

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 recovery 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 oil fouling for long term. A pilot scale cement-lined core-annular flow pipeline using No. 6 fuel oil never fouled in over 1000 hours of operation. Repeated and determined attempts to soil properly hydrated cement-lined pipes with heavy Venezuelan crudes always failed. Our experiments also show that cement lined pipes are easy to restart when stratified with oil and water.

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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 a intermittent interest in the technology of water lubricated transport of heavy oil since 1906 (Isaacs & Speed, US Patent #759,374). Heavy crudes are very viscous and somewhat lighter than water, though crudes heavier than water do exist. Typical crudes might have a viscosity of 1000 poise and a density of 0.99 g/cm^3 at $25 \text{ }^\circ\text{C}$. Light oils with viscosities of less than 5 poise 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 and Renardy [1992] and Ho and Li [1994]. This literature has many facets which include models for levitation (see Oliemans and Ooms [1986] and Bai, Kelkar and Joseph [1995] for two different approaches) empirical correlations giving the pressure drop vs. mass flux in laminar and turbulent flows (Arney, Bai, Guevara, Joseph, Liu [1993], Huang, Christodoulou and Joseph [1994]), classification of flow types (Charles Govier and Hodgson [1961], Bai, Chen and Joseph [1992]) stability studies (see Joseph and 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 the refinery at Ten Section. The line was run under the supervision of Veet Kruka for 12 years from 1970 until the reservoir was exhausted. When lubricated with water at a volume flow rate 30% of the total, the pressure drop varied between 900 psi and 1100 psi at a flow rate of 24,000 barrels/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 produced water which contained 0.6 wt% sodium *m*-silicate as a natural constituent. After that, the pressure drop never varied much from the acceptable 900 psi value and the CAF was stable as long as the flow velocity was at least 3 ft/sec (0.9 m/sec).

Even though lubricated flows are hydrodynamically stable, oil can foul the wall. This is an energetic 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. In our experiments, a water annulus which lubricates an oil core has been seen 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 blockage of the flow, as shown in Figure 1. This experiment used crude oil taken from the Zuata field of the Venezuelan Orinoco belt, hereinafter called Zuata. At 25°C, its density is 0.996 g/cm³ and its viscosity is 1150 poise. The Zuata was pumped through a 8" (20 cm) ID, 1 km pipeline with input fraction of 4% water and superficial oil velocity of 1.5 m/s. The pressure gradient increases monotonically from 29 psi up to 174 psi due to the gradual fouling of the pipes. If allowed to continue, the Zuata will completely foul and block the pipeline.

The experiments in Venezuela also showed that oil does not homogeneously foul the pipe. Critical positions of the line were more heavily subject to fouling than others. These locations are usually sections of the pipe closer to the pumping stations. This may happen because in these areas both the holdup and core wave structure are developing. We also observe that the hydrostatic pressure is highest at the head of the pipe. As core-annular-flow develops along the pipe, less and less fouling is observed. Fouling was also observed to be specially heavy around line irregularities such as unions, bends, flanges and curves. Another major problem arising from the continuous operation of core-annular flow is an unexpected shut-down in the line. In such cases, the oil and water stratify, causing the oil to stick to the pipe wall and form an oil plug, making it harder to restart the line. This aspect will be further discussed in Section 3.

It is desirable to lubricate the oil core with as little water as possible because a small water input reduces the problems associated with the emulsification of small water drops into the oil (a condition which can lead ultimately to failure -Bai et al. [1992]), and also because it 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 for this as well as other reasons.

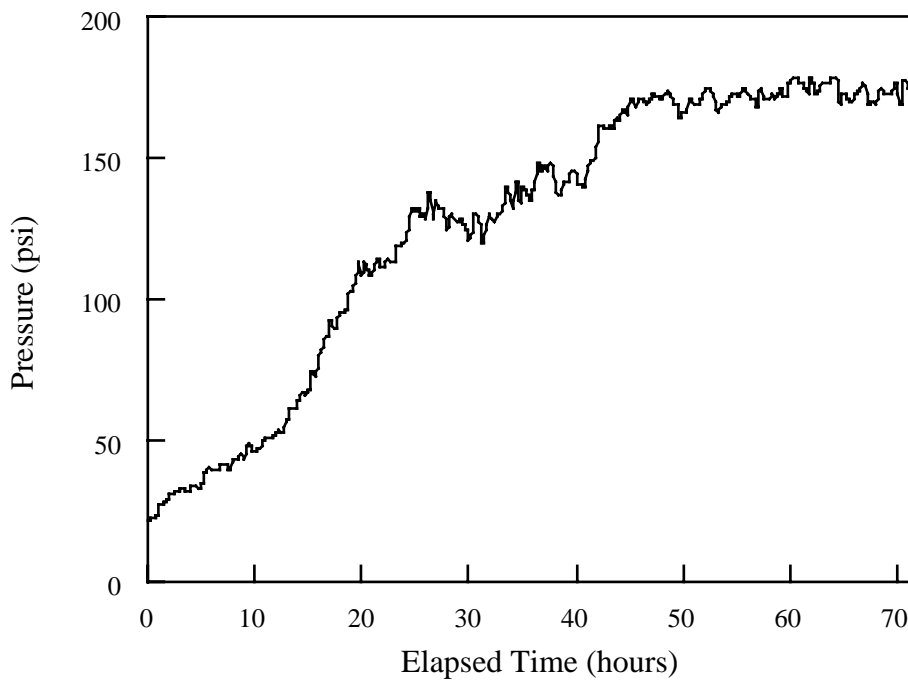


Figure 1. Fouling of the San Tome test loop with Zuata crude. Input fraction = 4%, superficial oil velocity = 1.5 m/sec. Pressure losses increase monotonically as the pipeline fouls. High blockage was experienced after 2 1/2 days of operation.

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 discussed by Arney [1994], Ribeiro [1994] and Ribeiro, Rivero, Arney, Hall and Joseph [1995] and only the most relevant will be mentioned just 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 oleophobic quartz glass oleophilic. 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 principally 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*-silicae 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 sulphonated ABS plastic (say, Cycolac ®) and some ordinary mortars of portland cement hydrated in a low concentration of sodium *m*-silicate solution (say 0.59 to 1%). The oleophobic and hydrophilic properties of the sulphonated 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 in curing. The addition of small amounts of sodium *m*-silicate appears to promote the calcium-silicate composition that renders the gel more hydrophilic. The hydrophobic 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 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 in US patent # 5,385,175 issued to INTEVEP S.A. for a “Conduit having hydrophilic and oleophobic inner surfaces for oil transportation.” Though the hydrophilic properties of C-S-H gels in cements are well known (but not well understood) the oleophobic properties 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 can be interrupted to one or more of the pumping stations). In this case, the pipe is filled with quiescent oil and water for a time during which the oil sediments to the top of the pipe (assuming that the oil is lighter than water) and sticks to the wall. 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 benefitted by remedies which reduce adhesion.

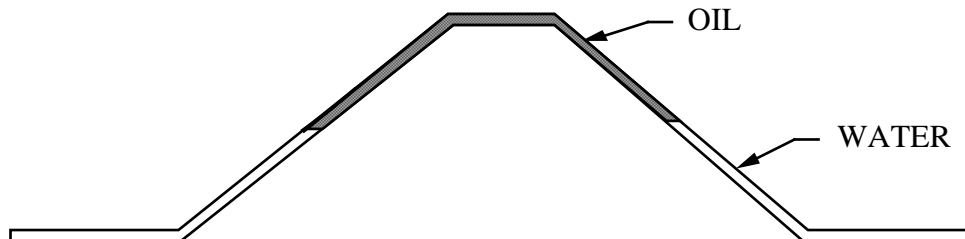


Figure 2. Oil-water stratification in a stopped pipeline going up and down a hill. The viscous crude oil rises to the crest completely blocks the flow.

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, density) of CND and Zuata are (12900 poise, 1.009 g/cm³), and (1150 poise., 0.996 g/cm³), 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. As stated previously, full results are found in Arney (1994) and Ribeiro (1994). To summarize their findings, 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. [1995]) 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 2" (5 cm) ID and was cut into three sections of 2 ft (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 one 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 silicate were filled with either a 50% oil-water mixture or with a 50% oil-49.5% water-0.5% sodium 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 7). The oil rose and completely filled the upper half of the pipe. After standing for six days, we opened the pipes by removing the top cap, inclining the pipe about 20° from the horizontal and opening the bottom cap. The results are described below, and summarized in Table 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 4a) 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 cm² in size, close to the top edge of the pipe. This oil spot could not be completely removed by running tap water.

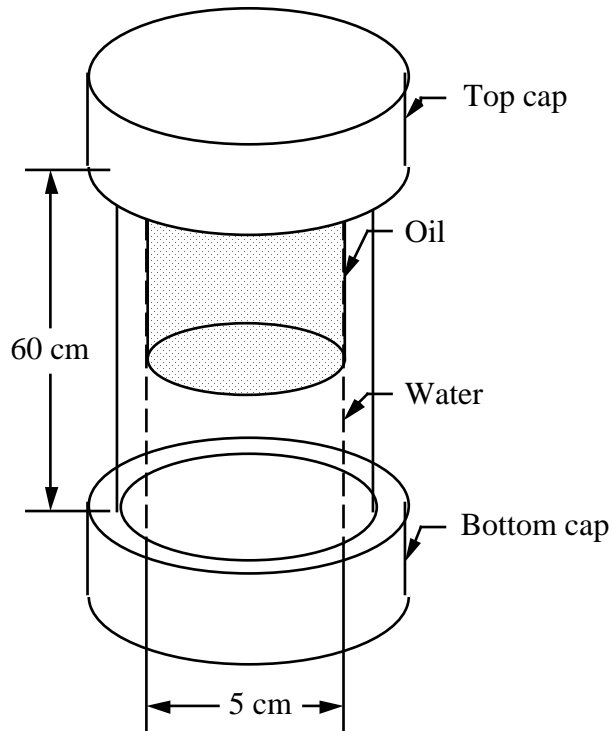


Figure 3. In this emptying test, the pipe is hydrated for a week. Then, over 50% of the pipe is filled with oil, the rest water. The pipe is covered and sits vertically with its axis aligned with gravity for six days. Then it is opened, emptied, and inspected. This test simulates an unexpected pipeline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

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 4b).

- **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 1.5-6 in² (10-40 cm²). 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

Figures 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

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).

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

Fig. 5 and 6

Table 2 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.

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

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.

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. We selected a 5 cm diameter cement-lined pipe, 4.8 m (16 ft) long, 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 from the pipe walls, but the streak could not be cleaned. To explain this fouling, we observe that the filling process consumed two hours, 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 12 ft (3.6m) long test sections were cut from a similar 2" (5 cm) ID 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 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 upon request.

A new hydration method was tried on the second section. Ribeiro et al (1994), 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. Dynamic tests

In emptying experiments, the forces which promote adhesion operate for a long time. Dynamic 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 dynamic 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 and by visually inspecting the pipes after each experiment. Arney *et al.* (1993) define the friction factor in a oil-water core-annular flow as

$$f = \frac{2\Delta p D_2}{\rho_c L V^2}, \quad (4.1)$$

where Δp is the pressure drop over a length L , D_2 is the pipe diameter, ρ_c is the composite density:

$$\rho_c = \eta^2 \rho_o + (1 - \eta^2) \rho_w, \quad (4.2)$$

ρ_o is the oil density, ρ_w the water density,

$$\eta = \frac{D_1}{D_2}, \quad (4.3)$$

D_I is the average core diameter, and

$$V = \frac{4(Q_o + Q_w)}{\pi D_2^2} \quad (4.4)$$

is the average velocity, Q_o and Q_w are the oil and water volume flowrates, respectively. η can be calculated as a function of the input flow rates by using the correlations for the hold-up fraction proposed by Arney *et al.* (1993). The Reynolds number for the oil-water core annular flow is defined in Arney *et al.* (1993) as:

$$Re = \frac{\rho_c V D_2}{\mu_w} (1 + \eta^4 (m - 1)), \quad (4.5)$$

where

$$m = \frac{\mu_w}{\mu_o}, \quad (4.6)$$

and μ_o and μ_w are the oil and water viscosities, respectively.

4.1. Apparatus.

For this purpose, we constructed a closed-loop continuous operation horizontal core-annular flow pipeline shown in Figure 7, which is designed for continuous operation. The oil and water are both stored in the 240 gallon (900 liters) 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

Figure 7

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 3.47m in the tests against galvanized steel and carbon steel pipe I, and 4.00 m in the tests against carbon steel II.

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

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 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 = 0.900 g/cm³, viscosity = 20 poise) 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 static tests.

4.2. Galvanized steel vs. 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 hours. No big changes in pressure were observed in either pipe. After the test, the pipeline was flushed with water and disassembled. Neither pipe fouled, showing that galvanized steel and cement pipes were able to resist fouling by No. 6 fuel oil for extended

times, using a small oil input ratio. However, galvanized pipes did not resist fouling by Zuata in static 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 vs. 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 in the previous experiment, both pipes were filled with water and allowed to stand for more than 24 hours. We started this experiment with a 90% oil input and an average Reynolds number of 2800. After 15 minutes, the pressure taps on the steel pipes filled with oil. After flushing the pipeline with water and dismantling, we found that the steel pipes were heavily fouled, but the cement-lined pipe was clean. We draw attention to the fact that the steel pipe was in the most dangerous position for fouling, just after the nozzle. Therefore, we decided to test the cement pipe in this position.

The carbon steel pipe was scrubbed with detergent and water until visibly clean, then thoroughly flushed with water and dried. This time, the cement-lined pipe was placed in Test Section #1 and the carbon steel pipes were placed in Test Section #2. Again, both pipes were hydrated with water for more than 24 hours. We began the experiment by first running at 62% oil input fraction, Reynolds number of 5500, measuring pressure as a function of time, for 15 hours. No appreciable change in the pressure gradient was observed. The input fraction was then changed to 70% oil, Reynolds number of 4600, and we measured pressure gradient vs. time for nine hours. 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 two 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 vs. 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 minutes. 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.

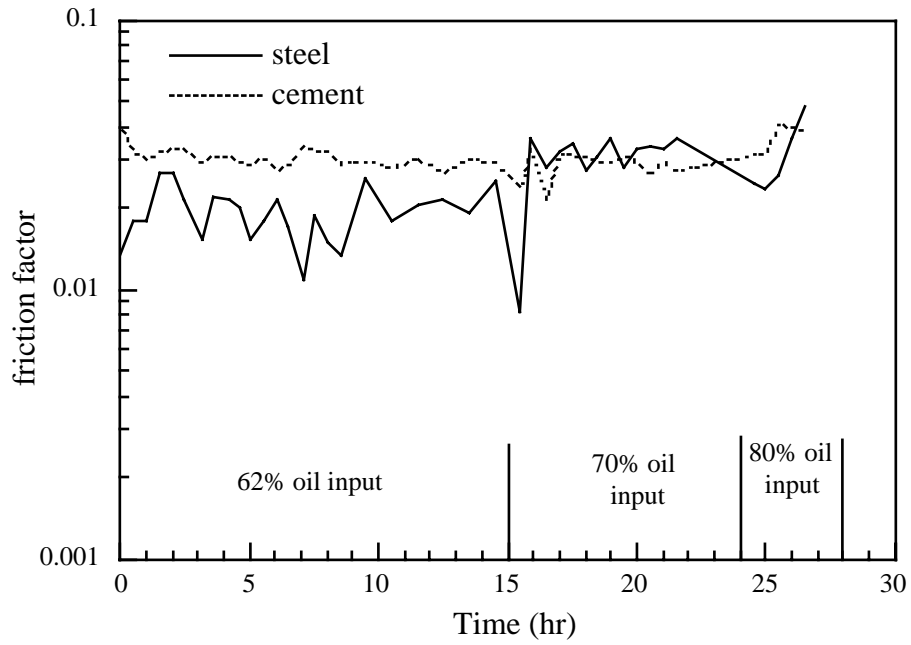


Figure 8. Friction factor vs. cumulative time for cement-lined and steel pipes. Frictional losses are steady for the cement lined pipe, but are erratic and increasing in the carbon steel pipe, indicating the accumulation of oil on the steel surface.

Figure 9 (pictures)

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 hours we stopped the line and disassembled the pipes. We discovered that the flanges had initiated fouling. In fact, heavy fouling was observed for about 12" (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 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, Reynolds number of 1600. The pipeline was run for five hours. 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 allowed them to soak for one 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 hours, during which the input fraction steadily decreased from

35% water to 25% water, while holding the superficial oil velocity constant at 0.27 m/sec. 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 hour 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 9a).

4.7. Summary of pipeline tests.

To date, over 1000 hours of run time have been logged on the pipeline. Cement-lined pipes never fouled; by contrast, the steel pipe always fouled. Also, based on friction factor data, fouling occurs at the higher input ratios and higher flow rates, and also around unions and flanges.

Dramatic fouling was never seen as in the case of the Venezuelan line (see Figure 1). Our friction factor plots only show small trends at the higher input ratios. The experiment was hampered by the repeated clogging of the pressure taps which occurred parallel to fouling activity. We also note that No. 6 fuel oil is much less sticky than Zuata crude.

Based on these findings, cement-lined pipes appear to be suitable for core annular flow processes, because they seem to avoid the fouling problems that occurs in carbon steel lines.

5. Restarting a pipeline filled with a oil-and-water mixture

As discussed earlier, any core-annular flow process can unexpectedly shut down and remain filled with stratified oil and water for days or even weeks. After the down time, the pipeline must be restarted in such a manner as to avoid damage to the pipes. A viable restart procedure is described in Zagustin, Guevara, Nuñez (1988), and will next be discussed. However, we have also found that the use of cement-lined pipes greatly facilitates the restart of pipes.

5.1. Current industrial practice

Many different methods are practiced 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 would result (see Zagustin et al. (1988), Figure 4), and could lead to line failures. Also, pumping water at a the steady state flow rate from the beginning of the operation would also lead to excessively high pressures.

Two measurements from the San Tome test loop are displayed Figure 10. One curve shows restart after a five hour rest, the other after a 96 hour rest. In both cases, the water rate is increased by 15 liter/min./min. After only five hours standing the oil had little chance to stratify and stick to the wall. Therefore, a smaller pressure (58 psi maximum) was needed to remove the oil. In the other case, after 96 hours of standing, the oil completely stratified and stuck to the pipe and thus required 2.5 times more pressure (150 psi maximum) for removal. But, as the next experiment shows, the restart conditions can be facilitated with the use of cement lined pipes.

5.2. Simulation experiments in the 1" line

Restart tests were carried out in the 1" horizontal pipeline shown previously in Figure 7 and discussed in 4.1. Our experiments do not address the problem of oil blockage at the crest of inclined sections (see Figure 42 and accompanying discussion). In any case, by testing the serial arrangement of cement-lined and steel pipes we were able to gather information on how much oil can be cleaned from each of these pipes after a horizontal line shut down and on the pressure required to remove the oil.

The aim of this experiment was to determine which pipe (cement-lined or steel) could be easily cleaned. These experiments cannot be called "restart tests" in the sense that the oil pump was not restarted. Like the procedure of the San Tome 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 San Tome loop, we then shut down and disassembled the pipeline, so that the extent of fouling could be visually determined.

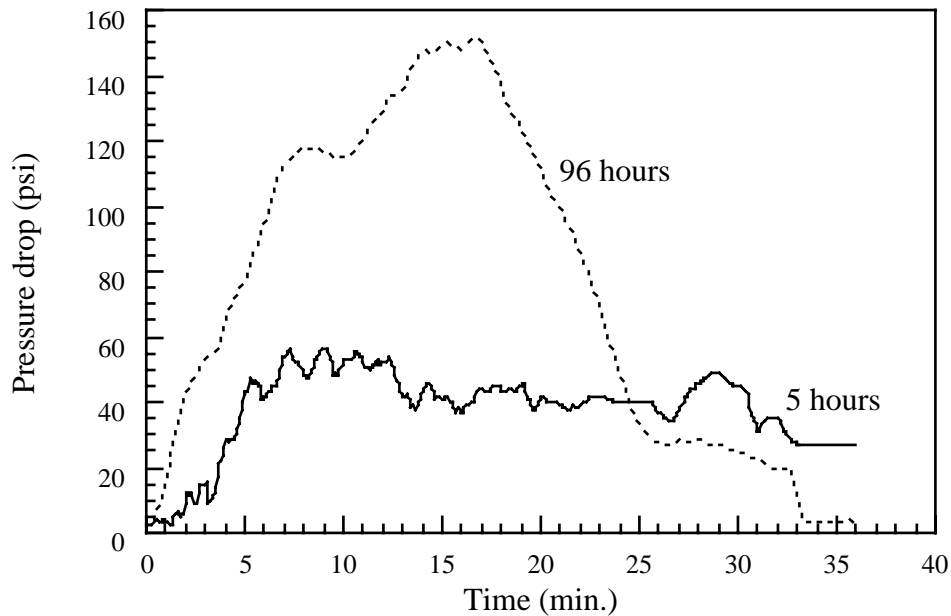


Figure 10. Restart of San Tome test loop after two different down-times. In each case, water flow rate is increased by 15 liter/min./min. The longer down time required 2.5 times more pressure to unclog the pipe.

Three different experiments were performed: a 24 hour 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 gradually increasing the water flow rate, while monitoring the pressure at the water manometer and observing the flow at the visualization sections.

• 24 hour shut-down

For this 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 hours. After this, the restart test commenced by first injecting water at 0.4 liter/min. Both glass pipes fouled early in the

experiment so we were not able to collect visual data. Also, the pressure taps in the steel pipe also quickly fouled, so pressure information could not be collected in this test. The water was running at 0.4 liter/min. for 10 minutes. The line was then flushed for one minute at a flow rate of 28 liter/min., the pump was turned off and the pipes were opened .

We observed that the cement-lined pipe was completely clean all the way through its extension. In contrast, the steel pipe held a sizable amount of oil inside and was particularly fouled at the regions closest to the injection nozzle. Apparently, No. 6 fuel oil can be more easily cleaned from horizontal cement-lined pipes than from steel pipes (and probably it is impossible to completely clean steel pipes).

- **Ten day shut-down**

After the previous restart experiment, the cement lined-pipe was filled with water and the steel pipe was cleaned. The glass visualization sections were also cleaned and hydrated in 1% sodium silicate for two 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 hours. The filling and stopping procedure was performed after which the pipeline rested for ten days.

For the restart procedure, the water flow rate was increased from zero to 0.4 liter/min. in about one minute, 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 (0.20 psi for the cement pipe, 0.23 psi for the steel pipe) and even higher in the section which includes the glass "J" and the entrance of the steel pipe (about 0.57 psi). As in the previous experiment, the glass sections were heavily fouled.

After approximately four minutes, the pressure drops were about 0.07 psi for the cement pipe and about 0.16 psi for the steel pipe. We also noted a pressure drop of around 0.35 psi in the glass J-section (which was still fouled with oil) and the entrance to the steel pipe. After five minutes of operation, the steel pipe's pressure taps were clogged with oil. The cement pipe's pressure taps, however, were clean and the pressure gradient had declined to a steady value

around 0.043 psi. Eight minutes into the experiment, the water flow rate was increased to 28 liter/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. Once again, the cement lining in the pipe facilitated an easy restart of a pipeline.

- **Five day shut-down**

Before the final 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 again done, after which the line rested for five days. During this restart experiment, more accurate pressure data could be collected by using a device invented for unclogging the manometer lines and pressure taps. However, the device required about 30 seconds to restore a clogged pressure tap therefore increasing its response time. The steel taps repeatedly clogged, and were systematically 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. Because of the position of the cement lined pipe, the pressure drop through it was higher than in the steel pipe during the first few minutes. However, it rapidly decreased and stayed at very low levels afterwards. In contrast, the steel pipe demanded higher pressure drops all through the rest of the experiment. After an hour, the pump was stopped and the pipes disassembled. Once more we saw a completely clean cement pipe (even in the critical region close to the injection nozzle) and a heavily fouled steel pipe.

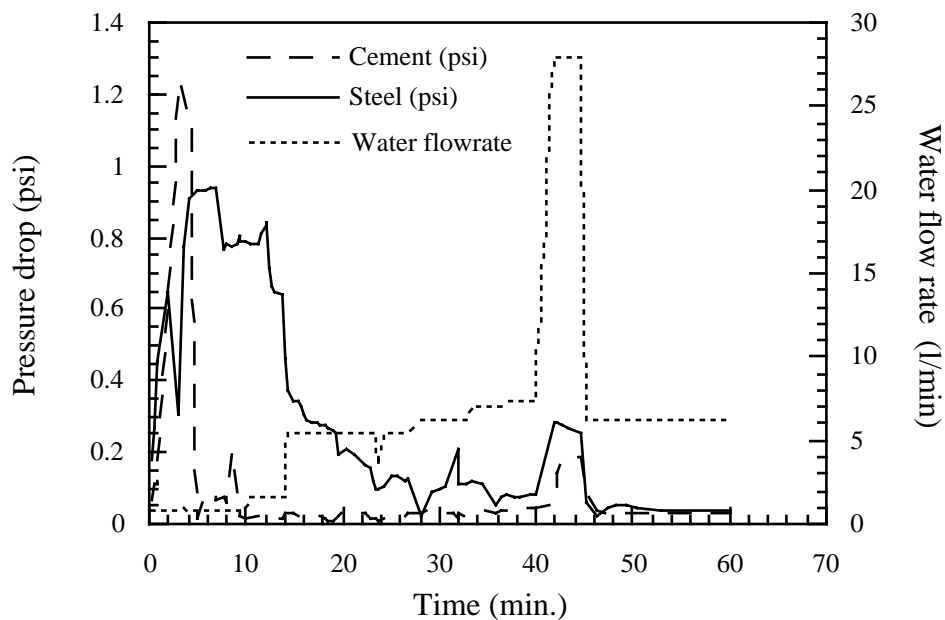


Figure 11. Restart after 5 days of rest in the 1" pipeline. The water flow rate is gradually increased. The cement-lined pipe is free of oil in a few minutes, while the steel pipe is noticeably fouled after 45 minutes. The peak from 40 to 44 minutes corresponds to a large increase in the water flow rate. 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).

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 two 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 hours over the course of 2 1/2 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.

Acknowledgments

This work was supported primarily by the DOE, Department of Basic Energy Sciences (O. Manley, monitor), by the NSF and ARO. The work of Geraldo S. Ribeiro was partially supported by the Brazilian National Scientific Research Council (CNPq). We are indebted to Mansel Rubenstein of Cement Lining Co. of Houston, TX for preparing ever so many samples of cement lined pipes, cheerfully and free of charge. We thank Timothy Hall for his ideas and collaboration in the experiments, and Dave Hultman for helping to put the pipeline together .

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