge of the pipe, but was otherwise clean. The steel pipe was fouled all through its length.

problems in day-to-day operations. It is important, therefore, to carefully join the pipe sections together so that the flow is streamlined.

4.5. Smoother pipes and higher input fractions

The sectioned carbon steel pipes were replaced with one long smooth steel pipe. Both cement and steel pipes were filled with water and soaked for more than a week. Then, we started our experiment by injecting oil at 94% input fraction and a Reynolds number of 1600. The pipeline was run for 5 h. A small buildup in frictional losses occurred in the steel pipe which was not duplicated in the cement pipe. Upon disassembly of the pipeline, we noticed that the steel pipe was badly fouled but the cement pipe was clean.

4.6. Longer tests on cement-lined pipes

We cleaned the steel pipe and filled both cement and steel pipes with a 1% aqueous sodium *m*-silicate solution and allowed them to soak for 1 day. The pipes were then emptied, and the pipeline was reassembled, filled with water and allowed to sit for another day. We then ran the pipeline continuously for 60 h, during which the input fraction steadily decreased from 35% water to 25% water, while holding the superficial oil velocity constant at 0.27 m/s. The pressure gradient in the cement-lined pipe declined with the input fraction. By contrast, the friction factor in the steel increased.

After the 60 h experiment was completed, we disassembled the pipeline and observed that the cement pipe was clean with only small spots just before the junction between the pipe and the glass J-tube, as in the previous experiment [figure 9(a)].

4.7. Summary of pipeline tests

In over 1000 h of testing with No. 6 fuel oil, cement-lined pipes never fouled and carbon steel pipes always fouled. Fouling occurs at the higher input ratios and higher flow rates, and also around unions and flanges. However, the fouling of carbon steel with No. 6 fuel oil was not so great as to produce a cumulative effect like that seen in the INTEVEP tests with Zuata shown in figure 1.

5. RESTARTING A PIPELINE FILLED WITH AN OIL–WATER MIXTURE

Many different methods are practised for restarting the pipeline after a shut-down. One procedure which provides a smooth restart is patented by Zagustin *et al.* (1988), where the water flow rate is gradually increased until the oil is completely detached from the pipe wall. If the crude oil pump is started too early, higher pressure levels and sharp pressure variations could lead to failure [see Zagustin *et al.* (1988), figure 4].

After the flow is stopped and the oil and water separate, the degree of oil sticking to the wall increases over time. Restart is harder for long down-times, as shown by the comparative measurements done at the INTEVEP test loop and displayed in figure 10: a maximum pressure of 400 kPa was needed after 5 h and 1000 kPa after 96 h to restart the flow.

We did restart experiments on our small test pipeline (figure 7) in which the cement-lined and carbon steel sections are connected in series. The aim of these experiments was to compare fouling and ease of cleaning of the two sections.

These experiments cannot be called "restart tests" in the sense that the oil pump was not restarted. Like the procedure of the INTEVEP loop, the water was injected at a slow rate, and gradually increased to a desired constant, where it was held until the pressure gradients in both pipes reached a steady state. But, unlike the tests in the INTEVEP loop, we then shut down and disassembled the pipeline, so that we could see how much the pipe fouled.

Three different experiments were performed: a 24 h down-time, a 10 day down-time and a 5 day down-time. To start the experiment, the pipeline was run at an input ratio of 94%. Then, the line was stopped by simultaneously switching off the oil and water pumps and closing all valves. Oil and water stratified in a few minutes. After each down period, the pipeline was restarted by

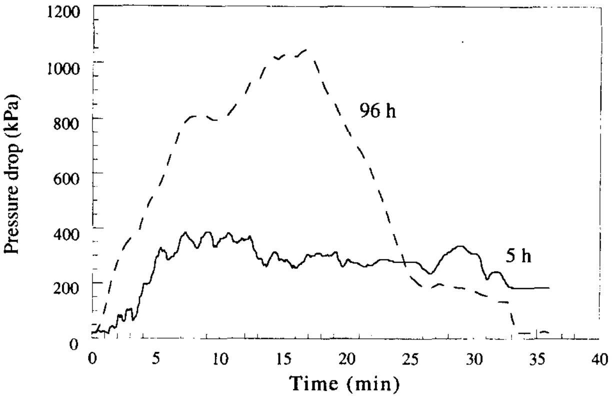

Figure 10. Restart of the INTEVEP test loop after two different down-times. In each case, water flow rate is increased by 15 l/min/min. The longer down-time required 2.5 times more pressure to unclog the pipe.

gradually increasing the water flow rate, while monitoring the pressure at the water manometer and observing the flow at the visualization sections.

For the 24 h shut-down experiment, the carbon steel pipe was placed adjacent to the nozzle, and the cement-lined pipe was placed after the glass "J"-section. The pipeline was filled with oil and stopped in the manner described above, and then rested for 24 h. After this, the restart test commenced by first injecting water at 0.4 l/min. Both glass pipes fouled early in the experiment so we were not able to collect visual data. The pressure taps in the steel pipe fouled too quickly to collect reliable pressure readings. The water flowed at 0.4 l/min for 10 min before stopping. The line was then flushed for 1 min at a flow rate of 28 l/min, the pump was turned off and the pipes were opened. The cement-lined pipe was completely clean; whereas the steel pipe was fouled throughout the pipe and heavily fouled close to the injection nozzle. No. 6 fuel oil can be more easily cleaned by running water through horizontal cement-lined pipes than steel pipes (it may be impossible to completely clean steel pipes).

After the previous restart experiment, the cement-lined pipe was filled with water and the steel pipe was cleaned in preparation for the 10 day shut-down. The glass visualization sections were also cleaned and hydrated in 1% sodium *m*-silicate for 2 days, in an attempt to make them more hydrophilic. The line was then reassembled with the cement-lined pipe next to the nozzle (so the cement could be tested under more severe conditions). The line was intermittently used for around 40 h. The filling and stopping procedure was performed after which the pipeline rested for 10 days.

For the restart procedure, the water flow rate was increased from 0 to 0.4 l/min in about 1 min, after which it was held constant. This time, the pressure taps did not foul so it was possible to gather some quantitative data as well. Two minutes into the experiment, the pressure drop was high in both pipes (1.4 kPa for the cement pipe, 1.6 kPa for the steel pipe) and even higher in the section which includes the glass "J" and the entrance of the steel pipe (about 3.9 kPa). As in the previous experiment, the glass sections were heavily fouled.

After approximately 4 min, the pressure drops were about 0.48 kPa for the cement pipe and about 1100 kPa for the steel pipe. We also noted a pressure drop of around 2400 kPa in the glass J-section (which was still fouled with oil) and the entrance to the steel pipe. After 5 min of operation, the pressure taps in the steel pipe were clogged with oil. The pressure taps in the cement pipe, however, were clean and the pressure gradient had declined to a steady value of around 0.30 kPa. Eight minutes into the experiment, the water flow rate was increased to 28 l/min, and the oil began peeling off the glass pipes. We could see oil drops passing through the glass observation section at the end of the pipeline, but no oil was coming from the cement pipe. Ten minutes into the experiment, the pipeline was shut down and the pipes were opened. The cement-lined pipe was completely clean, even in the section close to the injection nozzle. In contrast, the steel pipe was heavily fouled through its entire length.

Before the five day shut-down experiment the steel pipes were again cleaned and the line was reassembled with the cement-lined pipe in test section 1 (closest to the nozzle). The filling and stopping procedure was done again, after which oil and water stratified under gravity for 5 days.

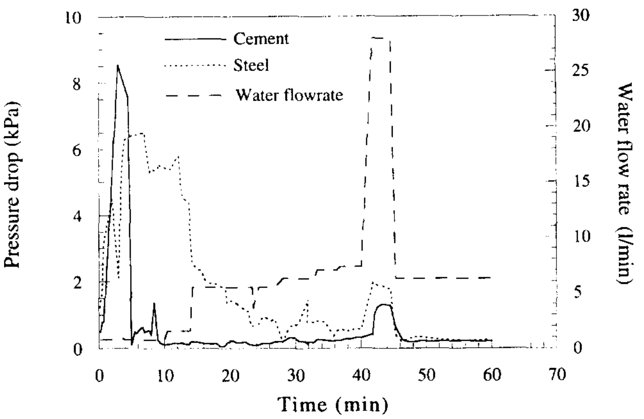

Figure 11. Restart after 5 days of rest in the 25 mm pipeline. The water flow rate is gradually increased. The cement-lined pipe is free of oil in a few minutes, while the steel pipe is noticeably fouled after 45 min. The peak from 40 to 44 min corresponds to a large increase in the water flow rate. At this time, the pressure gradient is much larger in the steel than in the cement-lined pipe and indicates the degree of fouling (normally, the pressure gradient in the smooth steel pipe is smaller than in the rough cement-lined pipe).

For this experiment, more accurate pressure data were collected by using a device invented to unclog the manometer lines and pressure taps; 30 s were needed to remove a clog, increasing the response time. The pressure taps in the steel pipe repeatedly clogged, and were unclogged. Because of this, the pressure drops in the steel pipes may have been underestimated.

Figure 11 shows the evolution of the water flow rate and the pressure drop in the cement-lined pipe and in the steel pipe for the duration of the test. Since the cement-lined pipe is in a dangerous position, the pressure drop was higher than in the steel pipe during the first few minutes, but rapidly decreased and stayed at very low levels afterwards. In contrast, higher pressure drops were required to move the flow through the steel pipes after the initial transient. After an hour, the pump was stopped and the pipes disassembled. Once again, the cement pipe was completely clean (even in the critical region close to the injection nozzle) and the steel pipe was heavily fouled.

6. CONCLUSIONS

In this paper, we have shown that cement-lined pipes can resist fouling by oil and facilitate the restart of a stopped pipeline. We have seen that repeated and determined attempts to foul properly hydrated cement-lined pipes and cement surfaces with Zuata crude and No. 6 fuel oil always failed. Industrial size cement-lined pipes were filled with 50% Zuata crude and 50% water, sat vertically for 2 weeks and, upon opening, the oil discharged in a lubricated plug leaving behind clean cement. Moreover, a pipeline using cement-lined pipes was operated for more than 1000 h over the course of 2.5 years, subjected to three shut-down experiments and never fouled. By contrast, steel pipes and steel surfaces either showed spotty fouling at best (with galvanized steel) or complete fouling at worst.

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