Self lubricated transport of bitumen froth

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Abstract

Bitumen froth is produced from the oil sands of Athabasca using the Clark's Hot Water Extraction process. When transported in a pipeline, water present in the froth is released in regions of high shear; namely, at the pipe wall. This results in a lubricating layer of water that allows bitumen froth pumping at greatly reduced pressures and hence the potential for savings in pumping energy consumption. Experiments establishing the features of this self lubrication phenomenon were carried out in a 1" diameter pipeloop at the University of Minnesota, and in a 24" (0.6m) diameter pilot pipeline at Syncrude, Canada. The pressure gradient of lubricated flows in 1" (25 mm), 2"(50 mm) and 24"(0.6 m) pipes diameters closely follow the empirical law of Blasius for turbulent pipe flow; the pressure gradient is proportional to the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe diameter, but the constant of proportionality is about 10 to 20 times larger than that for water alone. We used Reichardt's model for turbulent Couette flow with a friction velocity based on the shear stress acting on the pipe wall due to the imposed pressure gradient to predict the effective thickness of the lubricating layer of water. The agreement with direct measurements is satisfactory. Mechanisms for self lubrication are considered.

1. Introduction

The first studies of self lubrication of bitumen froth were carried out in 1985 unpublished studies by O. Neiman (Syncrude Research Report, March 1986). Tests were conducted using a 2" (50 mm) diameter by 47 meters pipeloop test facility and froth generated from an experimental extraction pilot unit.

The pipeline flow of froth was found to be governed by a special type of multi-phase behavior involving separated water. A concentration of water was observed to occur near the pipe wall, which effectively formed a lubricating water layer around the central plug of froth. As a result, measured pipeline headlosses were up to two orders of magnitude less than those theoretically predicted by assuming a homogeneous viscous behavior of the froth. As a result of his studies, Neiman concluded that "Pipelining of froth in the Syncrude expansion case may be considered technically and economically feasible".

Recently, Syncrude Canada announced that its proposed Aurora Mine Project would extract bitumen froth from an oil sand lease located about 35 Km from it current Mildred lake operations in Northern Alberta. One possible way of shipping bitumen froth from the remote extraction site to the current operations is pipelining froth in core-annular flow mode.

Neiman's study did not test the effect of some of the critical issues involved in commercializing the core-annular flow of bitumen froth. These issues are: bitumen fouling, lower temperature froth and flow restart characteristics following flow interruptions and have been addressed in the studies reported here. The Neiman and University of Minnesota studies were both batch studies with froth recirculated in return loops. In fact, this condition is more representative of a long commercial line than a continuous injection of new froth through the short pilot pipelines used in the laboratory studies. The Neiman studies were of short duration, usually one hour, two hours at most. The University of Minnesota studies were typically eight hours long, others were 48 hours and the longest one of them was 96-hours. The pilot-scale test were 2, 24 and 36 hours long.

The Neiman studies did not test the full range of the limits of operability of self lubrication. The University of Minnesota studies indicated that there is minimum velocity below which self lubrication fails but no such limitation has been found for high velocities.

Neiman used relatively fresh froth in his experiments, at varying water contents of 29-37%. In some tests water was added to increase the water content to as high as 62%. In the other hand, the University of Minnesota studies were carried out with two batches of froth: ,a batch from the commercial operation at Fort McMurray and, a batch from the experimental extraction pilot located in Edmonton. The water content in the two batches varied between 22 to 40%. The 22% froth was very stable and no free water was visible in the cans used to store it. This stable froth lubricated perfectly with the same low pressure gradient over 48 hours of running. In fact, all samples lubricated well independently of the water fraction.

The Neiman study did not explain the mechanisms of self lubrication of bitumen froth. Significant information exists in literature on bitumens in which water is added as a lubricant (see Joseph & Renardy [1992] or Joseph et al. [1996]), but no literature exists on self lubrication. The University of Minnesota studies have suggested that the produced water is essential to the development of self lubrication, mainly due to the presence of kaolonite (clay) particles in a colloidal suspension in the released water.

The froth pipelining temperatures in Neiman's studies ranged between 45 and 95 ˚C, with most of the test reporting either 50 ˚C or 80 ˚C. These are process temperatures for warm water and hot water extraction techniques, respectively. Most of the University of Minnesota tests were carried out in the range 35-47 ˚C, where the upper limit is due frictional heating. The temperature in the pilot-scale tests at Syncrude, Canada, ranged between 45 and 55 ˚C.

Another important feature not considered in Neiman's studies is the ability to restart the froth flow following flow interruption.

2. Fouling

Fouling of pipe walls is possibly the main impediment to the successful application of water-lubricated pipelining. 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 for this, as well as other reasons. The lubricated configuration with water on the wall is hydrodynamically stable. The water, the low viscosity constituent, always migrates to the places where the shear rate is high; to the pipe wall. However, it is inevitable that the waves which levitate core flows off the wall will actually touch the pipe wall from time to time. If the wall is very oleophilic, the oil will stick to it even though water near the wall is hydrodynamically stable. The carbon steels generally used for pipes are oleophilic and typically are fouled by oil. The fouling of pipe walls by oil may or may not lead to a continual increase of the pressure gradient required to drive the flow. A water annulus can lubricate an oil core even in a pipe whose walls are spotted with oil. Sometimes, however, the fouling builds up, leading to rapid increasing pressure drops, and even blocking the flow. The build up fouling is especially pronounced for heavy crudes with high asphaltene content like Zuata crudes from the Orinoco belt (see Joseph et al. (1997).

Fouling is more pronounced near pumping stations, where the pressure is highest and the holdup ratio (oil to water average velocities ratio) and core wave structure are developing or around line irregularities such as unions, bends, flanges and curves. Another major problem could be an unexpected shut-down in the line; the oil and water would stratify, causing the oil to stick to the pipe wall, making it harder to restart the line.

Although No. 6 fuel oil routinely would foul the carbon steel pipe walls of the University of Minnesota pipeline, no buildup was observed at any point in the intermittent studies over the course of several years. Neiman's [1985-1986] tests are slightly ambiguous about fouling, but overall they do not indicate any strong tendencies to foul; some of the pressure records show epochs of slight increase of the pressure gradient as time progresses, but the tests were too short to reach a definite conclusion. It is important to know that for some oils successful and permanent lubrication can be achieved in a fouled pipe without further buildup of fouling. This property of lubrication in a fouled pipe is related to the case with which the oil in the core attached to fouled oil on the pipe wall. The bitumen froth is well protected against such attachment by a protective layer of clay particles (see Section 7) but Zuata readily sticks to itself

3. The Experiments

3.1 MINNESOTA TESTS

3.1.1 Test Facility. A view of the test facility is shown in figures 3.1 and figure 3.2 is a schematic of it. Two loops (*main* and *secondary*) are connected in this facility. Froth circulates through the main loop; which principal components are a supply tank, a three stage Moyno pump, and 1” (25 mm) diameter, 6m long pipeline. The supply tank is made of cast steel with a conical bottom, which promotes the flow of froth to the Moyno pump. This tank is provided with a two-marine-blade mixer, used to homogenize the froth. The Moyno pump draws the froth from the supply tank, passes it through the test pipeline, either returns to the supply tank or to the pump inlet, by-passing the supply tank. The Moyno pump is driven by a variable speed (0-1,100 rpm) motor. Since the Moyno pump is a positive displacement pump, the flow rate or the speed of the froth in the pipeline is easily determined from the pump's rpm and the pressure discharge in the pump. For more accurate determinations, a high speed video camera may be used to measure flow rates and waves speed directly. The test section is a 1" (25 mm) diameter carbon steel pipe set in a horizontal "U" configuration. Due to the high viscosity of the froth and the suspended solids in the water layer, special pressure measuring devices were installed on the line. We have applied for a patent of a buffer chamber assembly which is mounted between the pipe and pressure gauges. This device allows only water to get into the chamber and thus prevents oil from sticking to the pressure gauges. The buffer chamber is shown in figure 3.1. Special attention has to be paid to the sampling system shown in the detail of figure 3.2. It is composed of a removable section and a bypass pipe. The removable section is a glass pipe straightway connected to the main test pipeline by means of two rubber unions thightly attached to the cast iron pipe. The principal parts of the secondary loop are a small tank (provided with and electrical resistance), a gear pump, a 1/4" diameter pipeline and a copper tube. This loop provides the main loop with water for flushing, establishing a slug or fast moving behind which we can restart froth flow. It is also to control the temperature of the flowing froth. Water can be heated by electrical resistance and kept at a certain temperature in the small tank, before it is pumped through the copper tubes rolled inside the supply tank, around the Moyno pump and around part of the pipeline.

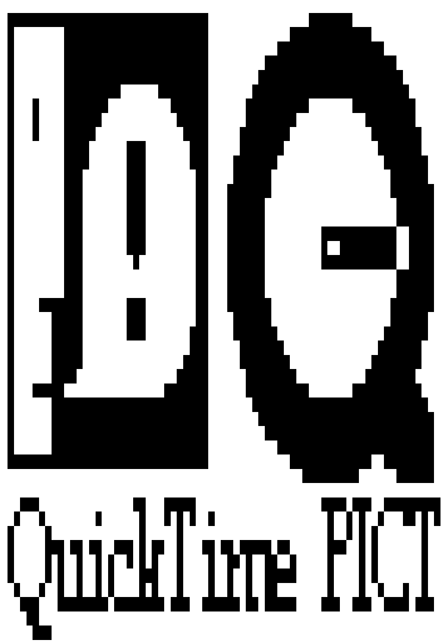


Figure 3.1. Test Facility at the University of Minnesota. The supply tank (top) and part of the test section (25 mm diameter. pipeline), with four pressure taps with analog indicators are shown (right).

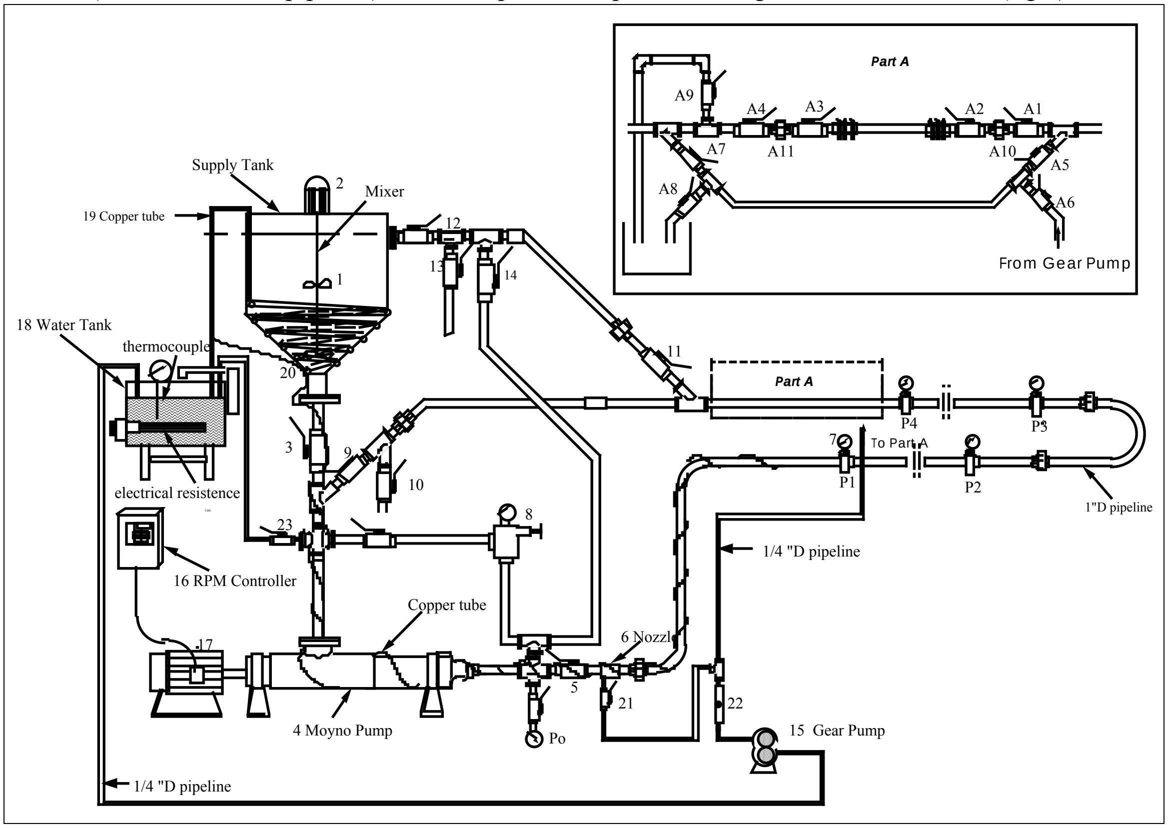


Figure 3.2. Test facility schematic. Two interconnected loops can be easily identified. First, a main loop, which principal components are a supply tank, a three stage Moyno pump and a 1”(25 mm) diameter.- 6 m long pipeline. Also a secondary or water loop which principal components a water tank, a 1/4”(6.25 mm) pipeline, copper tube and a gear pump. Bitumen Froth circulates through the main loop. Pressure taps are labeled as P_o, P_1, P_2, P_3, and P_4. The distances between them are: 3.86m (P_o-P_1), 3.96m (P_1-P_2 and P_3-P_4), and 4.37m (P_2-P_3). The sampling system (Part A) is shown in detail.

3.1.2 Test Procedures. Warm froth is loaded into the supply tank and the mixer is turned on. Meanwhile, warm water is circulated in the main loop driven by he gear pump. This flushing and warming ensures that the pipe is clean and warm enough to receive the pre-heated and pre-homogenized froth. Once the froth is homogeneous, it is injected through the Moyno pump to the main loop. Simultaneously the water is diverted. When the froth entirely replaces the water, it is circulated by the Moyno pump without further water addition. An important issue of the recirculation procedure is sampling to perform chemical and/or composition analysis. It carried out using the removable section and the bypass pipe shown in detail in figure 3.2. The shut-down procedure is the reverse of the start-up. The froth flow through the Moyno pump is stopped and water is injected to the line with the gear pump, completely diverting the remaining froth to the head tank, leaving only water circulating in the line.

3.2 SYNCRUDE TESTS

The pilot scale tests were carried out in a closed loop at Syncrude, Canada. A 24" (0.6m) diameter and 1000 m long pipeline was used. The bitumen froth was recirculated in the loop, driven by a centrifugal pump. Flow rate and pressure drop were measured using an ultrasonic flowmeter and pressure transducers. The data was automatically collected and recorded. Before and after each test, the loop was flushed with tap water. Pressure drop measurement as a function of flow rate were also carried out on produced water.

4. Results

4.1 STANDARD RHEOLOGICAL MEASUREMENTS

The froth viscosity is an ambiguous concept since the release of produced water in shear lowers the shear stress required to move the froth by orders of magnitude. However, it is still useful to measure it by means of other geometries than the capillary, because this is an easy way to characterize the froth and to provide upper limits of viscosity and thus a benchmark for computing safety and efficiency factors.

Measurements were carried out on a froth with a water fraction of 20-22% in a 22 mm (diameter) parallel plate viscometer (Rheometrics). This viscometer has a maximum allowed torque, limiting the measurements to the higher temperatures and lower viscosities.

Figures 4.1 and 4.2 show viscosity and shear stress as a function of shear rate, for four different temperatures, the viscosity decreases when temperature increases and the viscosity at a fixed temperature decreases with shear rate. Figure 4.3, shows that the measured shear stress dramatically changes it increasing rate for shear rates greater than 100 s^{-1}, for all the temperatures, but the effect is more dramatic at high temperatures. This leveling off the shear stress vs. shear suggests that the froth has entered into self lubrication; the shear stress does not change when you increase the shear rate.

The consequences of self-lubrication on measurements of viscosity may and probably are, instrument specific. A parallel plate has, in principle, a constant shear rate throughout, but the shear rate varies in capillary tubes, with the greatest shear rates at the wall, promoting water release there.

The produced water in the froth is a colloidal dispersion of small clay particles. The density of this water is slightly larger than the density of water, ρ=1.05 g/cm^3 at 20 ˚C.. The variation of density with temperature is small and we may take ρ=1 g/cm^3 with only negligible errors. We measured the viscosity as a function of temperature. The viscosity varies from 1.6 centipoise at 20 ˚C to 0.8 centipoise at 50 ˚C. In our estimates we use the value 1 centipoise for produced water.

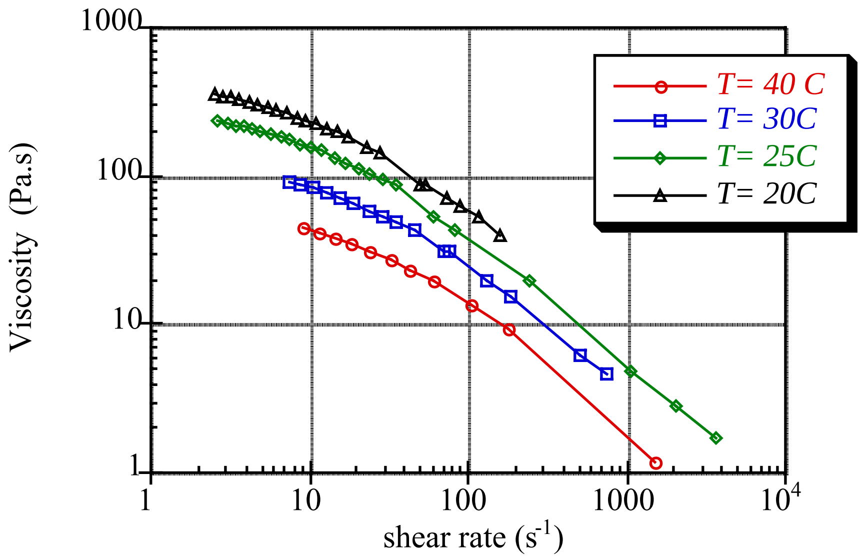


Figure 4.1. Viscosity as a function of shear rate at different temperatures for bitumen froth with a water content of 20-22%.

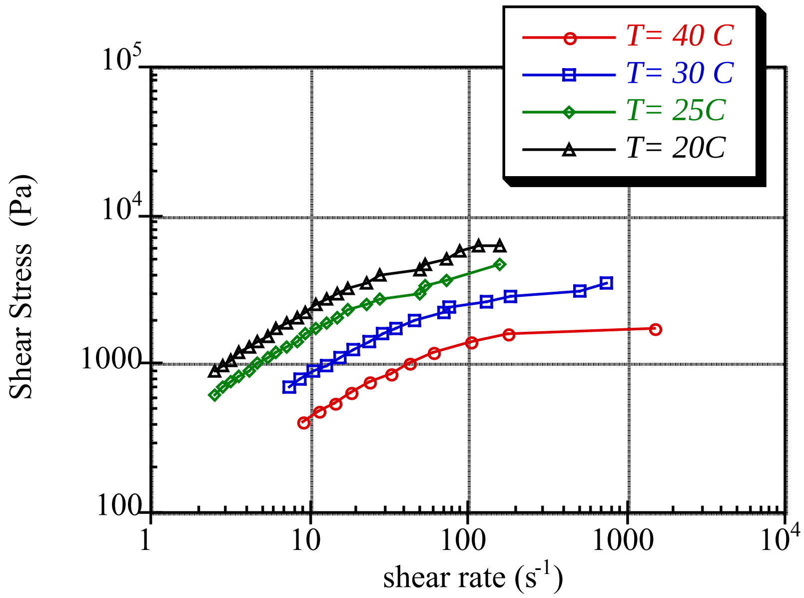


Figure 4.2. Shear stress as a function shear rate at different temperatures for bitumen froth with a water content of 20-22%.

4.2 ONE-INCH DIAMETER PIPE TESTS

Table 4.1 presents account of eight tests on self lubrication of bitumen froth carried out in the 1” (25 mm) diameter pipeline at the University of Minnesota. In this table each test is described listing the length of the test and the value of the following parameters: water content Φ; froth superficial velocity (volume flow rate divided by the pipe cross sectional area) *U* and; average temperature θ. Also listed are mass balances and figures in which pressure drop is plotted against time, speed or length.

Table 4.1. Account of tests on lubrication of bitumen froth carried out in a 1” (25 mm) diameter pipeline at the University of Minnesota.

Test No.	intervals	φ (%)	*U* (m/s)	θ (˚C)	period of time	mass balance	Figures
1	1	20-22	1.0	~35	3 h	no	-
2	4	27	-	-	-	-	-
	(a)		1.0	37	48 h	no	4.3
	(b)		1.5	43	4 h	yes	-
	(c)		2.0	46	30 min.	yes	-
	(d)		2.5	46	30 min		
	(e)		*	46	90 min.	no	4.4
3	6	27	-	-	-	-	4.7
	(a)		1.0	35	24 h	no	4.5
	(b)		1.5	37	24 h	no	4.6
	(c)		1.0	35	5 h	no	4.5
	(d)		0.5	35	24 min.	no	-
	(e)		1.25	35	19 h	no	-
	(f)		1.75	42	19 h	yes	-
4	1	40	1.0	37	9 h	no	-
5	2	22	-	-	-	-	-
	(a)		1.0	38	24 hr.	no	-
	(b)		1.5	41	24 hr.	no	-
6	1	~25	1.0	44	8 hr.	no	-
7	1	~25	1.0	55	8 hr.	no	-
8**	4	~25	-	-	-	-	-
	(a)		4.0		30 min.	no	-
	(b)		1.6		10 min.	no	-
	(c)		1.25		10 min.	no	-
	(d)		0.84		10 min.	no	-

* Sequence of 1.5, 1.25, 1.0 0.75, 0.50 and 0.25 m/s , 15 minutes each.

** This tests was carried out using a centrifugal pump instead of the Moyno Pump and without controlling the temperature. The froth recirculatation was started at about 1.5 m/s and it took 30 minutes to the system to reach a velocity of 4m/s and 71 °C of temperature.

Attention will be focused on the stability of the greatly reduced pressure gradients, which are associated with water lubrication, over long periods of time, showing that the buildup of fouling does not occur. This effect was shown most clearly in the longest tests, 2 and 3, which will be described in detail.

Test 1 was carried out with an old, low-capacity, one-stage Monyo pump (model 1L4). The carbon steel pipes used in this test were new, but thoroughly hydrated for one day in a 1% sodium *m*-silicate solution.

Based on our previous experience with core-annular flows, we decided to help lubrication by continuous injection of hot (55 ˚C) water plus 1% sodium *m*-silicate. We filled the line with the sodium *m*-silicate solution, then we introduced froth plus injected solution and we observed a good core flow for several minutes. After this, the injected solution began to dilute the froth and the initial core-flow pressure dropped from 22 psi to 12 psi, a characteristic value for the pipelining of water alone. We also tried to separate water and froth by gravity in the head tank. This procedure, that usually works well with water and oil, did not work in this case. From this we learned that the beneficial effects of sodium *m*-silicate do not apply to bitumen froth, and that gravity separation of water and froth does not work well.

In the next phase this test, we implemented the test procedure described in section 3.2. The froth self-lubricated immediately and flowed at a superficial velocity U = 1.0 m/s at a stable inlet pressure of about 40 psi, for three hours. At the end of the test, the pipeline was opened and we noticed that the inner wall of the pipe was coated with a thick layer of oil. After test 1 the old 1-stage Moyno pump (1L4) was replaced by a new 3-stage 5-Hp Moyno pump (3L4).

In test 2 bitumen froth was recirculated for 48 hours at U=1.0 m/s. The pressure reading P_o at the pump outlet was about 25 psi and all the other pressure readings were constant for about three hours. After about 25 hours, this pressure increased to 45 psi, before leveling off to 38 psi, the value we later established is near the usual value for self lubrication at U=1.0 m/s. The reason for this increase in pressure is not understood. Figure 4.3 shows the dimensionless pressure gradient $\frac{\Delta P}{L\rho g}$ history between two consecutive pressure taps in the forward and return legs of the pipeline (See figure 3.2).

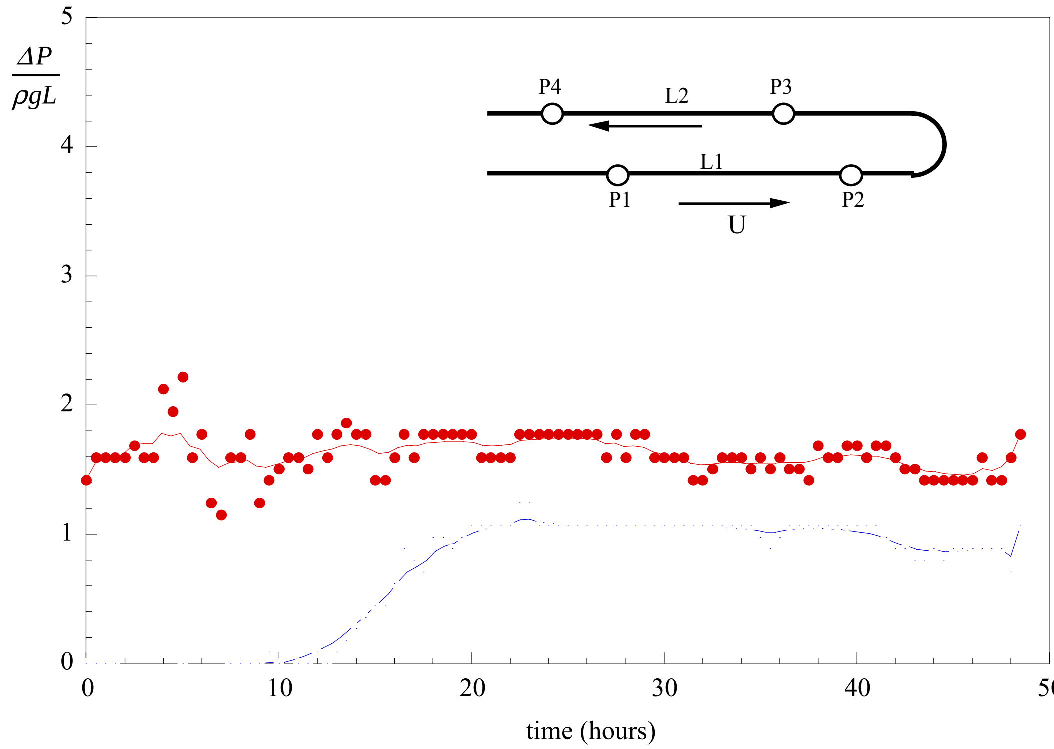


Figure 4.3 Dimensionless pressure gradient $\frac{\Delta P}{L\rho g}$ history between two consecutive pressure taps in the forward ● and return ○ legs of the pipeline for test 2 (a), 48 hours. $L_1 = L_2$ = 3.96 m. In this case, Φ=27%, U=1.0 m/s and θ=37˚C.

After 48 hours, the velocity U was increased to 1.5 m/s for four hours, then to 2 m/s for 30 minutes, and finally to 2.5 m/s for 30 minutes. The temperature increased from 37 ˚C to 46 ˚C, while increasing the velocity due to frictional heating. Then the velocity was systematically reduced following the sequence 1.5, 1.25, 1.0, 0.75, 0.50 and 0.25 m/s, keeping each velocity for 15 minutes. The pressure P_o at the pipe outlet, shown in figure 4.4 is evidently linear as it would be in laminar flow, even though the water flow in the annulus was visibly in turbulent regime.

The next step was an attempt to reproduce figure 4.4 by increasing the velocity in steps held over time intervals longer than five minutes. However at 0.5 m/s, we observed large increases and fluctuations in the pressure, before the lubricating pattern failed. We only were able to purge the system of froth after 20 minutes, adding tap water at the pump suction (inlet). We were able to reproduce the failure of lubrication at 0.5 m/s in test 3.

This failure appears to be associated with capillary instabilities in which slugs of bitumen froth form from a continuous core. The existence of a lower limit of speed for the successful operation of core-annular flow is well known for the pipelining of heavy crudes and is of obvious interest for the self lubrication of bitumen froth. In large diameter pipes, gravity is more important than capillarity and the failure at low speed will give rise to stratification of heavy and light components. The pipeline was open after test 2 and the inner walls were inspected for fouling. They were coated with less oil than in test 1.

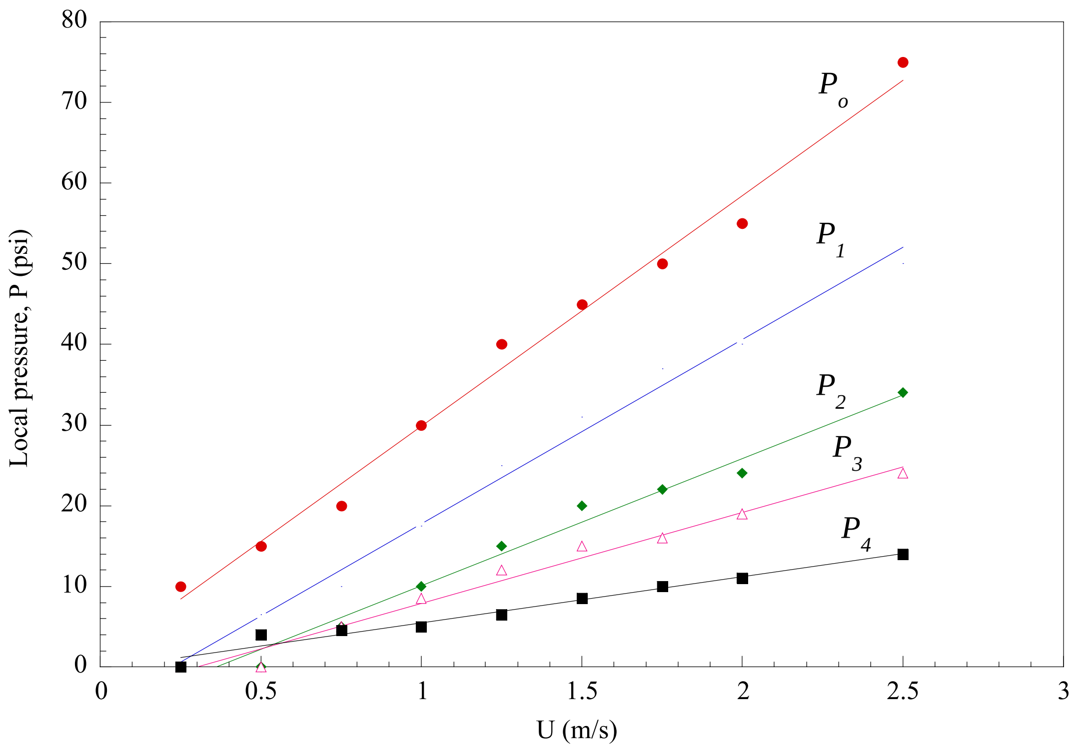


Figure 4.4 Pressure as a function of the flow velocity **U** at each pressure tap for test 2 (e), 90 minutes. Each velocity was kept for 15 minutes. P_o is the pressure at the pump outlet and P_1 ,$P_2 P_3$,P_4 are located on the line, so P_1 corresponds to the tap closest to the pump and P_4 is the most distant. In this case, Φ=27% and θ=46 ˚C·

Test 3 was a 96-hour test of continuous operation in which there was no buildup of fouling; the pressure gradients did not increase. The test started in a pipeline fouled from previous tests; flushing with tap water did not remove the oil on the wall. The superficial velocity of the core was changed during the 96 hours as described on table 4.1. The sequence (a)-(f) is chronological. The only reason for lowering the velocity U from 1.5 m/s to 1m/s was to check the reproducibility of the pressure measurements for a given flow rate. Figure 4.5 shows that the measured pressure at each tap is essentially the same for interval (a) and (c).

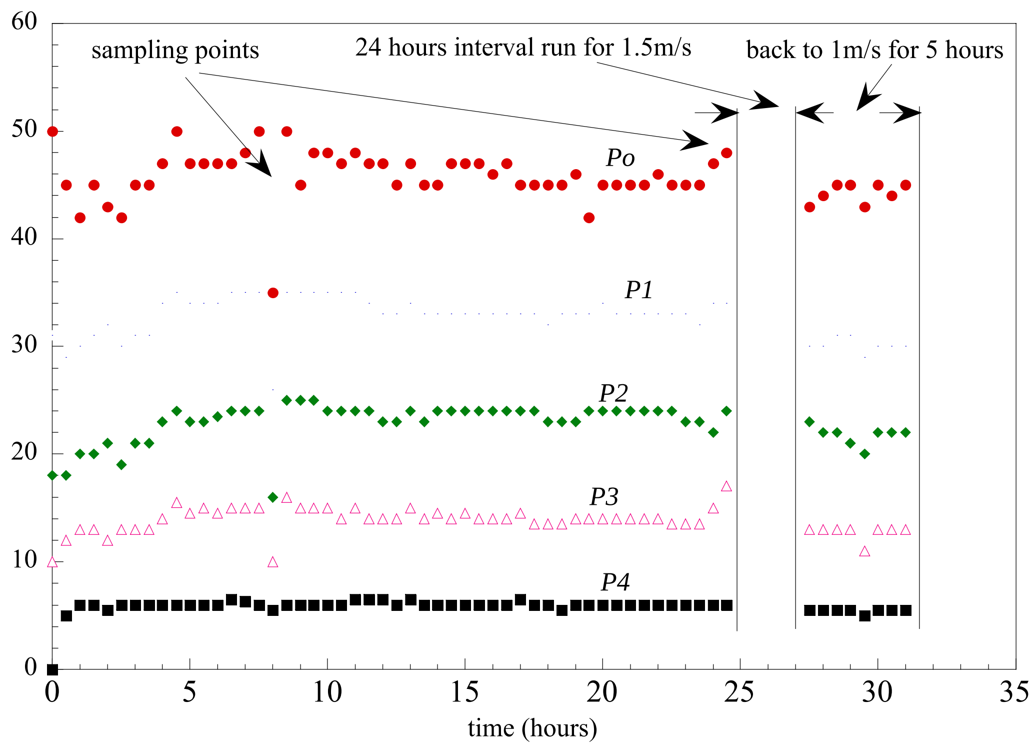


Figure 4.5 Comparison of the pressure history at each pressure tap for tests 3(a), 24 hours and 3(c), 5 hours. P_O is the pressure at the pump outlet and P_1 ,$P_2 P_3$,P_4 are located on the line. In this case, Φ=27%, U=1.0 m/s and θ=35 ˚C. There is no evidence of increasing pressure gradients over time.

The pressure gradients obtained during this test were nearly constant, as illustrated in figure 4.6. The transients which are induced by taking samples from the pipeline are short lived. These features show that the buildup of pressure, which would occur if there was an accumulation of fouling, does not occur.

At the end of interval (c) the velocity was dropped to 0.5 m/s, but the pressure was so unstable, that after 20 minutes we raised it to 0.75 m/s; pressure P_o at the pump outlet jumped to 100 psi and the pipeline strongly vibrated, driven by pressure oscillations. The speed was then immediately raised to 1 m/s. The transient pressure P_o at the outlet rose to

200 psi and the pressures along the line were over 100 psi. This indicates some partial blockage. After five minutes, the pressures reduced to normal values, 40-45 psi, at the pump outlet and the speed was raised to 1.25 m for m/s and kept for 19 hours. Then it was raised again to 1.75 m/s for other 19 hours.

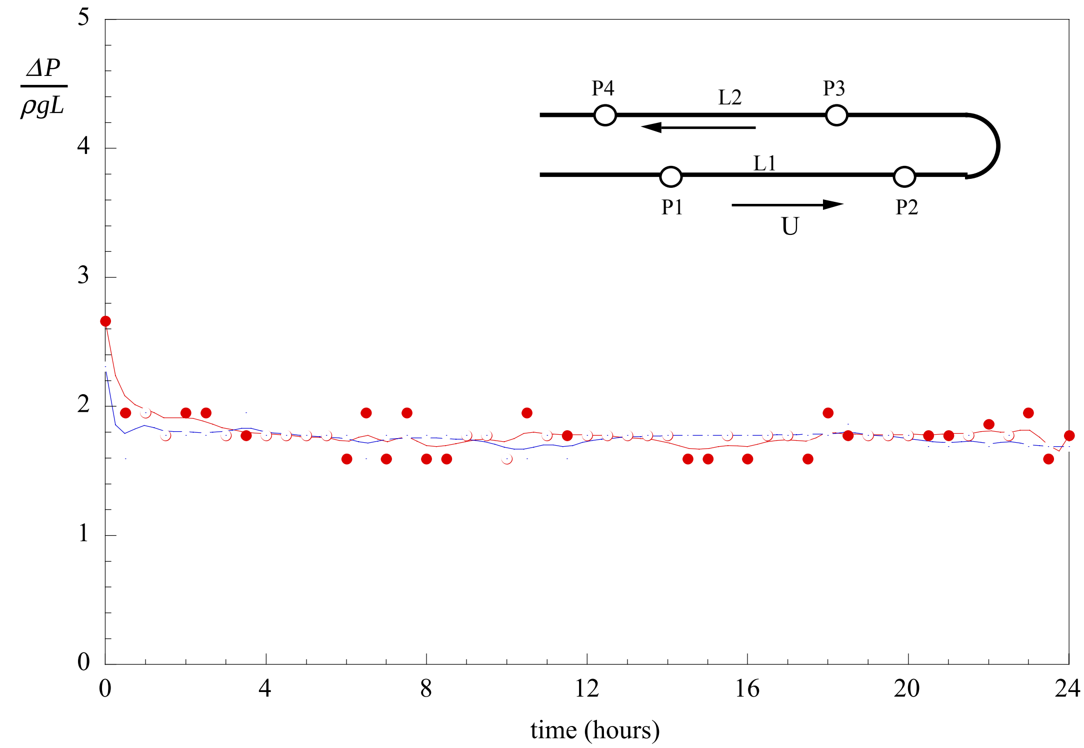


Figure 4.6. Dimensionless pressure gradient $\frac{\Delta P}{L\rho g}$ history between two consecutive pressure taps in the forward • and return ∘ legs of the pipeline for test 3 (b). L_1=L_2=3.96 m. In this case, Φ=27%, U=1.5 m/s and θ=37 ˚C.

Figure 4.7 shows the pressure distribution along the pipeline, parametrized by the velocity U for test 3. Mean values of the pressure were calculated for each tap at each velocity. A decrease of the length of the waves on the bitumen froth was observed at high speeds and it seemed that less free water was present. The average temperatures of the froth increased because of the frictional heating to around 42 ˚C. It is possible that some free water is reabsorbed into the froth at high temperatures as has been suggested by Neiman [1985], who found that heating and water-dilution affect the lubricating layer.

Heated and unheated froth possessed a similar headloss, which hardly changes, when the total separable water is increased above 35%.

After the 96-hour run, a sample was taken and cooler froth was injected to replace it; the temperature decreased from about 42 ˚C to 30 ˚C. The pressure transients vanished at this point. The velocity was then lowered to 0.7 m/s and the pump outlet pressure P_o increased to 80 psi. To remedy this increase of pressure, we injected a small amount of water and returned to stable flow at 1 m/s for 20 minutes. Then the flow velocity was lowered in decremental steps of 0.1 m/s to 0.5 cm/s. The core flow segregated into slugs of froth separated by water and the increased diameter of the slugs We were able to start the stopped line by slow injection of water from the Monyo pump. During the early stages of restart, the pressures were so high that we blew out the transducer at tap two and oil from the first pressure tap P_1 sprayed out of the hole. The restart took no longer than five minutes.

The pipeline was cleaned by running produced water through the line for one hour. After this cleaning, the pipe was opened. The first leg of the pipe as well as unions and joints were lightly fouled. The second leg of the pipe was very clean. It was the first time that we could clean a carbon steel line down to bare metal by washing, and we believe it is a special effect of the clay dispersion.

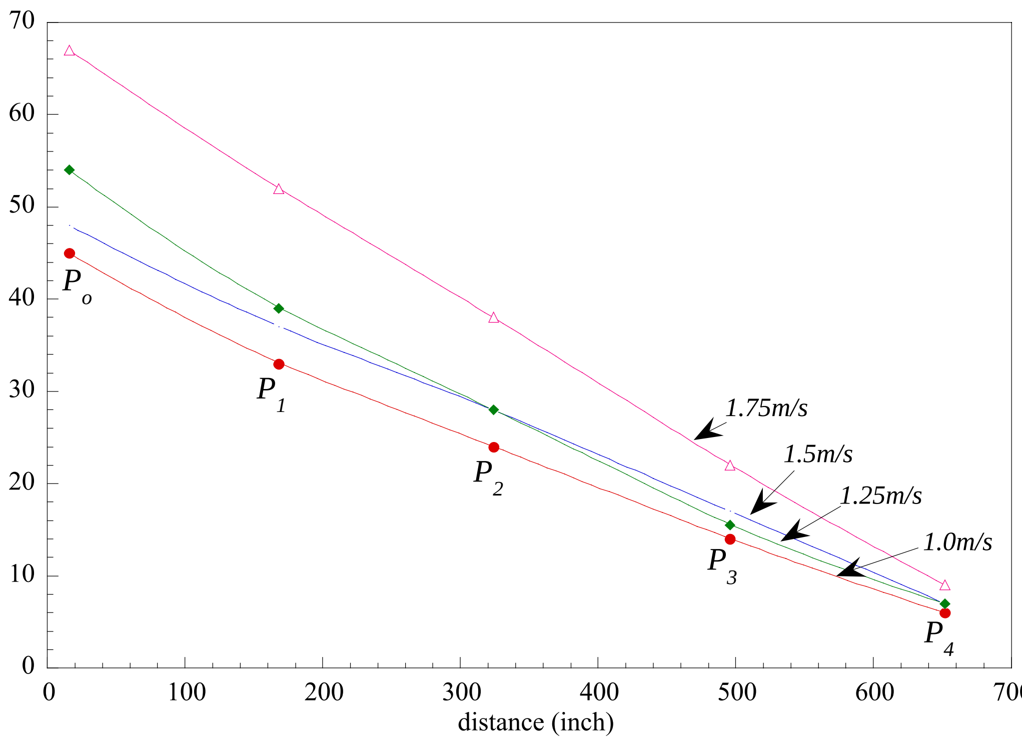


Figure 4.7. Pressure distribution along the pipeline, parametrized by the velocity **U** for test #3, 96 hours. P_o is the pressure at the pump outlet and P_1 ,$P_2 P_3$,P_4 are located on the line, so P_1 corresponds to the tap closest to the pump and P_4 is the most distant. In this case, Φ=27% and θ varied from 35 °C , for *U*=1.0 m/s to 42 °C, for *U*=1.75 m/s.

During tests 2 and 3, samples were taken for three different velocities, as shown in Table 4.1. These samples were weighted. Then, by carefully pouring the free or produced water into another container, froth and free water were separated and weighted. Finally the water content of the remaining froth was measured by distillation and the water content of unpumped froth was also measured. In this way, a complete mass balance was constructed and is given in table 4.2. The mass balances made on the pipelined froth, match the mass balances for the unpumped froth, within the expected error. It is of interest to note that the most water is released for the highest velocity.

Table 4.2. Mass Balances for the bitumen froth pipelined in tests 2 and 3 made on a 100gr base.

Test No.	U (m/s)	Original water/oil	Pipelined free water/core	Core water/oil	Total pipelined water/oil
2	1.5	27/73	5/95	23/72.2	28/72.2

2	2.0	27/73	7/93	21.4/71.6	27.4/71.6
3	1.75	-	2.7/96.3	25/71.4	27.7/71.4

The water content of the froth used in test 4 is the highest (Φ=40%) of all the samples tested. The dimensionless pressure gradient record (included in an internal report) for this watery sample shows more erratic behavior than less watery samples. However, the pressure levels are roughly those of other samples with different water contents. Moreover, there is again no evidence of a systematic increase of pressure which could indicate accumulation of fouling.

Test 5 was carried out at U=1 m/s and average temperature of θ = 38 ˚C for 24 hours. Then the velocity was increased to 1.5 m/s, for another 24 hours and the temperature increase to 41 ˚C. The weight fraction of water (Φ=22%), is the smallest of all the samples tested. The dimensionless pressure gradient record for this relatively dry sample shows less erratic behavior than all other samples and the pressure levels are uniformly low. There is absolutely no indication of accumulation of fouling. The usual free water layer appeared. Moreover, there was no indication of less free lubricating water in this than in other tests.

In tests 6 and 7, bitumen froth (Φ~25%) was recirculated during 8 hours at U = 1m/s and at temperature of 44 ˚C and 55 ˚C, respectively. We found that raising the temperature does not improve the already magnificent lubricating pattern in our 1" diameter pipe. Heating of bitumen froth can promote the reabsortion of the released water into the core, but it also lowers the bitumen viscosity; flow resistance is then determined by competing effects of water depletion and viscosity reduction.

For test 8 we used a Teel Centrifugal Pump (model J.L.) able to pump up to 50 GPM or to give a maximum pressure of 60 psi (for zero flow). Bitumen froth was recirculated for one hour. We changed the velocity U in four steps, 4.0, 1.6, 1.25 and 0.84 m/s. The froth recirculation was started at θ = 30 ˚C and U≈1.5 m/s; it took 30 minutes to reach a velocity of 4.0 m/s and a temperature of 61 ˚C. The temperature of the froth was not controlled in these experiments using a centrifugal pump. The observed rise in temperature can be attributed to frictional heating. Tiger waves (figure 6.1) were observed at all temperatures.

4.2 PILOT SCALE TESTS

The pilot tests were in a 24”(0.6m) diameter, 1000m long pipeloop at Syncrude, Canada. A narrative of tests results will now be given. The pump drive speed was initially set at 650 rpm to obtain a froth flow velocity of about 1.0 m/s. As the froth displaced the water in the pipeline, the pump discharge pressure increased. It took about 10 minutes to displace the water completely and to establish the core-annular flow. To ensure stable flow, the pump drive speed was gradually increased to 800 rpm. As the pump speed increased, the pump discharge head was well below that required for pumping water at similar flow rates. This operational setting was continued without change for about 24 hours. During this period, the pressure and flow readings were monitored. There was no increase of the pressure drop and other bitumen fouling related problems. However, both froth temperature (43°C vs. 47°C) and velocity (1.10-1.14 m/s vs. 0.90 m/s) decreased for a fixed pressure drop across the loop as the night approached.

In the next test core annular flow at a temperature of about 55°C was readily and predictably established in 10 minutes. The initial pump drive speed was set at 650 rpm and the froth flow velocity was maintained at about 0.9 m/s for 2 hours of steady operation. Then the pump drive speed was raised and lowered gradually from 650 rpm to 1000 rpm and back in steps of 50 rpm. At each speed, pressure and flow readings were monitored for about 10 minutes and the test ran for 2 hours. There was no hysteresis observed either in the velocity or pressure. The average of the two sets of data at a given speed was used for further analysis. Following the successful completion of the flow variability tests, flow interruption and restarting tests were carried out. However, the details will not be discussed here. A final test deserves consideration. Froth was continuously pumped for 36 hours; the froth temperature oscillated between 42 to 47°C. The temperature steadily decreased during 8 PM to 8 AM and gradually increased between 8 AM to 8 PM reaching the maximum by about 2 PM. The froth velocity also oscillated in the same manner; the froth velocity increased with temperature.

5 Analysis of data

5.1 HYDRODYNAMIC BEHAVIOR

Figure 5.1 presents the measured pressure gradient of bitumen froth β [Kpa/m] as a function of the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe radius, parametrized by temperature. Three regions can be easily identified, corresponding to the data collected in the 24" (0.6m), 2"(50 mm) and 1"(25 mm) pipelines. All the available data is shown in figure 5.1. The 2"(50 mm) diameter pipeline data of Nieman (1985) is greatly scattered and will be mostly ignored in our analysis.

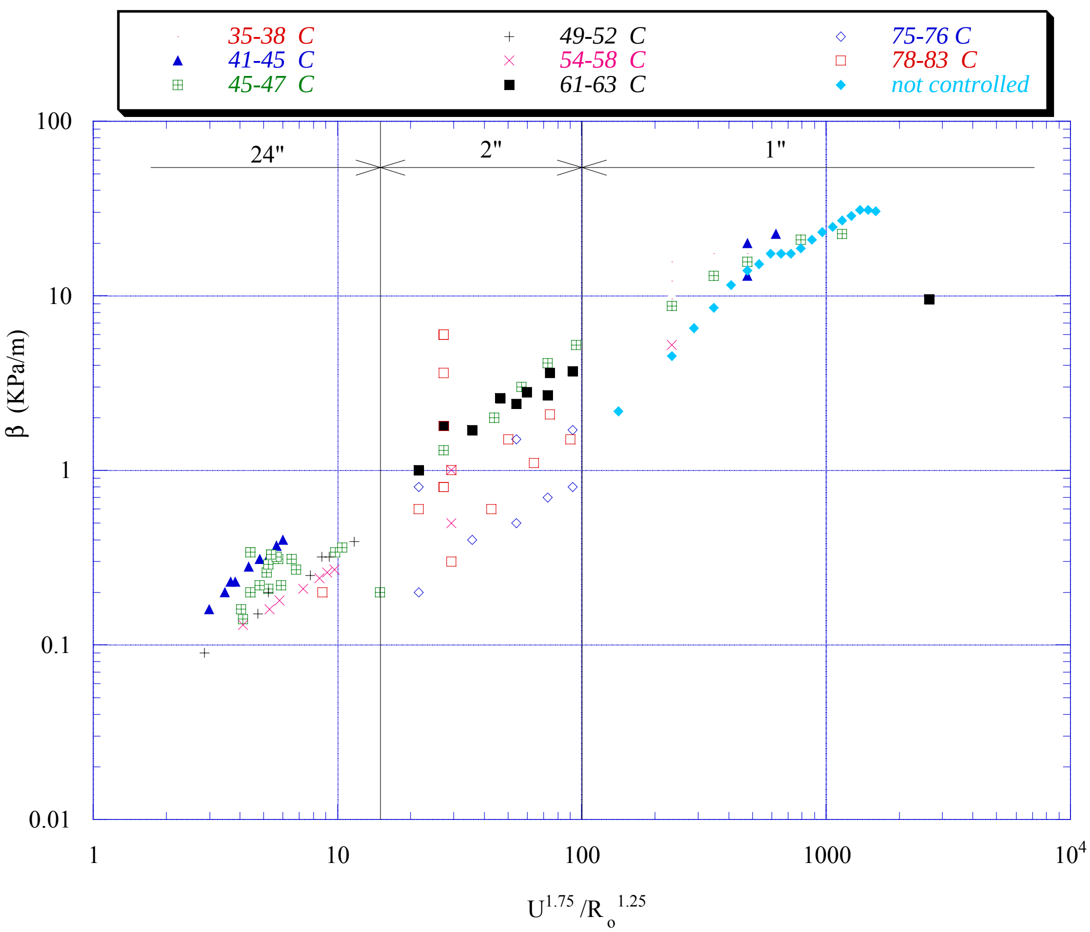


Figure 5.1 All available data for pressure gradient of bitumen froth β [Kpa/m] as a function of the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe radius, parametrized by temperature. Left: 24"(0.6 m) diameter pipeline; middle: 2"(50mm) diameter pipeline (Niemans' data); and right: 1"(25 mm) diameter pipeline.

Data contained in a high temperature (49-58 °C) and a low temperature (38-47 °C) ranges collapse into two curves parallel to the Blasius' formula for turbulent pipeflow (for

Reynolds numbers below $3x10^6$). These curves are shown in figure 5.2. The parameters defining these curves are presented in table 5.1 and were determined by the following considerations.

A force balance per unit length gives a relationship between the pressure drop β and the shear stress τ_w on the pipe walls:

$$\tau_w = \frac{\beta R_o}{2} \quad (5.1)$$

where R_o is the pipe radius. But the shear stress τ_w may be expressed as function of a friction factor λ defined as follows:

$$\lambda = \frac{8\tau_w}{\rho U^2} \quad (5.2)$$

We now introduce an empirical correlation (based on the Blasius'formula) for

$$\lambda = \frac{k}{Re^{1/4}} \quad (5.3)$$

where k is an unknown constant (k = 0.316 for Blasius' model) and Re is a Reynolds number defined as

$$Re = \frac{2R_o U}{\nu} \quad (5.4)$$

where ν is the kinematic viscosity of water.

Combining equations (5.1) to (5.5) we can obtain an expression for the pressure gradient β [Kpa/m], in terms of the 7/4th power of the velocity U [m/s] to the 4/5th power of the pipe radius R_o [m].

$$\beta = K\frac{U^{7/4}}{R_o^{5/4}} \quad (5.5)$$

K is a fitting parameter determined from a given value of U and R_o and measured β which determines the constant k previously defined.

Table 5.1 Fitting constant *K* for two temperature ranges, using equation (5.6).

Temperature Range (°C)	*K*	Corresponding *k* (approx.)	Correlation factor R
38-47	$40.5\text{x}10^{-3}$	6	0.999
49-58	$28.1\text{x}10^{-3}$	3	0.995

From table 5.1, we can conclude that the self-lubricated pipelining of bitumen froth requires 10 to 20 times more pressure gradient than the Blasius value for pure water (for k = 6, $\frac{6}{0.316} \approx 20$). Therefore, the increase in the pressure gradient over and above the Blasius value observed in figure 5.2 is of the order of 10 to 20 and it is independent of velocity or pipe size. This is amazing.

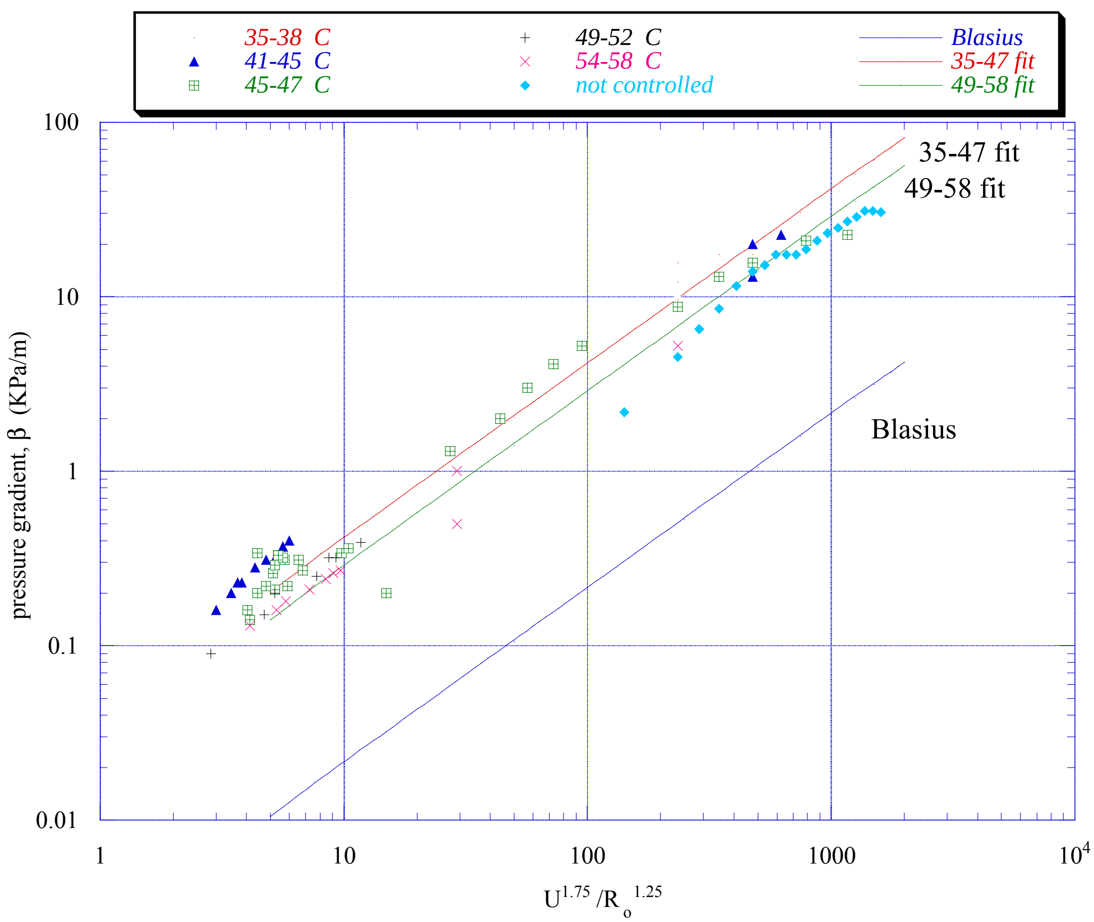
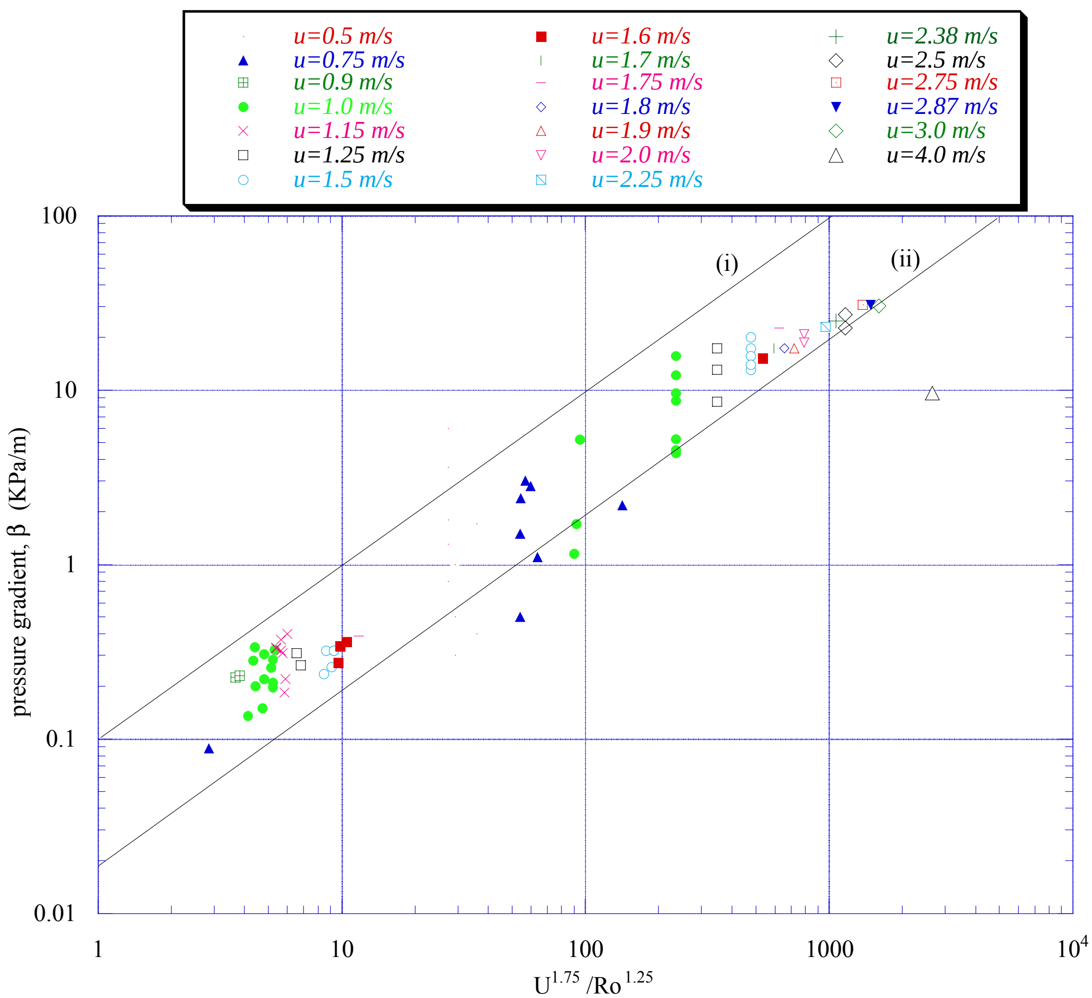
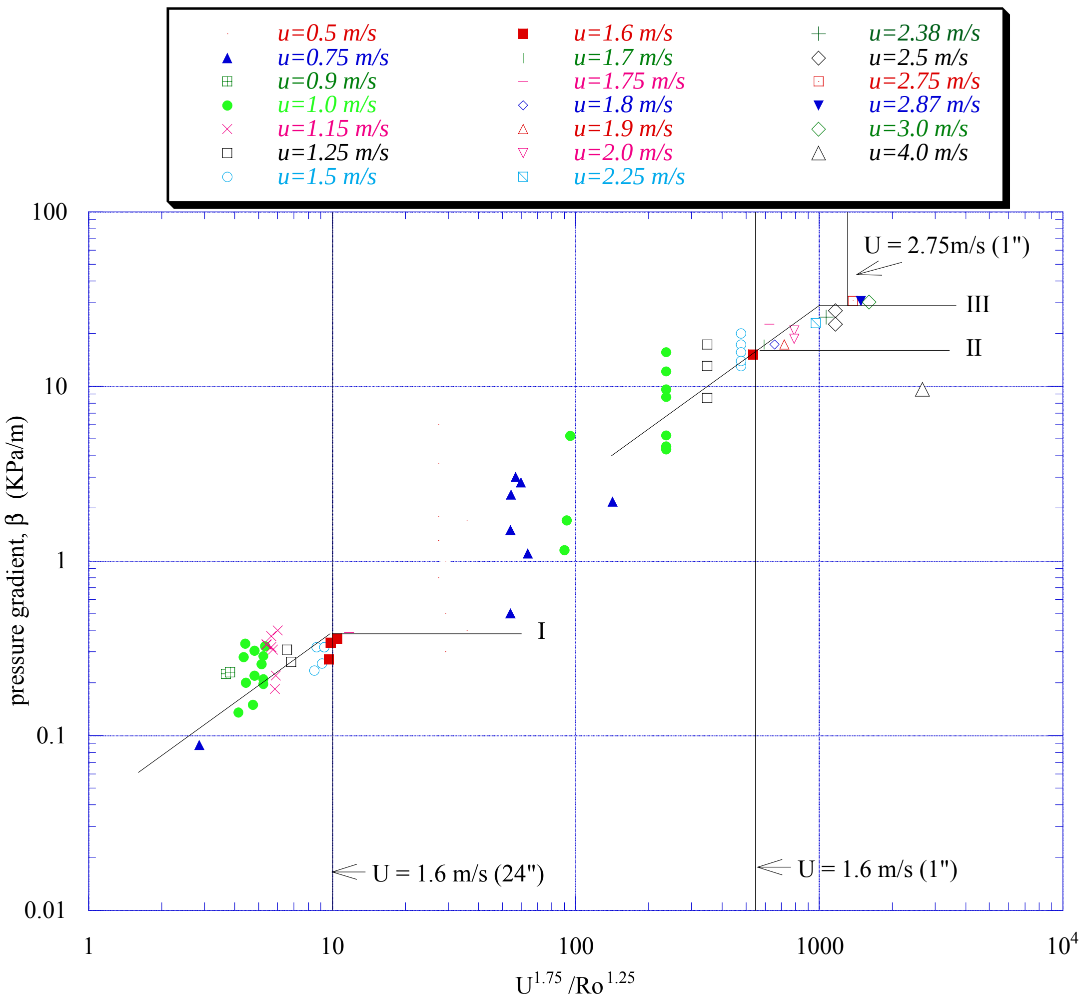


Figure 5.2. Fittings parallel to the Blasius correlation for turbulent pipeflow (bottom line), for two temperature ranges: 35-47 °C (top) and 49-58 °C (middle) presented in figure 5.1. Most of the 2”(50 mm) diameter pipeline data was ignored in these fits, due to its high scatter.

Figure 5.3 presents again all the available data, this time, parametrized by velocity rather than temperature. In figure 5.3(a), curves (i) and (ii) enclose most of the data, if the scatter in the 2”(50 mm) diameter pipeline data region is ignored. They are respectively the most pessimistic and least pessimistic predictions for β based on Blasius’ formula. Another point of view is given by figure 5.3(b). There, curves I and II and III predict the pressure gradient based on a velocity criterion, for the 24”(0.6 m) and 1”(25 mm) pipes, respectively. These curves are parallel to the Blasius formula and most of the points are located between curves (i) and (ii) (see figure 5.3(a)). The existence of critical values for a more complete lubrication is suggested by the data. At these values the pressure gradient turns flat on a plateau and does not increase as the velocity is increased. This kind of lubrication can be called “something for nothing”; it is possibly a robust phenomena associated with frictional heating of froth (see figure 5.4).



(a)



(b)

Figure 5.3 Pressure gradient of bitumen froth β [Kpa/m] as a function of the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe radius, parametrized by velocity. Left: 24"(0.6m) diameter pipeline; middle: 2" diameter pipeline (Niemans' data); and right: 1" diameter pipeline. (a) All available data, enclosed by the most pessimistic (i) and least pessimistic (ii) predictions for β based on Blasius' formula, and ignoring the scatter in the 2"(50 mm) diameter pipeline data region . (b) I and II and III are predicted pressure gradients β, based on a velocity criterion, for the 24"(0.6m) diameter pipeline data and 1"(25 mm) diameter pipeline data, respectively. Here the critical velocity is approximately U_c = 1.6 m/s for curves I and II and U_c = 2.75 m/s for curves III.

Figure 5.4 shows the pressure gradient vs. the Blasius parameter $U^{7/4}/R_o^{3/4}$ together with the froth temperature, in the case in which the wall temperature not controlled, the temperature values are marked on the response curve (each of four thermocouples, just inside the pipe wall at different positions covering the whole length of pipe, registered the same temperature). The points on figure 5.4 are included in the data shown in figures 5.1, 5.2 and 5.3; they follow the Blasius law up to the first critical value U = 1.6 m/s after which they exhibit a flattening "something for nothing" transition already discussed. At a value of U ≈ 2.0 m/s the curve begins to rise again to a second flattening transition at U = 2.75 m/s. The temperature increases monotonically with flow speed and the temperature rise is substantial.

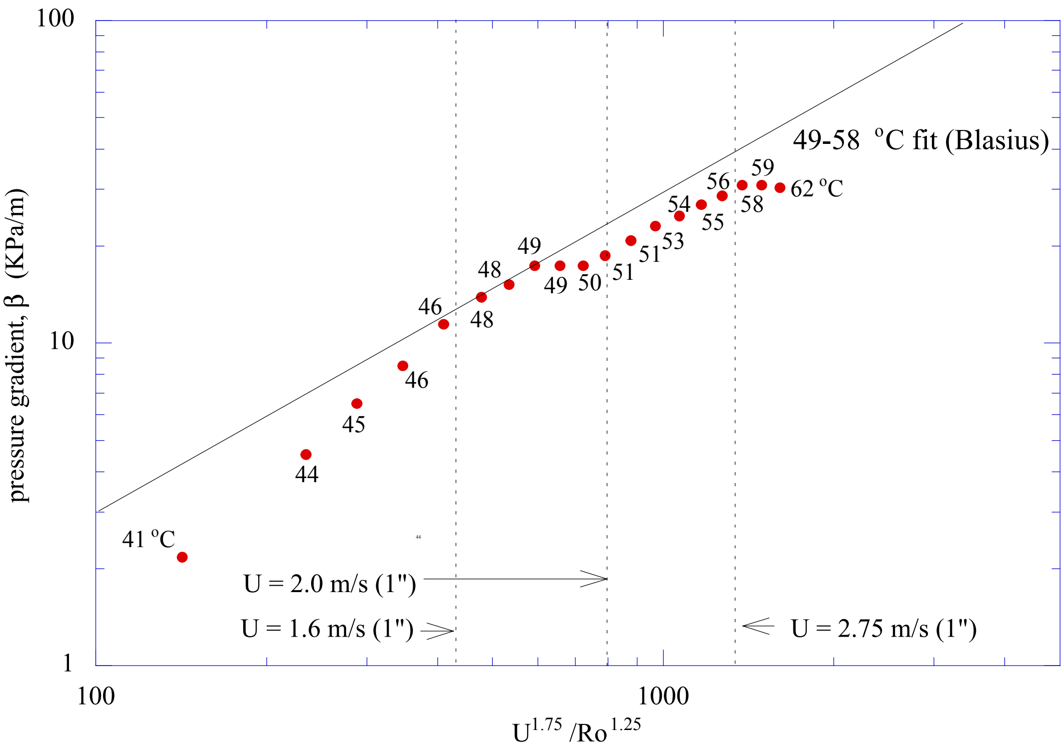


Figure 5.4 Pressure gradient vs. Blasius parameter in the 1" (25 mm) diameter pipe. The temperature of the room was 26 °C and the froth temperature was nor controlled; the increase in temperature is due to frictional heating as shown in figure 5.5.

Figure 5.5 shows the same data plotted as temperature vs. velocity. The temperature rise is nearly proportional to U^2; this is consistent with frictional heating generated by a heat source of magnitude $\bar{\mu}\left(\frac{d\bar{u}}{dy}\right)^2$ where $\bar{\mu}$ is an effective viscosity and $\frac{d\bar{u}}{dy}$ an effective shear rate in a layer of sheared froth near the wall. The data should be useful for modeling the effects of frictional heating.

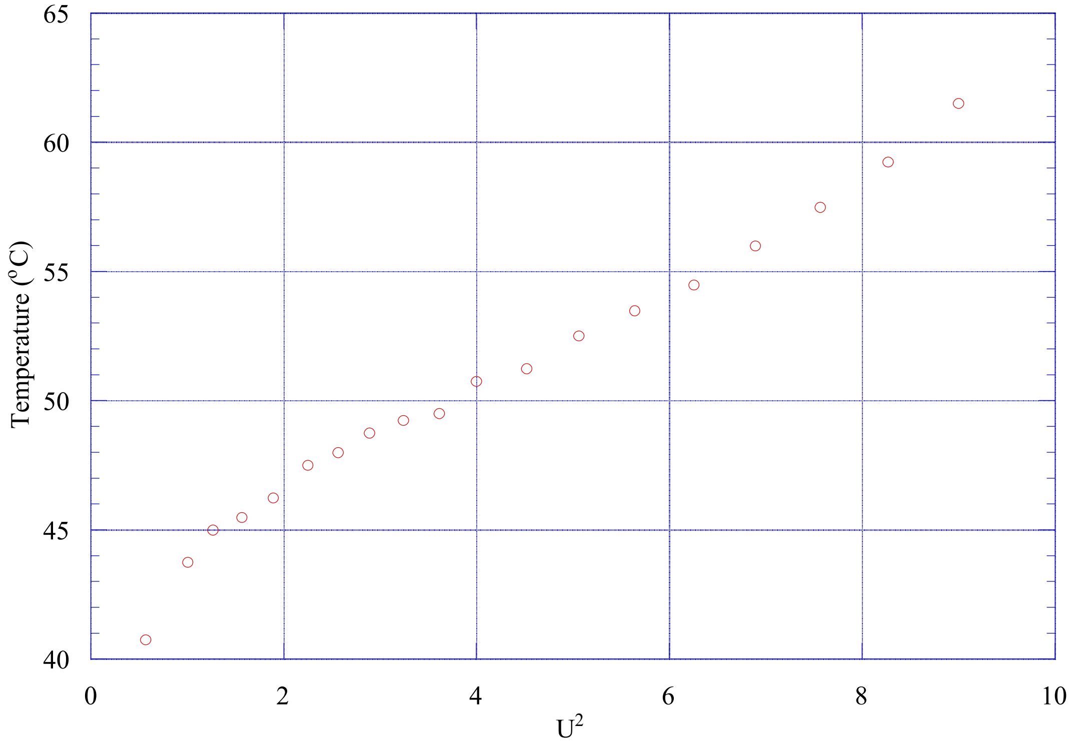


Figure 5.5 Temperature vs. the square of the flow speed for conditions specified in figure 5.4. the rise in temperature is approximately linear suggesting frictional heating.

We have already noted that there is a critical value for the start of self lubrication, in principle no larger and probably smaller than the start value. the critical value for lost of lubrication depends on the froth temperature which changes with speed. Hence, in principle we should find one loss value by reducing the pressure gradient in steps after allowing the temperature to equilibrate in each step. To see how this critical value varies with the ambient temperature we used our running water controller which allows to control the pipe wall temperature. The result of this study is shown in figure 5.6. Lubrication can be maintained at smaller speeds when the froth temperature is larger. The results suggest that lubrication might be difficult to maintain at very low temperatures. Fortunately the froth temperature is naturally and substantially raised in working pipelines by frictional heating.

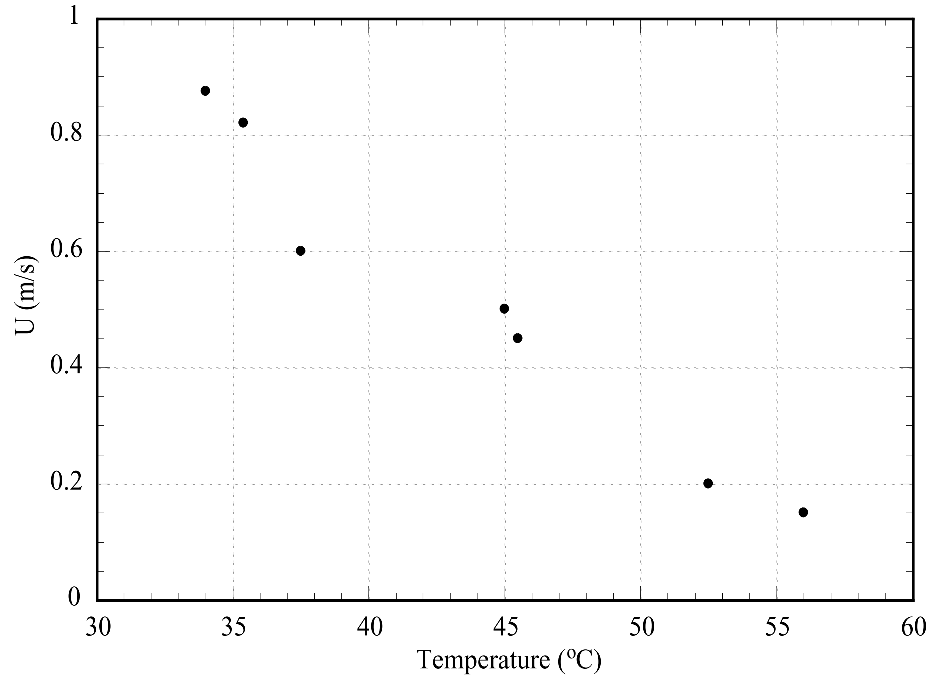


Figure 5.6 Froth velocity at which self lubrication is lost as a function of the froth temperature. Self lubrication is more persistent at high temperatures.

5.2 PREDICTION OF THE RELEASED WATER LAYER THICKNESS

It is possible to estimate the thickness of the water layer, as well as the associated water volume fraction, when bitumen froth is flowing with an average velocity *U* in a pipe of radius R_o. Figure 5.7 shows a cartoon of the released water flow, between the wavy bitumen froth core and the pipe wall. We can define an effective mean gap size δ, which would be the distance between the wall and a perfectly smooth bitumen froth core. We can also change the frame of reference; fix the core and let the wall move with the measured average velocity *U* of the froth.

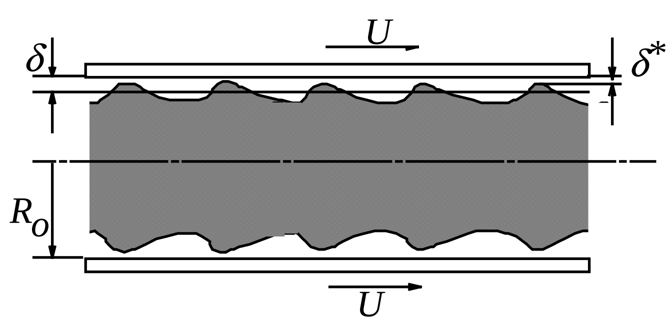


Figure 5.7 Released water layer thickness δ for self lubricated froth flow. R_o is the pipe radius and δ/R_o<<1. The frame of reference has been changed. The bitumen froth core is fixed and the pipe wall moves with the measured average velocity of the froth *U*.

Let X be the mass fraction of free water with mean depth δ for a given flow velocity U and a pipe radius R_o. We suppose that the mass fraction is equal to the volume fraction and the ratio of the volume of water in an annulus of thickness δ to the total volume of water is the same as the ratio of the area of the annulus to the total area. Hence,

$$X = \frac{R_o^2 - (R_o - \delta)^2}{R_o^2} = \frac{2\delta}{R_o} \tag{5.6}$$

when $\delta << R_o$.

Since our data fits curves parallel to the Blasius curve for turbulent pipeflow, an attractive way of predicting the water layer thickness δ is given by Reichardt's model of turbulent Couette flow (1956), which is a version of the universal law of the wall. Figure 5.8(a) illustrates this model: two parallel plates, separated by a distance δ_o, are moved in opposite directions with a velocity U_o. The fluid inside is sheared giving rise to a 'S' shaped velocity profile, which is described by equation 5.7.

$$\frac{U_o}{u^*} = 2.5\ln(2\eta_r) + 5.5 \tag{5.7}$$

η_r is a dimensionless length, defined as follows:

$$\eta_r = \frac{ru^*}{\nu} \tag{5.8}$$

where $r = \delta_o/2$ is the distance from the wall to the center of the channel, u^* is the friction velocity and ν is the kinematic viscosity of the water.

The friction velocity u^* is

$$u^* = \sqrt{\frac{\tau_w}{\rho}} \tag{5.9}$$

where ρ is the water viscosity and τ_w is the shear stress on the wall, given by equation 5.1

If we now change the frame of reference and let the wall move with a velocity $U_o = 2U$ and let $r=\delta/2$, as shown in figure 5.8(b), an expression for the released water layer thickness δ may be obtained from equation (5.6), as a function of U and u^*. That is

$$\delta = \frac{\nu}{u^*} \exp\left(\frac{0.5\frac{U}{u^*} - 5.5}{2.5} \right) \tag{5.10}$$

Equation (5.10) predicts values of δ of the order 10^{-3} mm for the 1”(25 mm) and 24”(0.6m) diameter pipelines data. These values do not agree with the values obtained from the mass balances carried out in the 1”(25 mm) diameter pipeline tests, which are listed on table 5.2. We presume that this small gap is between the pipe wall and the crests of the waves, indicated as δ^* in figure 5.7. However we are interested in predicting the mean gap size δ, which is much larger.

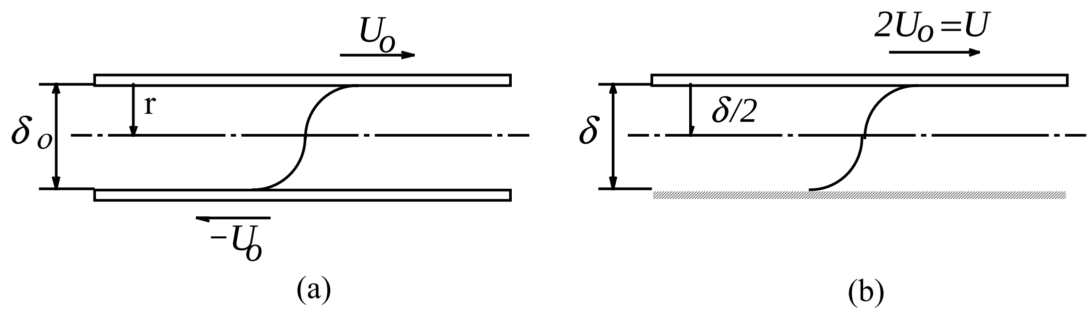


Figure 5.8 Turbulent Couette flow by Reichardt (1956). (a) Two parallel plates, separated by a distance δ, are moved in opposite directions with a velocity *Uo*. The distance from the wall to the center of the channel is denoted by r. (b) The frame of reference has been changed. Now the lower wall is fixed and represents the bitumen froth core, and the upper wall represents the pipe wall, moving at a velocity U = 2Uo. Here δ denotes the effective mean gap size.

Since we know that our data fits Blasius’ formula with a friction factor (k/0.316) times greater than the one given by equation 5.2, or

$$\lambda_k = \frac{k}{0.316} \lambda_{Blasius} \tag{5.11}$$

we can define a pseudo friction velocity as follows:

$$u^*_k = \sqrt{\left(\frac{0.316}{k}\right)\frac{\tau_w}{\rho}} \tag{5.12}$$

where the factor (0.316/k) shifts the measured value of the shear stress τ_w (obtained from the pressure drop). Now, if we let $u^* = u^*_k$, equation (5.10) becomes

$$\delta_k = \frac{\nu}{u*_k} exp\left(\frac{0.5\frac{U}{u*_k} - 5.5}{2.5} \right) \tag{5.13}$$

We used equations (5.13) and (5.6) with k=20, to calculate the values of the water layer thickness δ_k and the corresponding mass fractions X_k. These values are listed in table 5.2, where they are compared to the values obtained from the mass balances[†]. The agreement in the order of magnitudes is obvious. Effects of temperature, which are not considered in this model, may be the source of the discrepancy between the measured and calculated values of δ. Frictional heating is very important at high velocities and an increase in temperature may promote reabsorption of some of the released water. More research is required to validate and improve this model; for the moment, the predictions of the released water fraction for the 24"(0.6m)-diameter pipe data are satisfactory and consistent with the water fractions calculated for the 1"(25 mm)-diameter pipe data (see table 5.3).

Table 5.2 Measured and calculated released water layer thickness δ and volume fraction for self lubricated froth flow in a 1"(25 mm)-diameter pipe.

U [m/s]	Released water layer thickness [mm]		Released water mass fraction %	
	measured (δ)	calculated (δ_k)	measured (X)	calculated (X_k)
1.5	0.3	0.26	4.7	4.2
1.75	0.17	0.36	2.7	5.7
2.0	0.44	0.80	6.9	13

Table 5.3 Predicted released water layer thickness δ_k and volume fraction for self lubricated froth flow in a 24"-diameter pipe.

U [m/s]	Released water layer thickness δ [mm]	Released water mass fraction X %

[†] Given the mass (volume) water fraction X, the water layer thickness δ may be computed using equation (6.7)

1.0-1.75	1-7	1-5

6. Mechanism of Self-Lubrication of Bitumen Froth

Bitumen froth is a very special kind of multi-phase material. It combines properties of an oil continuous phase in which water is the dispersed phase with properties of a water continuous phase, like oil-in-water emulsions. In the usual oil-water mixture, dispersions of 22-40% water-in-oil are very stable and very viscous with viscosities even higher than the oil alone.

The dispersion of 22% water in bitumen which we studied in test 5 would be robustly stable as an ordinary two-phase mixture. You could not get a monosized dispersion of 78% bitumen drops in water because such a concentrated dispersion could not be packed. The 22% water froth in the pail looks like a pure bitumen, since no free water can be seen. That froth is extremely viscous to low shearing. However, the froth is unstable to faster shearing which causes produced water droplets to coalesce and form a free lubricating layer of free produced water. In fact, tests indicate a tendency for droplets of produced water to coalesce even under static conditions.

The unusual properties of bitumen froth with respect to the coalescence of water droplets leading to self-lubrication has everything to do with the fact that produced water is a dispersion of small clay particles in the water. The produced water is not clear, but has gray color of clay which can be called milky. The milky appearance is persistent because the small particles are of colloidal size $O(\mu)$, held in suspension by Brownian motions. When the free water is generated at the wall in a pipe flow, the water is opaque. You can't see through it except that "tiger" waves which are like the waves which develop in core-annular flows, poke through the milk where the produced water layer is thin (see figure 6.1). The free milky water is roughly 20-30% by weight of the original water in the sample, so that quite a lot of coalescence has occurred. (The weight fraction of the free water relative to weight of the mixture defining the froth core is just a few percent.)

The clay water inhibits the coalescence of bitumen froth and promotes the coalescence of clay water drops through a mechanism which can be called "powdering the dough: Dough is sticky, but when you put flour powder on it, the dough loses its stickiness and is protected against sticking by a layer of powder. The clay in the produced water is just like powder; it sticks to and prevents the bitumen froth from coalescing. Zuata crude is much more sticky than bitumen froth and it sticks strongly to glass and plastic bottles filled with water, but not when filled with produced water; this is very remarkable and totally unexpected.

The action of the clay particles is very much like the action of surfactants which are used to stabilize emulsions. Yan and Masliyah [1994] have investigated the absorption and desorption of clay particles at the oil water interface. They note that it is generally accepted that hydrophilic particles (clay) stabilize oil and water emulsions while hydrophobic solids stabilize water-in-oil emulsions. The fine solids absorbed on the droplet tend to act as a barrier, protecting the oil droplets from coalescing with one another. They study the effect of kaolinite clay particles on stabilization of oil in water emulsions using a multilayer absorption model. As in the theory of absorbed surfactants, absorption isotherms relating the bulk concentration to the surface excess are important. They note that "...To obtain a stable solids-stabilized oil in water emulsion, it is necessary for the droplets to be covered by at least a complete monolayer of particles". This is like the CMC in which the interface is fully saturated and cannot absorb more surfactant. Obviously, enough clay must be in the water to fully cover the drop surface, to powder the dough.

The produced water readily fingers through the froth since the collapse of the channel through it fingers is protected by the clay particles. The same mechanism works in self lubrication of bitumen froth with produced water. The droplets are strongly stretched by shear forces at the wall. The froth which is protected by absorbed clay particles is also stretched, but it cannot coalesce or pinch off the water streamers because of the protective particle layer. This promotes the coalescence of the extending droplets of produced water into sheets of lubricating water. The annulus of produced lubricating water can work perfectly well between "powdered" froth layers since these protected layers will not coalesce when touching. The bitumen froth may therefore foul the pipe wall with a layer of froth and still not interfere with the smooth lubrication of the froth core.

An idea suggested by self lubrication of froth in clay water is that fouling of pipe walls by heavy oils may be relieved by adding hydrophilic solids of colloidal size to the water in a concentration above that necessary for saturation of the oil water interface. This "powdering of the dough" works for clay particles.

To establish the idea that you can lubricate fouled walls with clay water we sheared some bitumen froth between two 3"(75 mm) diameter glass parallel plates. One plate was rotating and the other was stationary. We found that water was released inside, fracturing the bitumen. The internal sheet of water was sandwiched between two layers of bitumen, which stuck strongly to the glass plates. The bitumen on the moving plate rotated with the plate as a solid body. The froth fractured internally as a cohesive fracture and not as an adhesive fracture at the glass plates. Some of the water in the sandwich centrifuged to edges. The experiments proved that you can lubricate *froth from froth* with clay water.

(a) (b)

Figure 6.1 'Tiger' waves for U=1.0 m/s (a) and U = 1.5 m/s (b) in a 1"(25 mm) diameter pipe. The are like the waves that develop in core-annular flows and can be seen where the free milky water layer is thin. The produced water is a dispersion of small clay particles water.

7. Creation and removal of fouling

After running froth through the 1"(25 mm) pipeline, we opened the line to inspect it for fouling. This was done several times. We found that much of the pipe was lightly fouled, some heavily fouled, especially at junctions and points of resistance and some sections appeared not to be fouled. The 24"(0.6m) pilot-scale pipe was found to be lightly fouled after running, but not much of the 24"(0.6m) pipe was so inspected. however, no buildup of fouling has ever been observed in many experiments.

The fouled pipe is always being cleaned or washed by clay water. We see blobs and drops of oil in the clay water which enter the viewing section continuously in the working 1"(25 mm) pipeline. We may postulate that the pipe is continuously fouled and cleaned by running clay water without depletion or accumulation.

After all the experiments were finished in the Minnesota series, the froth was downloaded and cleaned with water. Oil drops from the pipeline were always in abundant evidence in the viewing section. The pressure drop found this way is just slightly smaller than the pressure drop for froth. After several hours of cleaning, pressure gradient versus velocity data was generated. This is shown in figure 7.1.

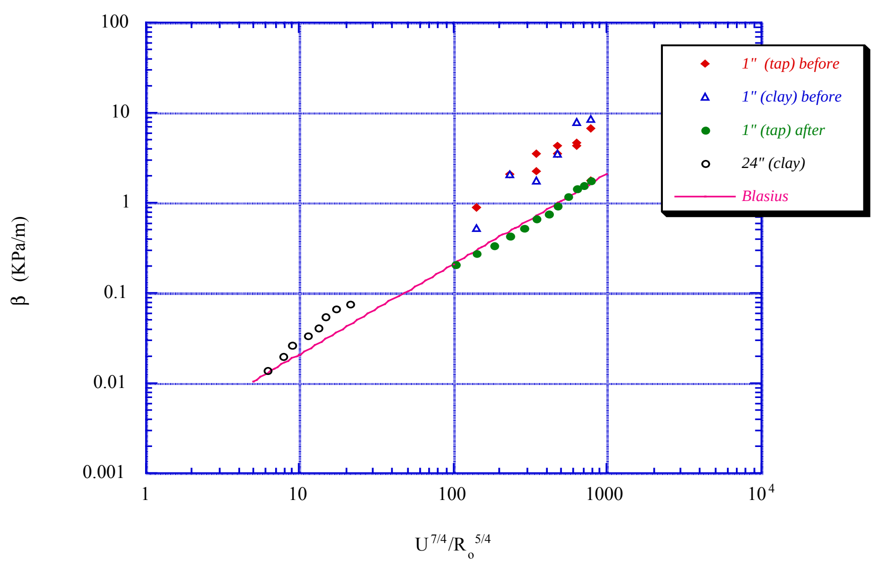
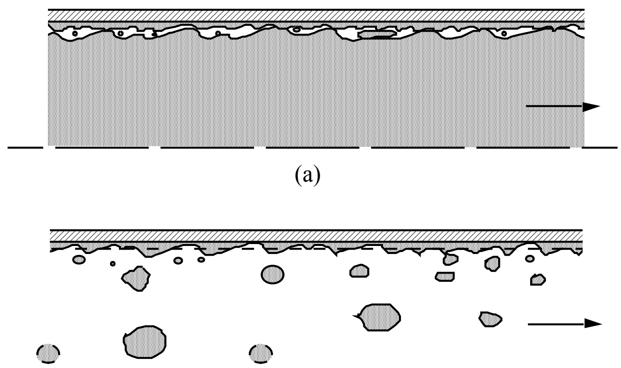


Figure 7.1 Pressure gradient β [Kpa/m] of tap and/or produced (clay) water : ◆ tap water and Δ produced water for the 1"(25 mm) pipeline before cleaning, ● tap water for the 1"(25 mm) pipeline after cleaning, and ○ produced water for the 24"(0.6m) pipeline. The bottom line is the Blasius correlation for pipe which when expressed in terms of the friction factor l is $\lambda = \frac{0.316}{Re^{1/4}}$.

The pressure drop for self lubrication of froth was compared with the measured pressure drop for water alone in the 24"(0.6m) pipe and it was 10 to 20 times larger. Faced with this discrepancy, we compared measured values with water alone in both pipes with the Blasius formula (5.4) and (5.5) with ought to apply. The Minnesota data was nearly 10 times larger than the theoretical value; the Syncrude pilot data was also higher but much less so (figure 7.1). The explanation for this is in the degree of fouling. We found that the pressure gradient in water flow in the 1" pipeline could be reduced nearly to the Blasius value by running clay water until oil drops no longer appear in the viewing window. This shows that a fouled pipe can be thoroughly cleaned by running water; pigging is never required. However, we must emphasize that cleaning up a fouled pipeline is not necessary, because fouling and cleaning are in equilibrium when froth is pipelined.

A pressure gradient price must be paid to wash oil off a fouled wall. Waves must develop on the parts of the wall fouled by oil. These waves probably propagate ever so slowly, because the fouling layer is very viscous and very thin. Apparently it is even possible that basically standing waves are on the wall and the crest of these waves are torn away to form the oil blobs and drops which appear in the viewing window. A cartoon to visualize this scenario is shown in figure 8.2 This explanation does not explain why the observed increase in the pressure gradient is independent of velocity or pipe diameter.



(a)

(b)

Figure 7.2 Cartoon of standing waves of fouled oil with drops being sheared off the crests, and (a) Tiger waves of the core in self lubrication of froth, (b) Water alone pipelining.

8. Critical conditions for self-lubrication

The results of the 1985-1986 experiments of Neiman and the 1996 experiments at the University of Minnesota indicate that a lubricating layer of water will not form unless the flow speed is large enough. The Neiman experiments in 2” pipes do not mention this point explicitly, but data for self-lubrication is given only for flow velocities greater than critical where the critical is of the order of 0.3 m/s.

The University of Minnesota experiments addressed this point explicitly and they showed that self-lubrication was lost when the flow velocity was reduced below 0.5-0.7 m/s. They also were unable to establish self-lubrication by increasing the speed of the froth trough non-lubricated slug flow regimes. In these regimes, the froth is weak but the pressure gradients are an order of magnitude greater than the value in self-lubricated flows. We expect that if the flow velocity would be increased through the non-lubricated slugging regimes, critical speed would be found for a sudden drop of the pressure gradient. This experiment could not be done because the high pressures which are needed to raise the flow speed are beyond capacity of the Moyno pump .

The critical criterion can be possibly expressed by a critical shear stress for water release which depends on the froth, on its composition and temperature. Whenever and wherever this stress is exceeded, water will be released and the maximum stress in the froth is where it is most sheared, at the water-froth interface. The shear stress is continuos across the interface and in the water it scales with the shear rate. A similar self-lubrication of water in oil emulsions (5 to 60% water by weight) at a certain shear rate for a certain period of time is claimed and supported by data for tests by V. Kruka [1977] using 10% water in three different Midway-Sunset crudes flowing in a 1" pipe. It follows from this argument that water will appear whenever the shear rate is greater than critical, so that the shear rate in the froth must then be less than critical and just critical and not larger in the water.

Experiments have established that there is a critical speed for self-lubrication; below this speed the pressure gradient required is very high and depends on the froth rather than water viscosity. The critical speed may be related to a critical shear stress, but more research is necessary.

9. Start-up and restart of self-lubrication

The bitumen froth first sticks to the wall where it is stretched in the direction of the flow. Spherical drops of water stretch into elongated fingers of water which coalesce; the bitumen does not close off the water streamers because it is protected from sticking to itself by a layer of adsorbed clay. The streamers coalesce into water sheets which lubricate the flow. In fact water streamers which percolate through the froth in regions of high shear are good for lubrication. The shear required to produce percolated strings of coalesced water drops which ultimately form sheets of lubricating water penetrate only so far in the froth. The factors that control the penetration depth have not yet been identified.

High shear rates at the wall are required for self-lubrication. Such shear rates are easily obtained. By injecting the froth behind fast moving water will do this; we take advantage of flow development . Even a low speed fully developed flow can have a high rate at the wall when it is developing. Water release and formation of the tiger waves are characteristic of self-lubrication and appear almost immediately after the froth is injected at high speeds behind the turbulent water flow. Pure water or produced water can be used for start-up but the velocity of the water and the froth must be above the critical. In the field application one would start the froth behind a high velocity water flow and the water would be automatically expelled from the pipe.

Restarting a pipe after shutdown is difficult because the stopped line is full of static froth. The static froth expels lubricating water over time and it becomes harder and harder to restart the flow in the lubricated mode with low pressure gradients. It is necessary to raise the froth speed to a value high enough to generate a shear rate large enough to produce water release and coalescence. The University of Minnesota experiments suggested that it would not be possible to raise the shear rate to a high enough value to produce water release at acceptable pressure gradients without first washing out some froth by straight water injection. In the most extreme case all the froth would be expelled and the restart begun as a straight startup, behind fast moving water. It is probable that all the froth in a stopped line need not be expelled to raise the froth velocity to the critical value at an acceptably low value of the pressure gradient.

Restart after expelling froth is always possible, and since fouled pipes can be cleaned by water flushing, expensive pigging operations will never be required.

10. Concluding Remarks

Part of the problem of self-lubrication has been solved. The mechanism of self-lubrication depends on froth weakness and clay covering of bitumen which allows water to coalesce and keeps the bitumen from sticking to itself. There is a critical speed for froth lubrication and startup and restart procedures can be framed with this knowledge. The questions are: Can this critical condition be expressed usefully as critical stress? What is the precise character of this condition? The scale up of the pressure gradient for self-lubricated froth flow follows closely the Blasius curve, but with a friction factor 10 to 20 times higher. It remains to understand why it is so. A second critical speed may be identified. After a critical flow rate for a fixed pipe diameter, the scale up looks different; it seems that increasing the flow rate does not require additional pressure head. This issue needs more testing. A fouled pipeline may be run without any buildup of fouling or pressure gradient penalty; the fouled oil on the pipewall acts like a protective coating since the oil is protected from further fouling by the core by clay covering. A fouled pipeline may by cleaned by merely running clay water for sufficiently not too long time with no other interruptions. It is possible to predict the thickness of the lubricating water layer, at least, in order of magnitude. However, more experiments are required to validate and improve this model.

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