Factors Governing Friction Losses in Self-lubricated Transport of Bitumen Froth: 1. Water Release

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Syncrude Canada Ltd. transports bitumen froth, a viscous intermediate product of the oil sand extraction process, 35 km via pipeline. Pipeline transport is feasible because some of the water that occurs naturally in the froth forms a thin lubricating layer around a bitumen-rich core, thereby greatly reducing friction losses and transportation costs. In this paper, the effect of froth composition (namely, water content) on the formation of the lubricating layer is reported. Tests were conducted with a 25 mm diameter pipe loop and a concentric cylinder froth rheometer. Measurements of pressure gradient and water holdup (free water fraction), along with visual observations, showed that froth containing a lower total water content yielded less free water to the lubricating layer. In the froth rheometer, the conditions for which stable, self-lubricated flow could be maintained were comparable to those required to maintain self-lubricated flow in the 25 mm pipe loop.

Syncrude Canada Ltd. transporte de la mousse de bitume, un produit intermédiaire visqueux du procédé d'extraction des sables bitumineux, via un pipeline de 35 km. Le transport par pipeline est réalisable parce qu'une partie de l'eau qui est présente naturellement dans la mousse forme une fine couche lubrifiante autour du noyau riche en bitume, réduisant ainsi grandement les pertes de friction et les coûts de transport. Dans cet article, on décrit l'effet de la composition de la mousse (à savoir, la teneur en eau) sur la formation de la couche lubrifiante. Des essais ont été menés avec une boucle de conduite de 25 mm de diamètre et un rhéomètre de mousse à cylindre concentrique. Les mesures de gradient de pression et de rétention d'eau (fraction libre de l'eau), ainsi que les observations visuelles, montrent que la mousse contenant une plus faible teneur en eau totale produit moins d'eau libre pour la couche lubrifiante. Dans le rhéomètre pour mousse, les conditions pour lesquelles un écoulement stable auto-lubrifié peut être maintenu sont comparables à celles requises pour maintenir un écoulement auto-lubrifié dans la boucle de conduite de 25 mm.

Keywords: bitumen froth transport, lubricated pipelining, Couette flow.

Syncrude Canada Ltd. produces approximately 250,000 barrels of synthetic crude oil daily from the surface mineable portion of the Athabasca Oil Sands deposit located in northern Alberta, Canada. Syncrude's operation consists of mining, extraction, upgrading and utilities facilities. The extraction process involves mixing oil sand with water to form a dense slurry. The slurry is prepared for extraction in pipelines as it is being transported from the mine to the extraction plant. Bitumen, which is a very heavy crude (viscosity 5.5 Pa·s at 50ºC), is released from the oil sand and subsequently separated from the other oil sand constituents (sand and clay) in large gravity settling vessels. The product from the primary settling vessels is known as bitumen froth and contains, on average, 60% bitumen, 30% water, and 10% solids (by mass).

For Syncrude's Aurora mine, which is located 35 km from the existing froth treatment and upgrading facilities, bitumen froth is transported from the Aurora extraction facilities to the existing froth treatment plant via pipeline, using self-lubricated froth flow technology. This technology utilizes a type of flow that occurs under certain conditions when froth is flowing in a pipeline: water droplets dispersed in the bitumen-continuous froth migrate in the area of high shear near the pipe wall and coalesce to form a lubricating sheath that surrounds a bitumen-rich core. As a result, pipeline friction losses are orders of magnitude lower than would be predicted based on the apparent froth viscosity.

Self-lubricated froth flow technology was developed by researchers at Syncrude and the University of Minnesota, and is described by Neiman et al. (1999) and Joseph et al. (1999). In the latter, results of flow experiments conducted in pipelines of 0.025 m, 0.05 m, and 0.6 m diameter are presented. It is shown that the pressure gradients measured for froth flow in different diameter pipelines can be represented using a modified Blasius equation, which is an empirical equation used to describe turbulent flow in a smooth pipe.

In this paper, we will describe froth flow tests that were conducted in a 25 mm diameter pipeline loop at the University of Minnesota. We will look specifically at the effects of the froth water content on self-lubricated flow. Our attempts to measure the ratio of free water to dispersed water during a series of 25 mm pipeline flow loop tests will be presented. Finally, conditions required to initiate and to maintain self-lubricated flow in pipe flow and in a type of concentric cylinder viscometer referred to as a froth rheometer will be described.

In Part 2 of this work (Sanders et al., 2004), we will describe the results of froth flow tests from which we determined that the lubricating water layer is separated from the pipe wall by a thin coating of bitumen. We

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will then look at the results of pipe flow tests conducted with cement- and glass- lined test sections to determine the effect of a hydrophilic pipe wall on fouling and pipeline friction losses. Couette flow experiments involving plastic and aluminum cylinders will also be discussed.

Previous Studies

There are many methods available to decrease the friction losses and thus reduce the costs associated with the transport of very viscous fluids (Núñez et al., 1998), including solvent addition, heating, emulsification, and lubricated flow. Each of these methods has benefits and deficits that are process-specific. For example, both the solvent addition and heating techniques are simple and well understood. However, solvent addition processes require the construction of twin pipelines and extraction facilities to separate the solvent from the viscous fluid. Consequently, capital and operating costs are quite high. Operating costs for methods where viscosity is reduced through heat addition are also very high. Emulsification processes are sometimes employed, but are neither technically feasible nor economically viable in many situations.

Lubricated pipelining, however, is not encumbered by high capital or operating costs, and is a particularly attractive alternative for long distance bitumen froth transport, as water already contained in the froth forms the lubricating layer so that large volumes of water from an external source are not required. This also is the distinguishing feature between the more frequently described core-annular flow (CAF) and self-lubricated flow (SLF): typically, in core-annular flow, water is injected to reduce pipeline pressure gradients.

An initial description of water lubrication of oil flow in a pipeline appears to come from the patent application of Isaacs and Speed (1904), who studied oil/water flows for which the densities of the two phases were nearly identical, and flows where the oil was less dense than the water. Clark and Shapiro (1950) and Chilton and Handley (1958) also described methods by which water is injected to reduce power requirements for viscous oil transport by pipeline.

Important experiments describing reduced pressure gradients for both lubricated crude oil flows and idealized (density-matched) oil/water flows were conducted by Russell and Charles (1959), Charles (1960) and Charles et al. (1961). These papers represent valuable initial contributions to the identification of the different flow regimes associated with liquid-liquid flows (Charles et al., 1961); to field tests of lubricated oil pipelining (Charles, 1960); and to the study of the benefits of both stratified and lubricated oil-water flows (Russell and Charles, 1959).

In the 1990's, Joseph and co-workers conducted a series of laboratory investigations and theoretical analyses of core-annular flows. Numerous studies of lubricated crude oil and fuel oil pipeline flows were conducted including vertical free- and forced- flows (Chen et al., 1990; Bai et al., 1992) and horizontal pipeline flows (Arney et al., 1993). Theoretical analyses focused on prediction of core-annular flow characteristics using the linear theory of stability (Bai et al., 1992; Hu and Joseph, 1989) and models that assume turbulent flow in the lubricating water layer (Arney et al., 1993; Huang et al., 1994). A comprehensive review of this work is provided by Joseph et al. (1997).

More recently, Bannwart and Vanegas Prada (1999) and McKibben et al. (2000a,b) conducted experiments showing the conditions for which free (injected) water would reduce pressure gradients during the production and transport of heavy crude oils.

Research has shown that water-lubricated flows will occur in horizontal lines even if the oil and water are not density-matched. In these situations, the core is levitated off the pipe wall as a result of waves that are sculpted on the core surface. For very viscous oils, the waves are essentially standing waves that are convected with the core as it moves through the pipeline (Ooms et al., 1984, Joseph et al., 1997). These waves are also present during self-lubricated bitumen froth flow (Joseph et al., 1999).

Very few references to self-lubricated flow exist in the literature. Kruka (1977) postulated that water droplets in a water-in-crude emulsion migrate to a position near the wall, thus decreasing friction losses in some crude oil pipelines.

Self-lubricated flow of bitumen froth was first studied by Neiman (1986) using a 50 mm diameter pipeline loop, although this work was not published outside of Syncrude. Results of froth flow tests conducted with a 25 mm pipeline at the University of Minnesota, along with a 600 mm x 1000 m pipeline field pilot test conducted on-site at Syncrude, were reported by Joseph and coworkers (Joseph et al., 1999). Pressure gradients for froth flow were found to be 10 to 20 times greater than those measured for water and an empirical correlation, similar to the Blasius equation, was presented to show the effect of flow rate and pipe diameter on pipeline friction losses:

$$R_o - \frac{W_{Ft}}{W_o} \tag{1}$$

where the value of m is dependent upon froth temperature (m = 28.1 for T = 49–58°C; m = 40.5 for T = 37–48°C).

Subsequent studies (Schaan et al., 2002; Shook et al., 2002) have shown that the froth water content and the extent of bitumen fouling on the pipe wall primarily determine the friction losses associated with self-lubricated froth transport. The coating also reduces the cross-sectional area available for flow. Because of this effect of the wall coating, and considering the fact that velocity distributions are not known, the superficial velocity, $U = Q/A$, is typically used in place of the mean velocity in describing these flows.

In the present study, the relationship between free water and total water content of the froth is studied, along with the development of self-lubricated flow in a concentric cylinder apparatus. In Part 2 of this work (Sanders et al., 2004), we report our attempts to improve the stability of self-lubricated flow and reduce friction losses using cement- and glass-lined pipes.

Equipment, Procedures and Materials

The University of Minnesota 25 mm Froth Pipeline Loop Test Facility

The University of Minnesota test loop facility is shown in Figure 1. The main components of the loop include the loading tank, supply tank, 13 m of 25 mm diameter pipe, and a variable speed, progressive cavity pump (Moyno 3L4). The test facility has been described in detail elsewhere (Joseph et al., 1999), although a number of changes were made before the tests described here were conducted. The temperature

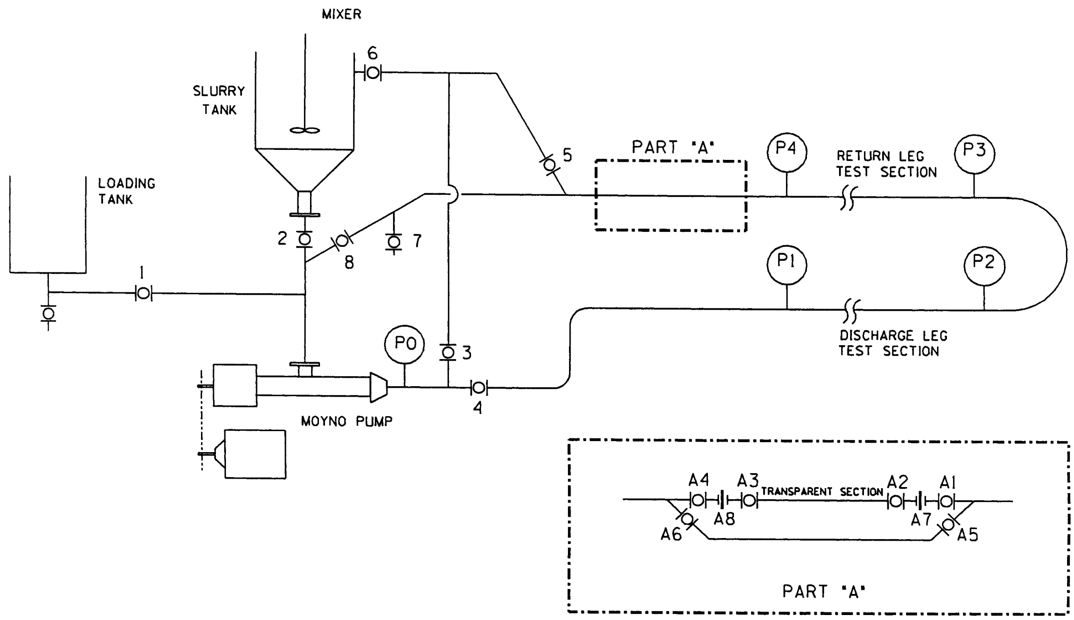

Figure 1. The 25 mm diameter pipeline loop test facility at the University of Minnesota.

control system was upgraded so that the loop was jacketed with PVC pipe. Water was pumped through the annulus between the PVC pipe and the carbon steel (process) pipe to heat or cool the froth as it flowed through the inner pipe. A loading system was also designed and implemented so that froth would not have to be loaded manually into the main supply tank. It is important to note that previously the loop loading procedure called for froth to be pumped into the loop behind flowing clay slurry (Joseph et al., 1999). For the tests described here, froth was loaded into an empty loop. Although the loop was emptied before the froth was loaded, the pipe walls would still be water-wet.

The following data were collected during tests conducted with the 25 mm pipeline: pump speed (rpm), pump discharge pressure, pressure drop along the pipeline, froth temperature, heat exchange fluid temperature, ambient temperature, high-speed video images of the flowing froth through a glass viewing section, and free water fraction. The superficial velocity, U, was determined from the relationship between pump speed and delivered flow rate for the pump. Calibration tests were conducted before this study was initiated. In these tests, delivered flow rates were determined by collecting a measured volume of froth within a certain period of time. The calibrations tests showed that the volumetric flow rate could be determined to within 3% from the measured pump speed. It should be noted that progressive cavity pumps, such as the one used in this study, act much like positive displacement pumps provided the rotor and stator are in good condition and the pump discharge pressure is not high.

Pressure gauges were located as shown in Figure 1. P0 measured the pump discharge pressure. Pressure gauges P1 and P2, located 3.96 m apart, were used to determine the pressure gradient in the discharge side test section. Pressure gauges P3 and P4, also located 3.96 m apart, were used to determine the pressure gradient in the return leg test section. The discharge and return legs are both horizontal pipe runs and are at the same elevation. The inner diameter of the carbon steel test sections was taken as 0.0266 m (based on the specifications for 25 mm, schedule 40 carbon steel pipe). Pressure measurements were recorded manually by the operator.

Froth temperature was measured along the pipeline loop using thermocouple wires that had been inserted into the pipe loop upstream of the discharge and return leg test sections. The ambient (room) temperature and temperature of the cooling/heating water were also measured. The operator recorded temperature measurements manually.

Images of the froth flowing through the transparent observation section were obtained with a high-speed video capture system (Kodak Ektapro EM Motion Analyzer).

The holdup measurement test section, used to determine the amount of water released from the froth during transport, has been described previously (Joseph et al., 1999). The apparatus is shown in the inset of Figure 1. The holdup (free water) measurement section is designed so that froth flowing between valves A1 and A4 is trapped when these two valves are closed simultaneously. In order to maintain flow in the rest of the loop, valves A5 and A6 must be opened at the same time. Once the section of pipe between valves A1 and A4 has been isolated, valves A2 and A3 are closed. The section is then removed from the loop by breaking the unions (denoted A7 and A8) located between the two sets of valves. The froth-filled transparent section, which has an i.d. of 0.0234 m, is then stood on end, at which time the froth and free water separate by gravity and the volumes of each can be determined by measuring the height of each layer. Samples of the froth layer are removed and the water content in these samples is determined by extractive distillation.

At the end of each pipeline loop test, the loading tank was filled with dilute clay slurry. Valve 7 was then opened and valve 8 was closed, and the clay slurry was pumped into the pipeline loop, thus displacing the froth from the loop through the port located downstream of valve 7. Post-test circulation of the clay slurry through the loop was found to provide more effective wall cleaning than if water were used.

University of Minnesota Froth Rheometer

A schematic of the froth rheometer is shown in Figure 2. The cup, or outer cylinder (D = 0.0889 m) is mounted on the base of a drill press. The spindle, or inner cylinder (D = 0.0758 m; L = 0.152 m) is connected to the drill press motor. The motor is connected to a speed controller/torque indicator. The outer cylinder is immersed in a temperature-controlled water bath so that the froth temperature can be held constant. A thermocouple is connected to the cup in order to monitor the froth temperature.

Bitumen Froth Samples

A number of different samples of froth were tested in the University of Minnesota 25 mm pipeline loop and froth rheometer from April 1997 to December 1998. Some of the samples were obtained from Syncrude's Mildred Lake operation, and other samples were obtained from the Exploratory Extraction Pilot (EXP), which is located at Syncrude's Edmonton Research Centre. The bitumen froth, which initially contains a significant volume fraction of air, was completely deaerated by the time it was tested at the University of Minnesota.

The samples of bitumen froth were shipped to the University of Minnesota in 20 L containers. Generally, 120 to 160 L of froth was collected at a time. When the pails were being filled, smaller (< 1L) samples were also collected. The small samples were then submitted to the Syncrude Research analytical laboratory for bitumen/water/solids (B/W/S) determination. For the tests described here, froth samples collected on three separate occasions were used. The average composition for each froth sample is shown in Table 1.

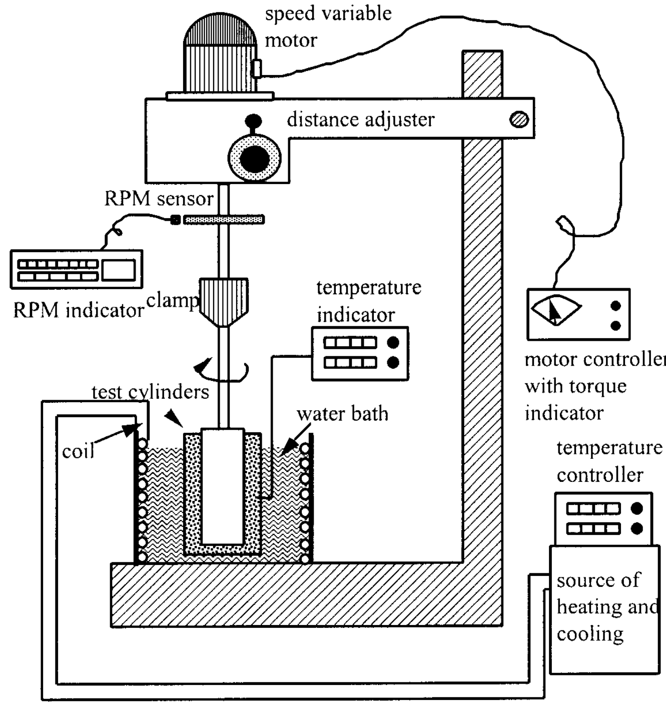

Figure 2. Schematic illustration of the University of Minnesota froth rheometer.

Table 1. Average froth composition for samples tested at the University of Minnesota, 1997–98.

Sample No.	Source	Composition (B/W/S, % by mass)
1	Syncrude Mildred Lake	63 / 27 / 10
2	Syncrude EXP	59 / 31 / 10
3	Syncrude EXP	70 / 19 / 11

Results

Effect of Froth Composition on Pipeline Friction Losses

The results of the tests conducted to measure pressure gradient as a function of superficial velocity, *U*, for a temperature range of 48 to 54°C, are shown in Figure 3. The average composition of each type of froth is listed in the legend of Figure 3 as B/W/S (bitumen/water/solids, composition by % mass).

Note that most of the data points for tests conducted with the froth containing a greater water fraction fall near the curve representing the Blasius froth correlation. The pressure gradients measured for the froth containing 19% water are greater than the pressure gradients calculated with the Blasius froth correlation. At the highest velocity, however, it appears that the pressure gradient measured for the froth containing less water approaches the value obtained with the Blasius correlation.

These results indicate that the reduced froth water content adversely affects the self-lubricating froth flow mechanism. High-speed video images captured during the two sets of flow tests illustrate the difference in flow patterns for the froth containing different water fractions. Typical images are shown in Figure 4, where Figure 4a was obtained during the tests conducted with the froth containing 31% water, and the image shown as Figure 4b was captured during the tests conducted with froth containing 19% water. The superficial velocity was 1 m/s and the froth temperature was 51°C when each of the images was taken. In each case, stable self-lubricated flow was established well before images were captured.

The so-called tiger waves (Joseph et al., 1999), which are characteristic of self-lubricated froth flow, are evident in both photographs. The characteristic wavelength is different, however. The relationship among wavelength, superficial velocity and water holdup has been discussed previously (Bai, 1995; Oliemans et al., 1987). Comparison of the two photographs indicates that the there is less water at the pipe wall for the rich froth (Figure 4b) than for the froth containing 31% water (Figure 4a).

The relationship between froth water content and pipeline friction losses is explored further in the following section, where we describe the results of hold-up measurements that show the fraction of water contained in the froth that migrates to form the lubricating layer.

Holdup (Free Water) Measurements in the 25 mm Pipeline Loop

A number of tests were conducted with the University of Minnesota 25 mm pipeline loop to determine the amount of

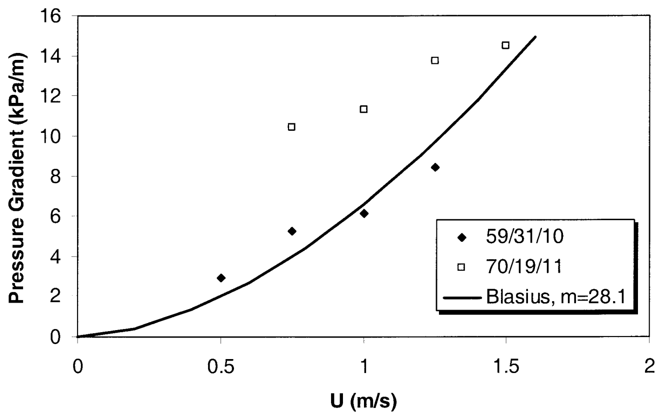

Figure 3. Pressure gradients measured for self-lubricated froth transport tests in the 25 mm pipeline loop (T = 48–54°C). Froth composition reported as Bitumen/Water/Solids (% by mass).

water released from froth during pipeline transport. The holdup measurement test section and test procedures were described previously. During each test, superficial velocity and temperature were held constant. Once the holdup measurement test section is removed from the loop and the froth and water layers have been allowed to separate, the volume of free water, V_{fw}, is calculated from the height of the free water layer. Similarly, the volume of froth (including the bitumen, solids and dispersed water), V_f, is determined from the height of the froth layer. The volume of dispersed water not released from the froth, V_{dw}, is determined when samples of the froth layer are removed and subjected to extractive distillation. The total volume of water is therefore $V_w = V_{fw} + V_{dw}$ and the volume fraction of water is $C_w = V_w/(V_f + V_w)$.

Bitumen froth samples shipped from Mildred Lake were used for the holdup measurement test program. The average water content was 27% (by mass), or 29% by volume, as shown in Table 1. However, there can be variations in froth composition among the different 20L samples, which will be demonstrated subsequently.

The results of the holdup tests are shown in Figures 5 and 6. Figure 5 shows how the ratio of the free water volume, V_{fw}, to the total froth volume, $V_f + V_w$, varied with temperature for superficial velocities of 0.75, 1.25 and 1.75 m/s. It appears that the fraction of water released to the lubricating water layer increases with increasing temperature for a given superficial velocity. Also, the water holdup decreases with increasing velocity for a given froth temperature. Note that there was one set of tests where the volume fraction of water in the froth determined from the holdup measurements was less than the water fraction of the initial froth sample. This may be a result of some variation in water content among the froth samples, or it may be that the ratio U_o/U_w increases with superficial velocity.

Figure 6 shows the pipeline pressure gradient measurements that were collected just prior to each holdup measurement. As in the previous figure, each point on the graph was obtained for a unique operating condition (superficial velocity, temperature). The results presented in Figure 6 clearly show that the pressure gradient measured for self-lubricated froth flow is dependent upon the free water fraction, i.e. the amount of water that is released from the froth to form the lubricating layer. It is interesting to note that

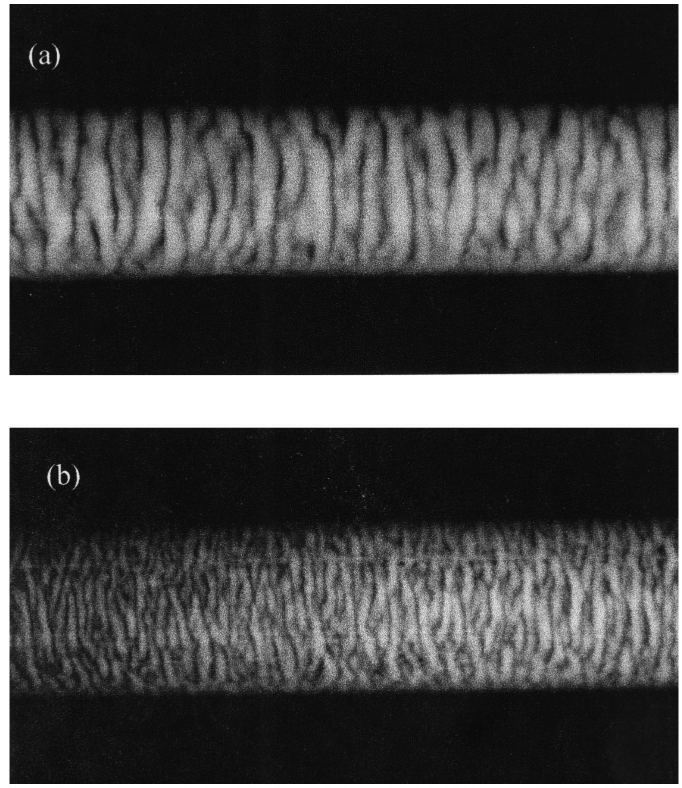

Figure 4. Bitumen froth flowing through the transparent glass section of the 25 mm pipe loop at 1 m/s and 51°C. Bulk froth compositions: (a) 59/31/10; (b) 70/19/11 (B/W/S, % by mass).

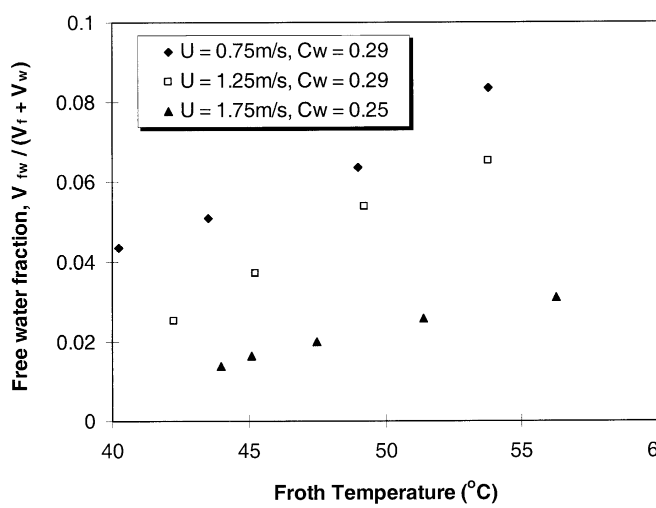

Figure 5. Variation of free water fraction (water holdup) with froth temperature and superficial velocity.

for heavy crude oil – water flows, where water is injected to reduce pipeline pressure gradients, McKibben et al. (2000b) found that a minimum water fraction of 0.1 was required to produce and maintain the beneficial flow regime described by the authors as continuous water-assisted flow. This is in good agreement with the results presented in Figure 6, where the pressure gradient is shown to increase sharply as the free water fraction is reduced.

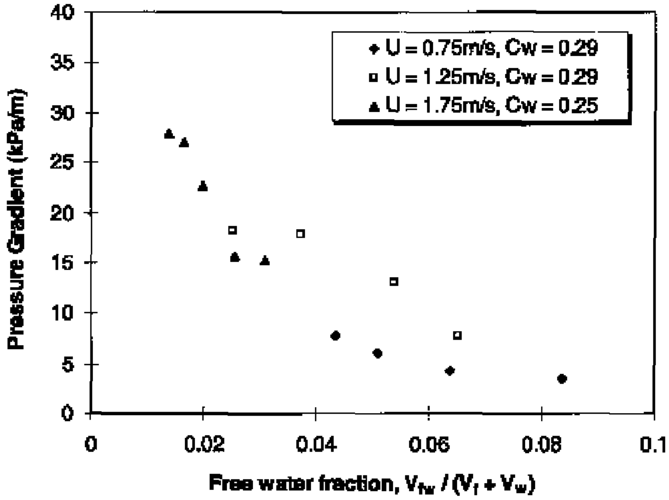

Figure 6. Effect of free water fraction (water holdup) on pipeline pressure gradients measured for self-lubricated froth flow in the University of Minnesota 25 mm pipe loop.

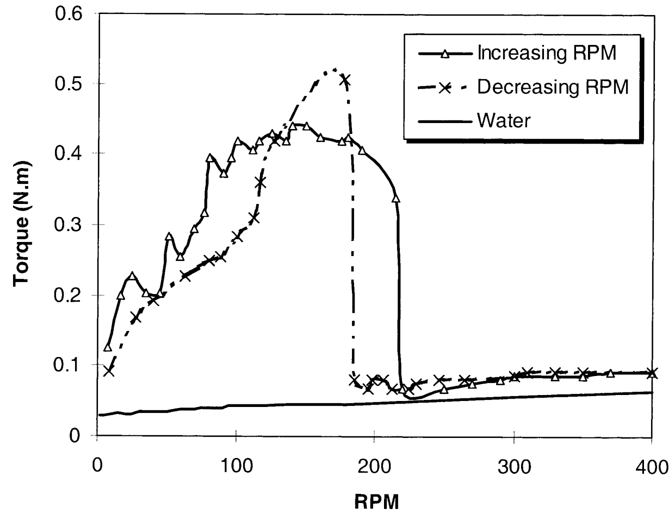

Figure 7. Torque measured as a function of spindle rotational speed for froth in the University of Minnesota froth rheometer, T = 30°C.

Figures 5 and 6, considered together, partially explain why friction losses for self-lubricated froth flow are strongly dependent upon superficial velocity and froth temperature. The additional effect on friction losses of the bitumen coating that forms on the pipe wall is discussed in Part 2 of this series (Sanders et al., 2004).

Although the results presented in Figures 5 and 6 must be treated with some caution (one type of froth, single pipe diameter) they do provide important new insights for self-lubricated froth transport. For a dry froth, only a very small fraction of the total water content is released to form the lubricating, free water layer. If the lubricating layer is very thin, contact between the bitumen coating on the pipe wall and the bitumen-rich core would occur more frequently, which would cause pipeline friction losses to increase. This trend is evident in Figure 3, where the froth with the lower total water content provides the highest friction losses. Conversely, froth having a higher water concentration is able to release more water to the lubricating layer, and would thus be associated with lower pipeline friction losses.

It is worth repeating that the results discussed here are for a single batch of froth and tests were conducted using only one pipeline diameter. It is likely that the relationship between operating conditions (temperature, velocity) and free water fraction will depend upon the initial water droplet size distribution in the froth, and may also change with pipe diameter.

Water Release Studies Using a Froth Rheometer

A series of tests was conducted to determine if self-lubricated flow would occur in Couette flow under conditions comparable to those for which self-lubricated pipeline flow occurs.

For the froth rheometer tests, a froth sample collected from Syncrude's Mildred Lake operation was used. The torque on the motor used to turn the spindle (inner cylinder) was measured as a function of RPM and froth temperature. A plexiglass cup (outer cylinder) was used for the experiments described here. In Part 2 of this two-part series, the results of froth rheometer tests conducted with an aluminum cup are discussed (Sanders et al., 2004).

Table 2. Critical spindle speed required to initiate and maintain self-lubricated froth flow, measured with the University of Minnesota froth rheometer.

	Critical RPM	
Froth Temp.°C	Increasing	Decreasing
24	280	240
28	240	175
30	220	185
34	180	145

The onset of self-lubricated flow is indicated by a sharp decrease in the measured torque. Once lubricated flow was established, it could be sustained at a range of spindle speeds lower than the one initially required to promote lubricated flow. This tendency is depicted in Figure 7. Also shown in Figure 7 is the torque measured as a function of RPM for water. This curve clearly shows that the torque sensor cannot accurately measure low torque values. The utility of this froth rheometer, then, is in the ability to distinguish between the high torque associated with non-lubricated flow, and the low torque that results from water release and self-lubricated flow.

Table 2 shows the critical RPM required to promote and maintain self-lubricated flow as a function of temperature in the froth rheometer, for tests where RPM is increased in a stepwise fashion, and for tests where RPM is decreased in increments after self-lubricated flow is initiated. The critical values for increasing spindle speeds represent the lowest values for which lubricated flow occurs; for decreasing spindle speeds, the critical value denotes the lowest speed at which the low torque (indicating self-lubricated flow) is measured.

In Figure 8, we compare the critical velocities from the froth rheometer tests with those measured during a series of pipe flow tests conducted with the University of Minnesota 25 mm pipe loop. The critical velocity for the froth rheometer is the angular velocity of the inner spindle at the critical

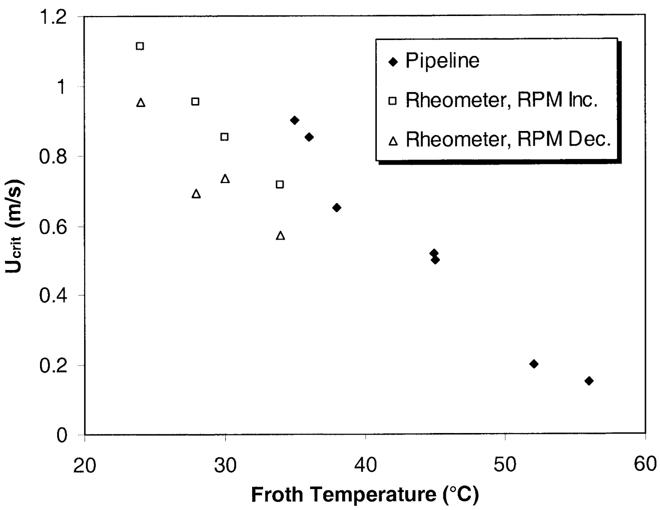

Figure 8. Comparison of the critical velocity required to maintain self-lubricated froth flow as a function of froth temperature, in the University of Minnesota 25 mm pipeline loop and concentric cylinder froth rheometer.

RPM. For the pipe loop, the critical velocity is taken as the superficial velocity that is required to maintain self-lubricated flow. In Figure 8, critical velocities for the two flow geometries are plotted as a function of froth temperature. These results are similar to those reported previously (Joseph et al., 1999). We see that there is reasonable agreement between the critical velocities determined with the froth rheometer and those obtained from pipe loop tests, for froth samples from the same source. These results provide the first indication that the parameters affecting self-lubricated pipeline transport of froth may be studied using a concentric cylinder shearing apparatus.

Conclusions

The following conclusions can be drawn from the results presented above:

1. The amount of water released to form the lubricating layer during froth transport depends upon the froth water content, superficial velocity, and froth temperature.
2. The pipeline flow measurements obtained during this study, including friction losses, high-speed imaging and water hold-up, clearly indicate that less free water is available to form the lubricating water layer when the total water content of the froth is reduced.
3. Froth composition, and specifically the water content of the froth, is shown to affect pipeline pressure gradients for self-lubricated froth flow. Pipeline tests conducted with froth containing 19% water (by mass) yielded higher friction losses than similar tests conducted with froth containing 31% water.
4. Holdup tests showed that the free water fraction was consistently less than 10% of the total froth volume, which is a much lower water fraction than would normally be considered feasible for stable water-lubricated pipelining of viscous crude oils.
5. Tests showed that the effects of froth temperature and shear on the self-lubricating phenomenon are similar for pipeline and Couette flow.

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Nomenclature

A	pipe cross-sectional area, (m^2)
C	volume fraction
$-dP/dz$	pressure gradient, (Pa/m)
D	diameter, (m)
L	length, (m)
P	pressure, (Pa)
R	pipe radius, (m)
Q	volumetric flow rate,(m^3/s)
T	temperature, (°C)
U	superficial velocity, (Q/A, m/s)
V	volume, (m^3)
z	axial position, (m)

Subscripts

c	critical
dw	dispersed water
f	froth
fw	free water
o	oil
w	water

References

Arney, M.S., R. Bai, E. Guevara, D.D. Joseph and K. Liu, "Friction Factor and Holdup Studies for Lubricated Pipelining I: Experiments and Correlations", Int. J. Multiphase Flow **19**, 1061–1076 (1993).

Bai, R., K. Chen and D.D. Joseph, "Lubricated Pipelining: Stability of Core-Annular Flow, Part 5: Experiments and Comparison with Theory", J. Fluid Mech. **240**, 97–132 (1992).

Bai, R., "Travelling Waves in a High Viscosity Ratio, Axisymmetric Core Annular Flow," Ph. D. Dissertation, University of Minnesota, MN (1995).

Bannwart, A.C. and J.W. Vanegas Prada, "Production of Heavy Oil Via Core Flow", SPE Latin American and Caribbean Petroleum Engineering Conf., Caracas, Venezuela, 21–23 April. SPE 53688, 1–8 (1999).

Charles, M.E., "The Reduction of Pressure Gradients in Oil Pipelines: Experimental Results for the Stratified Flow of a Heavy Crude Oil and Water", Trans. C.I.M. **63**, 305–309 (1960).

Charles, M.E., G.W. Govier and G.W. Hodgson, "The Pipeline Flow of Equal Density Oil Water Mixtures", Can. J. Chem. Eng. **39**, 27–36 (1961).

Chen, K., R. Bai and D. D. Joseph, "Lubricated Pipelining: Stability of Core-Annular Flow, Part 3: Stability of Core-Annular Flow in Vertical Pipes", J. Fluid Mech. **214**, 251–286 (1990).

Chilton, E.G. and L.R. Handley, "Method and Apparatus for Lubricating Pipelines", US Patent 2,821,205 (1958).

Clark, A.F. and A. Shapiro, "Method of Pumping Viscous Petroleum", US Patent 2,533,878 (1950).

Hu, H.H. and D.D. Joseph, "Lubricated Pipelining: Stability of Core-Annular Flow, Part 2", J. Fluid Mech. **205**, 359–396 (1989).

Huang, A., C. Christodoulou and D.D. Joseph, "Friction Factor and Holdup Studies for Lubricated Pipelining II: Laminar and k-ε Models of Eccentric Core Flow", Int. J. Multiphase Flow **20**, 481–491 (1994).

Isaacs, J.D. and J.B. Speed, "Method of Piping Fluids", US Patent 759,374 (1904).

Joseph, D.D., R. Bai, C. Mata, K. Sury and C. Grant, "Self-lubricated Transport of Bitumen Froth", J. Fluid Mech. **386**, 127–148 (1999).

Joseph, D.D., R. Bai, K.P. Chen and Y. Renardy, "Core-annular Flows", Ann. Rev. Fluid Mech. **29**, 65–90 (1997).

Kruka, V. "Method for Establishing Core-Flow in Water-in-Oil Emulsions or Dispersions", Canada Patent No. 1,008,108 (1977).

McKibben, M.J., R.G. Gillies and C.A. Shook, "A Laboratory Investigation of Horizontal Well Heavy Oil–Water Flows", Can. J. Chem. Eng. **78**, 743–751 (2000a).

McKibben, M.J., R.G. Gillies and C.A. Shook, "Predicting Pressure Gradients in Heavy Oil–Water Pipelines", Can. J. Chem. Eng. **78**, 752–756 (2000b).

Neiman, O., D.D. Joseph, R. Bai, C. Grant and K. Sury, "Process for Pumping Bitumen Froth Through a Pipeline", US Patent No. 5,988,198 (1999).

Neiman, O., "Froth Pipelining Tests", Syncrude Canada Ltd. Research Progress Report **15** (1) 373–407 (1986).

Núñez, G.A., H.J. Rivas and D.D. Joseph, "Drive to Produce Heavy Crude Prompts Variety of Transportation Methods", Oil Gas J., Oct. 26 (1998) pp. 59–68.

Ooms, G., A. Segal, A.J. van der Wees, R. Meerhoff and R.V.A. Oliemans, "A Theoretical Model for Core-Annular Flow of a Very Viscous Oil Core and a Water Annulus Through a Horizontal Pipe", Int. J. Multiphase Flow **10**, 41–60 (1984).

Oliemans, R.V.A., G. Ooms, H.L. Wu and A Duijvestijn, "Core-Annular Oil/Water Flow: the Turbulent-Lubricating-Film Model and Measurements in a 5 cm Pipe Loop", Int. J. Multiphase Flow **13**, 23–31 (1987).

Russell, T. W. F. and M. E. Charles, "The Effect of the Less Viscous Liquid in the Laminar Flow of Two Immiscible Liquids", Can. J. Chem. Eng. **37**, 18–24 (1959).

Sanders, R.S., T. Ko, R. Bai, P. Dougan and D. D. Joseph, "Factors Governing Friction Losses in Self-Lubricated Transport of Bitumen Froth: 2. Pipeline Fouling", submitted to Can. J. Chem. Eng. (2004).

Schaan, J., R.S. Sanders, C. Litzenberger, R.G. Gillies and C.A. Shook, "Measurement of Heat Transfer Coefficients in Pipeline Flow of Athabasca Bitumen Froth", in "Proc. 3rd North American Conf. Multiphase Technology", C. Sarica and G. Gregory, Eds., Banff, AB, June 6-7, 2002, BHR Group, Cranfield, UK (2002), pp. 25–33.

Shook, C.A., R.G. Gillies and R.S. Sanders, "Pipeline Hydrotransport: With Applications in the Oil Sand Industry", SRC Publications, No. 11508–1E02, Saskatoon, SK (2002).

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