Lubricated pipelining of viscous fluids

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10. SPECIAL INFORMATION AND SUPPLEMENTARY DOCUMENTATION

11. PROPRIETARY INFORMATION

1. [Face page]

2. [Budget pages]

3. Project goals

The project aims at understanding and technological development of lubricated pipelines of heavy oil and emulsions. Lubricated pipelining of heavy oil is possible because core-annular flow with the oil core lubricated by an annulus of water outside is robustly stable; water inside is unstable. The role of the steep forward facing waves on the oil-water interface in centering the oil core when the oil and water have the same density and in levitating the oil core off the wall when the oil and water have different densities needs further clarification; the role of intertia in levitating core flows, the effects of low surface tension and the variation of the viscosity ratio on the wave forms in laminar and especially in turbulent flow of the lubricating water are proposed for study.

A second focus for the studies proposed here is the self-lubrication of water-in-oil emulsions of which bitumen froth from the Canadian oil sands is the main example. This froth is a stable water-in-oil emulsion with the additional special feature that the water has enough clay present as a colloidal dispersion to protect the bitumen from sticking to itself, in the same way that colloidal clay particles can protect oil-in-water emulsions from coalescing. This special material self-lubricates; when the flow velocity is large enough the clay water coalesces in the region of high shear, at the wall, in an annular film of clay water which lubricates the froth; no water is added. Self-lubricated core flow of bitumen froth leads to huge savings in pumping energy and is environmentally benign. Many fascinating problems concerning the mechanisms governing water release, the effects of flow speed temperature and frictional heating on core flow performance need study. Based, in part, on our previous work on self-lubricated bitumen froth, Syncrude Canada Ltd. has taken the decision to build a commercial line from the new Aurora mine to the Lake Mildred plant where froth is upgraded to a sweet synthetic crude; the line is to be 35km long at a cost possibly in excess of 2 million dollars per kilometer. We are collaborating with Syncrude Canada by studying the flow fundamentals of self-lubrication.

4. Progress Report

Here I am going to give a brief review of the main results obtained from our DOE sponsored research (DOE/DE-FG02-97ER13798) for the period of Sept 1993-1998. Four topics were proposed for study: (I) fluid dynamics of core flows, (II) lubricated transport of concentrated oil/water emulsions, (III) fouling of pipe walls with oil, (IV) migration of particles leading to lubricated configurations. We are proposing more studies of core flows and the new topic of self-lubricated core flows of bitumen froth. We plan some study of the viscosity oil/water emulsions and to test the anti-fouling property of cement-lines pipes in pipelining of bitumen froth, but these two topics are not a focus in this proposal for future work. Migration of particles (IV) will not be considered in this proposal. Self-lubrication of bitumen froth (V) was not a topic proposed for study in our last proposal but it became a focus.

4.1 FLUID DYNAMICS OF CORE FLOW

I am asking for funds to continue studies of (I), fluid dynamics of lubricated core flows of the conventional type produced by controled injection of water, and a new topic, self-lubrication of bitumen froth, for which we have already many results. A detailed review of the fluid mechanics and applications of lubricated core flows prior to 1993 can be found in “Fundamentals of Two-Fluid Dynamics” by Joseph & Renardy and prior to 1997 in the Annual Review of Fluid Mechanics article “Core-Anular Flow” by Joseph, Bai, Chen and Renardy [1997].

Since 1993 we have published 55 papers which acknowledge DOE support. Most of the papers (mainly since 1994) are listed under the section on biographical sketches in this proposal. The numbers of the papers in this list which are on lubricated pipelines or are otherwise relevant to this proposal are [203, 215, 218, 221, 222, 231, 236, 237, 239, 244, 247, 250]. Some of the results given in these papers ran against conventional understandings and need further elaboration from studies we propose here. In Feng, Huang and Joseph [1995], I put forward an argument about the steepening of wave fronts which suggests that inertia is required to center the oil core when the oil and water have the same density and to levitate the oil core off the pipe wall when the oil and water have different densities. The conjectures given in Feng et al. [1995] were confirmed and extended by Bai, Kelkar and Joseph [1996] as is described in the abstract to their paper:

> A direct numerical simulation of spatially periodic wavy core flows is carried out under the assumption that the densities of the two fluids are identical and that the viscosity of the oil core is so large that it moves as a rigid solid which may nevertheless be deformed by pressure forces in the water. The waves which develop are asymmetric with steep slopes in the high-pressure region at the front face of the wave crest and shallower slopes at the low-pressure region at the lee side of the crest. The simulation gives excellent agreement with the experiments of Bai, Chen & Joseph (1992) on up flow in vertical core flow where axisymmetric bamboo waves are observed. We define a threshold Reynolds number and explore its utility; the pressure force of the water on the

> core relative to a fixed reference pressure is negative for Reynolds numbers below the threshold and is positive above. The wave length increases with hold-up ratio when the Reynolds number is smaller than a second threshold and decreases for larger Reynolds numbers. We verify that very high pressures are generated at stagnation points on the wavefront. It is suggested that a positive pressure force is required to levitate the core off the wall when the densities are not matched and to centre the core when they are. A further conjecture is that the principal features when govern wavy core flows cannot be obtained from any theory in which inertia is neglected.

- **Industrial Experience**

There is a strong tendency for two immiscible fluids to arrange themselves so that the low-viscosity constituent is in the region of high shear. We can imagine that it may be possible to introduce a beneficial effect in any flow of a very viscous liquid by introducing small amounts of a lubricating fluid. Nature’s gift is evidently such that the lubricating fluid will migrate to the right places so as to do the desired job. This gives rise to a kind of gift of nature in which the lubricated flows are stable, and it opens up very interesting possibilities for technological applications in which one fluid is used to lubricate another.

Water-lubricated transport of heavy viscous oils is a technology based on a gift of nature in which the water migrates into the region of high shear at the wall of the pipe where it lubricates the flow. Since the pumping pressures are balanced by wall shear stresses in the water, the lubricated flows require pressures comparable to pumping water alone at the same throughput, independent of the viscosity of the oil (if it is large enough). Hence savings of the order of the oil to water viscosity ratio can be achieved in lubricated flows. Heavy crudes are very viscous and usually are somewhat lighter than water, though crudes heavier than water are not unusual. Typical crudes might have a viscosity of 1000 poise and a density of 0.99 g/cm^3 at 25°C. Light oils with viscosities less than 5 poise do not give rise to stable lubricated flows unless they are processed into water/oil emulsions and stiffened.

Oil companies have had an intermittent interest in the technology of water-lubricated transport of heavy oil since 1904. The history of patents for this technology is reviewed by Joseph et al. [1997]. In general, lubricated flows are more effective when the oil is more viscous; the water/oil emulsion is an “effective” thickened oil whose density is closer to water. Kiel 1968 of Exxon patented a CAF process for pumping heavy oils and water in oil emulsions, surrounded by water, for fracturing subterranean formations to increase oil and gas production. Ho & Li 1994 of Exxon produced a *concentrated* water in oil emulsion with 7 to 11 times more water than oil, which they successfully transported in CAF.

Syncrude Canada Ltd has undertaken studies of lubricated transport of a bitumen froth which is obtained from processing of oilsands of Alberta for upgrading to Synthetic crude. The oil (bitumen) is extracted from mined oilsands rather than pumped directly from the reservoir. A hot-water extraction process is used to separate bitumen as froth from sand and the average composition of the froth is 60, 30 and 10 weight % bitumen, water and solids, respectively. Internal studies led by Neiman et al 1985 and recent studies at the University of Minnesota have shown that the produced bitumen froth will self lubricate in a pipe flow.

Lubricated transport of concentrated oil-in-water emulsions is also an issue. The viscosity of such emulsions can be much smaller than the viscosity of the oil and may be independent of the oil viscosity for large viscosities. This has motivated the consideration of pumping heavy crudes through pipelines as concentrated oil-in-water emulsions. Lamb & Simpson 1973 reports a commercial line in Indonesia which carries 40,000 barrels/day of 70% oil/water emulsion in a 20-inch diameter line, 238 kilometers long. Another commercial lubricated transport of Orimulsion®, a coal substitute fuel of 70% oil-in-water produced in Venezuela and marketed by Bitor, can be accomplished naturally since the water for lubrication is already there and will stick to the wall if the surfactant used to stabilize the emulsion and the material of wall construction is suitable (Núñez et al 1996).

Probably the most important industrial pipeline to date was the 6-inch (15.2 cm) diameter, 24-mile (38.6 km) long Shell line from the North Midway Sunset Reservoir near Bakersfield, California, to the central facilities at Ten Section. The line was run under the supervision of Veet Kruka for 12 years from 1970 until the Ten Section facility was closed. When lubricated by water at a volume flow rate of 30% of the total, the pressure drop varied between 900 psi and 1,100 psi at a flow rate of 24,000 barrels per day with the larger pressure at a threshold of unacceptability which called for pigging. In the sixth year of operation the fresh water was replaced with water produced at the well site which contained various natural chemicals leached from the reservoir, including sodium metasilicate in minute 0.6 wt.% amounts. After that the pressure drop never varied much from the acceptable 900 psi value; the core flow was stable as long as the flow velocity was at least 3 ft/s. Industrial experience suggests that inertia is necessary for successful core flow.

- **Levitation of core flows**

A surprising property of core flow is that the flow in a horizontal line will lubricate with the core levitated off the wall even if the core is lighter or heavier than the lubricating water.

This levitation could not take place without a hydrodynamic lifting action due to waves sculpted on the core surface. In the case of very viscous liquids, the waves are basically standing waves which are convected with the core as it moves downstream. This picture suggests a lubrication mechanism for the levitation of the core analogous to mechanisms which levitate loaded slider bearings at low Reynolds numbers. Ooms et al 1984 and Oliemans and Ooms 1986 gave a semi-empirical model of this type and showed that it generated buoyant forces proportional to the first power of the velocity to balance gravity. In this theory, the shape of the wave must be given as empirical input.

Consider water-lubricated pipelining of crude oil. The oil rises up against the pipe wall because it is lighter than the water. It continues to flow because it is lubricated by waves. However, the conventional mechanisms of lubrication cannot work. The saw tooth waves shown in Figure 1 are like an array of slipper bearings and the stationary oil core is pushed off the top wall by lubrication forces. If *c* were reversed, the core would be sucked into the wall, so the slipper bearing picture is obligatory if you want levitation.

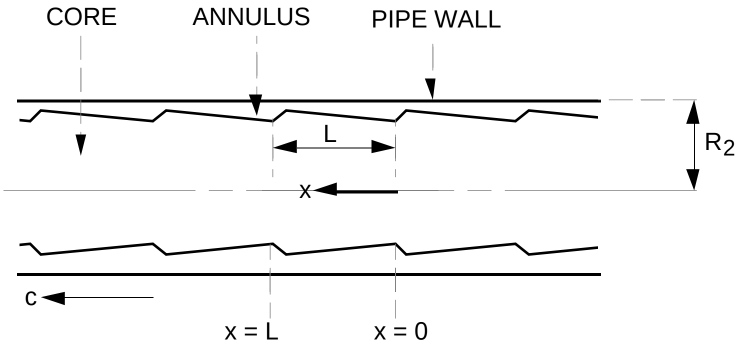

Figure 1. The core is at rest and the pipe wall moves to the left.

Obviously the saw tooth waves are unstable since the pressure is highest just where the gap is smallest, so the wave must steepen where it was gentle, and smooth where it was sharp. This leads us to the cartoon in Figure 2. To get a lift from this kind of wave it appears that we need inertia, as in flying. Liu’s [1982] formula for capsule lift-off in a pipeline in which the critical lift off velocity is proportional to the square root of gravity times the density difference is an inertial criterion. Industrial experience also suggests an inertial criterion, since core in the Shell line could be maintained only when the velocity was greater that 3 ft/s; at lower velocities the drag was much greater.

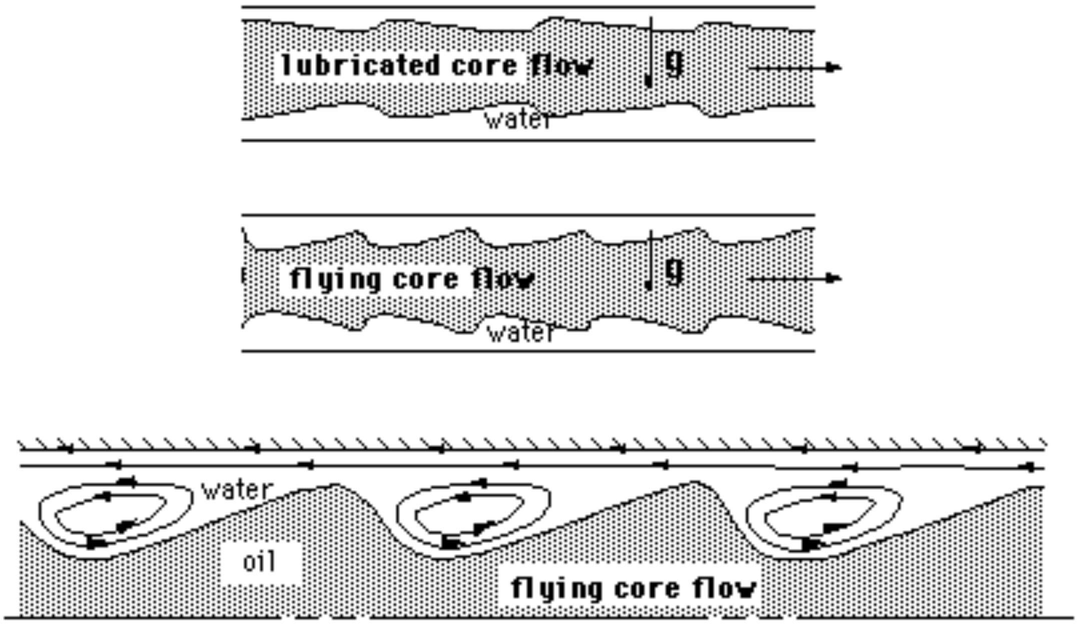

Figure 2 (After Feng et al 1995) (*top*) The interface resembles a slipper bearing with the gentle slope propagating into the water. (*middle*) The high pressure at the front of the wave crest steepens the interface and the low pressure at the back makes the interface less steep. (*bottom*) The pressure distribution in the trough drives one eddy in each trough.

Joseph [1997] suggested that steep wave fronts produced by mechanisms similar to those in core flows could explain the steep wave fronts which are observed on slipping polymeric liquids and even rubber abrasion:

> **Abstract**
> Steep wave fronts tend to develop in many regimes of lubricated, slipping flows in which waves appear. Problems of slip, spurt, fracture and extrudate distortion can be framed in terms of lubrication theory with paradigms arising from the lubrication of heavy oil with water for some problems and concepts from the theory of boundary lubrication for others. In water lubricated pipelines, high pressures are produced at the front side of a wave on the oil when water is forced through the wavecrest and the wall; low pressures develop at the back of the wave where the gap opens. The steep waves which develop on cores of heavy oil lubricated by water are irregular and look like melt fracture. Direct numerical simulation of regular periodic waves give rise to sharkskin solutions in which the wave length decreases with the wave amplitude as the gap size decreases, preserving the steep wave front. Wave steepening seems always to occur in extrusion when the polymers slip, in the abrasion of rubber samples and in Schallamach's waves of detachment.

- **Direct numerical simulation**

Analysis of problems of levitation, transitions between flow types, pressure gradients and hold-up ratios will ultimately be carried out by direct numerical simulation. Bai et al 1996 did a direct simulation of steady axisymmetric, axially periodic CAF, assuming that the core viscosity was so large that secondary motions could be neglected in the core. They found that wave shapes with steep fronts like those shown in Figure 2 always arise from the simulation, see Figure 3. The wave front steepens as the speed increases. The wave shapes are in good agreement with the shapes of bamboo waves in up-flows studied by Bai et al 1992.

A new and important feature revealed by the simulation is that long waves do not arise when the gap size tends to zero as is usually assumed in long wave theories. As the gap size decreases, $\eta \to 1$, the wavelength $\bar{L}(\eta)$ decreases linearly with η. This means that the wave shape hardly changes and a steep wave will stay steep in this limit. It is the first solution ever to show how "sharkskin" waves arise as a natural consequence of the dynamics of lubricated flows without the special assumptions sometimes made in the rheology literature to explain such waves shapes in extrudate flows.

Bai et al 1996 found a threshold Reynolds number corresponding to a change in the sign of the pressure force (the area under the pressure curve) on the core from suction at Reynolds numbers below the threshold, as in the reversed slipper bearing in which the slipper is sucked to the wall, to compression for Reynolds numbers greater than the threshold, as in flying core flow in which the core can be pushed off the wall by pressure forces.

The existence of this threshold does not prove that inertia is required for levitation of core flows in which the density is not matched and the centering of flows of matched density because in the axisymmetric case studied by Bai et al 1996, the pressure forces are always balanced by an equal and opposite force an the other side of the core.

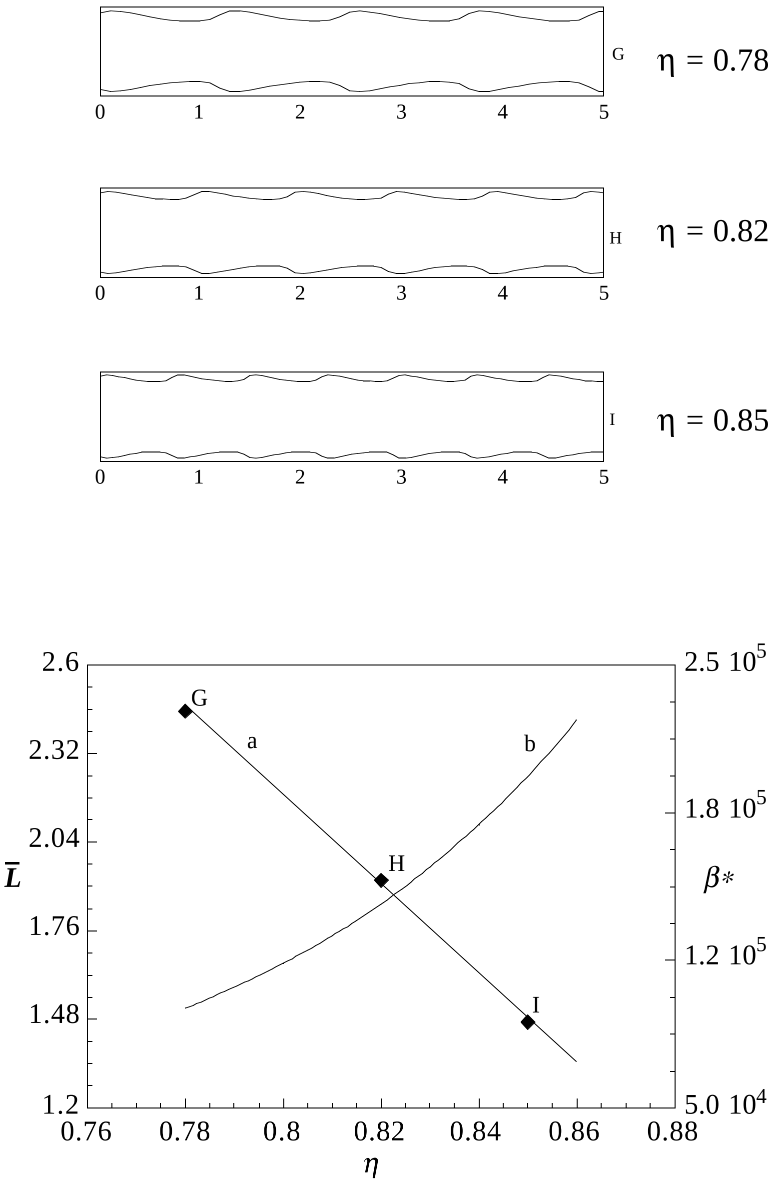

Figure 3. Numerical calculation of BKJ (1996). Wavelength $\overline{L}$ = 13.5 - 14.1η for ($\mathbb{R}$, h) = 600, 1.4). The wavelength and amplitude tend together to zero as $\eta \to 1$. ($\mathbb{R}$, h, η) = (Reynolds number, holdup, radius ratio)

- **Turbulence**

In most pilot and test loops, and all commercial lines, the water in the annulus surrounding the oil core is turbulent and the flow in the viscous core is laminar. If the oil viscosity is very large, as is true of heavy oils and bitumen froth, secondary flows and the pressure gradients which produce them may be ignored. Arney et al. [1993] collected all published data on conventional core flows and they established that most of the data fits a standard Blasius correlation for a modified friction factor vs. a modified Reynolds number (figure 4). They also developed a correlation formula which estimates the holdup fraction was introduced and evaluated for all available experimental data.

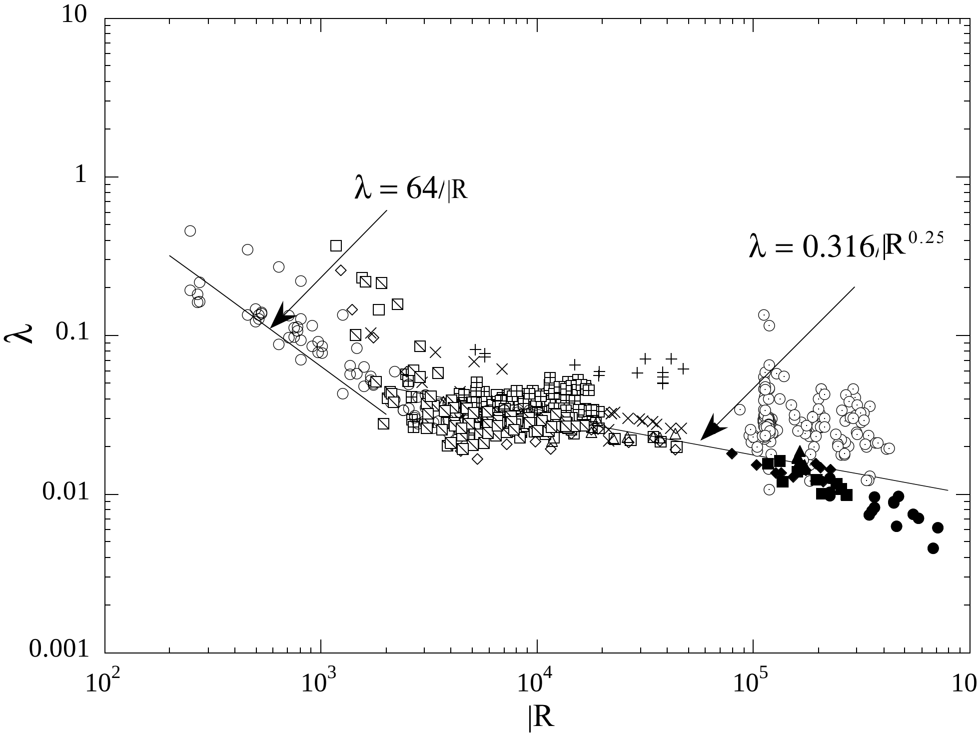

Figure 4. (after Arney et al 1993) Reynolds numbers vs. friction factor λ for all known literature data.

Huang, Christodoulou and Joseph [1994] developed a κ-ε model for a turbulent water annulus and laminar core which they compared with data given by Arney et al. [1993]:

> **Abstract.** A model of core-annular flow in which the oil core is a perfect cylinder with generators parallel to the pipe wall, but off-center, is studied in laminar and turbulent flow to asses the effects of eccentricity and the volume flow rate ratio on the friciton factor and holdup ratio. The study is tilted toward water lubrication of heavy crude viscous oil For the turbulence analysis, the water is assumed to be turbulent and the core laminar. A standard κ-ε model with a low Reynolds number capability is adopted for the turbulent case. The agreement between model predictions, which have no adjustable parameters, and experimental and field data form all sources, is satisfactory.

We are going to modify the work of Huang et al. [1994] for applications to data on self-lubrication. We can also take advantage of simplifications which arise in the high viscosity limit to compute the shape of waves on a very viscous oil core dragged forward by turbulent water in the annulus.

4.2 LUBRICATED TRANSPORT OF CONCENTRATED OIL/WATER EMULSIONS

The flow resistance of concentrated oil/water emulsions depends on how the phases are distributed and different distributions are realized in practice. Lubricated configurations are those for which water rich layers are at the walls. Núñez, Briceño, Mata, Rivas, and Joseph [1996] did possibly the first study of flow characteristics of very concentrated (≥70%) dispersions of very viscous bitumen drops:

> **Synopsis**
> This article advances ideas and presents experiments on the flow characteristics of concentrated emulsions of Venezuelan bitumen in water plus surfactant. These emulsions are studied under a variety of flow conditions, namely, between rotating cylinders, in a colloid mill, and in pipes. The ideas advanced here concern the modeling of the highly viscous bitumen drops as solid spheres and their fracture under contact forces between neighboring drops, as in comminution, rather than break-up by hydrodynamic forces. Further, we observe and discuss the local inversion of an emulsion due to local increases of the bitumen fraction induced by flow and the conditions that lead to slip flow, in which the drag is reduced by the formation of the lubricating layer of water at the wall. We believe that the results presented here unveil mechanisms that take place in the pumping and pipelining of oil-in-water emulsions and therefore contribute to the understanding of the dynamic stability of these systems.

4.3 FOULING OF PIPE WALLS WITH OIL

Arney et al. [1995] did studies of anti-fouling coatings and additives. Sodium metasilicate additives in small concentrations were effective with Venezuelan crudes but not with bitumen froth. Cement-lined pipes did not foul when they were water wet; however the cement pipes would foul when dry, and once fouled, a cement pipe cannot be cleaned.

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

4.4 MIGRATION OF PARTICLES LEADING TO LUBRICATED CONFIGURATIONS

These studies are now being pursued under an NSF grand challenge high performance computing grant which is a cooperative effort over 4 institutions; my CO PI’s are H. Hu (University of PA), Roland Glowinski (Houston), G. Golub (Stanford) and A. Sameh (Purdue). We are doing direct numerical simulation of fluidized suspensions in Newtonian and viscoelastic liquids; thousands of particles in parallel 2D simulations and hundreds in

3D. The goals we set in 1993 were achieved and extended far beyond. These results, which are not directly relevant for the present proposal are described under http://www.aem.umn.edu/Solid-Liquid_Flows/.

4.5 SELF-LUBRICATED TRANSPORT OF BITUMEN FROTH

Syncrude Canada Ltd. contacted us in 1994 to study self-lubrication of bitumen froth. They were particularly interested in fouling as a possible show stopper for self-lubricated pipelining which in-house 1985 studies of O. Nieman suggested might be a viable option for pipelining froth from the mine. Our studies showed that though the pipelines fouled initially, no buildup of fouling would occur. Results of our studies of start and restart of a stopped line were similarly successful. Motivated by the success of the Minnesota studies, Syncrude built a 24"× 1km pilot loop in Fort McMurray. The results of these tests confirmed the Minnesota studies and they provided a database from which we determined a powerful scale-up result described in the abstract of the still proprietary 1997 report on “Self-lubricated transport of bitumen froth” by Joseph, Bai, Mata, Sury, and Grant:

> **Abstract.** Bitumen froth is produced from the oil sands of Athabasca using the Clark’s Hot Water Extraction process (add reference). 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"(25mm), 2"(50mm) and 24"(0.6m) 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 pipewall 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.

Motivated by these favorable results, Syncrude’s management decided to build a commercial line by 2001 from the new Aurora mine to the upgrading facility at Lake Mildred where froth is made into synthetic crude. The line is to be 35km at a cost of over 2 million dollars per kilometer. Publication of our research results is being delayed prior to the filing of the following two provisional patent applications.

- **Provisional patent application - NS305:** Technique to promote lubrication of bitumen through the addition of colloidal particles in the water by D.D. Joseph, K.N. Sury, and C. Grant.

Summary

The reduction of fouling of a pipewall by very viscous oil is promoted by the protective coating of the oil by small particles. For example, one way of preventing fouling is through the use of appropriate amounts of water with dispersed clay. Bitumen froth contains about 20 to 30% water in which small clay particles are well dispersed. The froth is unstable to shearing which leads to the coalescence of a portion of the water droplets to form a lubricating layer of free water. The clay-containing water inhibits the coalescence of bitumen froth, and promotes the coalescence of clay water droplets through a mechanism called “Powdering the dough”. The analogy is that bread dough is sticky, but when flour is spread on it, the dough loses its stickiness. The dough is protected from sticking by a layer of powder. The clay in the produced water acts like flour, it sticks to and prevents the bitumen in froth from coalescing. The role of the clay particles resembles the role of surfactant in stabilizing emulsions. The fine solids surrounding an oil droplet tend to act as a barrier protecting the droplets from coalescing with one another. Thus the fouling of a pipewall by heavy viscous oil may be relieved by the addition of hydrophilic solids of colloidal size to the water in a concentration above that necessary for saturation of the oil water interface. Moreover a pipe lightly fouled with protected oil would act to protect the fouled wall from further fouling. This is a novel concept.

- **Provisional patent application - NS306:** Method for Establishing Self-Lubricated Flow of Bitumen Froth or Heavy Oil in a Pipeline, D.D. Joseph, R. Bai, O. Neiman, K. Sury, and C. Grant.

Summary:

The start-up procedure for establishing self-lubrication of bitumen froth is to introduce the froth behind a water flow at speeds greater than critical. Lubrication is established immediately by this method and the water is then diverted from the pipeline to allow continuous self-lubricated froth flow. It is important to introduce the froth at speeds high enough to promote coalescence of the bitumen drops into a film of lubricating water. Speeds of the order of 1 m/s have been repeatedly successful in 1", 2" and 24" pipes, though somewhat lower speeds may also work. It is believed that the success of this method of start-up is due to the fact that the walls of the pipe are wet by running water prior to the introduction of the froth; the froth enters the pipe as a plug flow at speeds large enough so that even the small annular gaps of water are in turbulent flow. All these factors are favorable to the generation of high shear rates promoting the coalescence of clay water drops required for self-lubrication. Start-up procedures using fast froth injection behind moving water do not generate high pressure surges or the high pressure required in start from rest procedures used in the prior art (Kruka 1977). The method of fast froth injection behind moving water also circumvents the need to add water during start up (see Zagustin et al. 1988) which has undesirable consequences for maintaining froth integrity and dewatering after pipelining. Pure water or clay water can be used for the water flow prior to froth injection.

5. Research Tools

It is very important for a subject like this one which is aimed at practical energy applications to check all the results of analysis and numerical computation against experiments. Our lab is well positioned to do all these various kinds of study.

5.1 EXPERIMENTAL EQUIPMENT

We have two horizontal 1" diameter × 240" long pipelines; one is equipped for simultaneous injection of water and oil and the other is equipped for studies of pipelining of bitumen froth. The froth line is jacketed in a plastic tube in which cooling water can be circulated. A vertical 0.48 D vertical U loop, 180" high is used to study vertical up and down flow. Many measuring devices, high speed and high resolution video cameras, analytical software for image processing and a wide range of rheometers, are available for our use. We also plan to do some tests in the 4"×1440" horizontal line recently constructed in Syncrude’s Edmonton lab.

Our lab has the computational resources needed to do numerical simulations of core flows. We have our own SGI work stations and have access to our department’s SGI power challenger and to supercomputers, the Cray T3E and Origin 2000, at the Minnesota Supercomputer Center and at the DOE’s NERSC center.

5.2 NUMERICAL METHODS

The calculation of Bai, Kelkar and Joseph [1996] was the first, and to date the only, direct numerical simulation of core flow. The simulation used a modification of the numerical package SIMPLER created to handle interface problems (see the appendix in Bai et al. [1996] for a discussion of this package. We have not yet done a general calculation using SIMPLER; we solved the core flow in the special limit in which the core is so viscous that secondary motions in the oil do not occur. This limit is of general interest and is of particular interest to our future work; it will be discussed under (iii) below.

We do not think that SIMPLER can be easily adapted to core flow at finite viscosity ratios. For these more general problems we are developing a core flow code based on S. Osher's (1988, 1994, 1996) method of level sets. I sent Clara Mata, my graduate student, to Los Angeles to work with Osher and his post docs. The work she started there is proceeding satisfactorily.

5.3 ASYMPTOTIC SOLUTIONS IN THE LIMIT OF HIGH VISCOSITY

I recently developed a rigorous perturbation theory for the steady flow of immiscible liquids when the dispersed phase is much more viscous than the continuous phase, as is the case in emulsions of highly viscous bitumen in water and in water-lubricated pipelines of heavy crude. The perturbation is non-singular, but non-standard; the partitioning of the boundary conditions at different orders is not conventional. At zeroth order the dispersed phase moves as a rigid solid with an as yet unknown, to-be-determined, pressure. The flow of the continuous phase at zeroth order is determined by a Dirichlet problem with prescribed velocities on a to-be-iterated interfacial boundary. The first order problem in the dispersed phase is determined from the solution of a Stokes flow problem driven by the previously determined shear strain on the as yet undetermined interfacial boundary. This Stokes problem determines the unknown, to-be-determined, lowest order pressure distribution. At this point we have enough information to test the balance of normal stresses at lowest order; by iterating the interface shapes we may now complete the description of the lowest order problems.

The perturbation sequence in powers of the viscosity ratio has a similar structure at every order and all the problems may be solved sequentially with the caveat that the interface shape must be determined iteratively in each perturbation loop.

I hope to solve the problem of core-annular exactly in the limit of a highly viscous dispersed phase. A partial solution has been given by Bai, Kelkar and Joseph [1996]. To understand what has been solved and what remains to solve it suffices to briefly describe the lowest order problem; ε is the ratio of viscosities $\mu_w/\mu_o \to 0$, v and ϕ is the velocity and pressure in the water and $\mathbf{u}$ and ψ is the velocity and pressure in the oil. The solution is developed in powers of $\varepsilon = \mu_w/\mu_o$. To do the perturbation we write $\mu_o = \mu_w/\varepsilon$ wherever μ_o appears and then develop the solution in powers of ε. At the lowest order, we write

$$(1) \qquad \begin{cases} \mathbf{u}(r,z;\varepsilon) = \mathbf{u}_o(r,z) + \varepsilon\,\mathbf{u}_1(r,z) & \text{oil velocity} \\ \psi\,(r,z;\varepsilon) = \psi_o(r,z) & \text{oil pressure} \\ v(r,z;\varepsilon) = v_o(r,z) & \text{water velocity} \\ \phi\,(r,z;\varepsilon) = \phi_o(r,z) & \text{water pressure} \end{cases}$$

We require that all these solutions be periodic in z with period L. The position of the interface $r = f(z,e)$ is unknown and is determined by the governing system of equations. The flow rates and volumes of oil and water are prescribed. The volume of oil is given by the mean radius R_1 of the oil-water interface. This data determines the ratio of the average velocity of oil c_o to the average velocity of water c_w and is called holup ratio

$$(2) \qquad h = \frac{c_o}{c_w} = \frac{Q_o / Q_w}{R_1^2 / (R_2^2 - R_1^2)},$$

hence h and R_1 are prescribed.

If we put (1) into our equations, assuming all of the variables in (1) are bounded as $\varepsilon \to 0$, we find that $\mathbf{u}_o$ = const, independent of $f(z)$. In coordinates fixed on the oil $\mathbf{u}_o = 0$ and the oil moves as a rigid solid. Then, whatever $f_0(z)$ may be, the viscous component of the normal stress in the water vanishes.

$f_o(z)$ is not prescribed; it is determined ultimately by the prescribed constant holdup h_o at zeroth order; $h_o = 2$ for perfect core flow without waves and $h = 1$ when the water is trapped between wavecrests touching the pipe wall. For wavy flow $1 < h < 2$; $h = 1.4$ occurs frequently in experiments; the selection mechanism is related to stability and is not understood. Here

$$(3) \qquad h_o = 1.4$$

is prescribed, so waves are inevitable.

To get $f_o(z)$ we have to iterate; if $f_o(z)$ is given and $\mathbf{u}_o(r,z)=0$, $r \leq f,(z)$; then the water flow must satisfy

$$(4) \qquad \rho_w v_o \cdot \nabla v_\mathrm{o} - \beta \mathbf{e}_z + \nabla \phi_o - \mu_w \nabla^2 v_o = 0 = \mathrm{div}\, v_o$$

where, on the pipe wall

$$(5) \qquad v_o(R_2, z) = -c_o \mathbf{e}_z$$

and

$$(6) \qquad v_o(f_o(z), z) = 0$$

on the interface of the rigid stationary core. L periodic solutions of (2)-(6) exist, and were found in the numerical simulation of Bai, et al. [1966]. From this solution we may compute the shear strain

$$(7) \qquad \tau\cdot\mathbf{D}[v_o]\cdot\mathbf{n} = \dot{\gamma}(f_o(z),z)$$

at each point on the interface. Here $\mathbf{D}[v_o]$ is the rate of strain tensor, τ is tangent and $\mathbf{n}$ the outward normal of the interface. Since $\mathbf{u}_o$=0, the lowest order velocity in the oil is $\mathbf{u}_1(r,z)$ satisfying

$$(8) \qquad -\beta\mathbf{e}_z\nabla\psi_o = \mu_w\nabla^2\mathbf{u}_1,\ \mathrm{div}\mathbf{u}_1 = 0$$

$$(9) \qquad \mathbf{u}_1(f_o(z,z)) = 0$$

$$(10) \qquad \tau\cdot\mathbf{D}[\mathbf{u}_1(f(z),z))]\cdot\mathbf{n} = \dot{\gamma}(f(z),z)$$

We seek L periodic solutions of the Stokes flow problem (8), (9), (10). This problem is not coupled to (3), (4) and (5); they are to be solved sequentially for a given $f_o(z)$.

The normal stress balance is given by

$$(11) \qquad -\phi_o + \psi_o - 2\mu_w\ \mathbf{n}\cdot D[\mathbf{u}_i]\cdot\mathbf{n}=2H\sigma$$

where H is the mean curvature and σ the surface tension. This will not be satisfied for any $f_o(z)$ and closes a lowest iteration loop for the lowest order approximation.

Bai et al [1996] solved these equations with ψ_o and $\mathbf{u}_1$ neglected. Their solution gives rise to steep waves. We are proposing so solve (8), (9), (10) and (11) to find the shape of $f_o(z)$ of the interface satisfying all equations at the lowest order in ε.

6. Research Projects

6.1 LEVITATION AND WAVE SHAPE IN WAVY CORE FLOW. EXPLANATION OF THE EFFECTS OF GRAVITY. FIND THE STABLE OFF-CENTER POSITION OF THE CORE

(a) *Plane model of eccentric core flow.*

A simple model is proposed for horizontal core flow in a channel in which the effect of gravity, due to the difference in the densities of the two fluids, is considered. The main assumption here is that the viscosity of the oil is so large that it moves as a rigid solid which may nevertheless be deformed by pressure forces in the water. We expect to prove that inertia is required for levitation of core flows. We will adapt the modification of the numerical package SIMPLER created by Bai et al. (1996) to handle the interface problem of the steady axisymmetric, axially periodic CAF. We want to split the domain at the center of the core and characterize each subdomain by means of local variables, for instance the holdup ratio. The analytical solution of PCF in a channel shows that the smallest global pressure drop is achieved if and only if the local holdup ratios are equal and equal to the global holdup ratio and this only happens when the core is centered. We want to exploit this result in our direct simulation of wavy core flow in a channel. We expect to obtain asymetric waves with steep slopes in the high pressure region at the front face of the wave crest an shallower slopes at the low pressure region at lee side of the crest, as Bai et al. describe (1996). We also expect to confront two new issues in our 2D simulation. First, the shape and length of the upper and lower waves may be different, after experimental results. Second, buoyancy forces may induce a displacement of the core, which can thought to represent eccentricity. Our ultimate goal is to prove that a positive pressure force is required to levitate the core off the walls when the densities are not matched and that the difference in the upper and lower waves shape restore the effect of the eccentricity by allowing the local holdup ratios to be equal to the global holdup ratio and thus the pressure drop be the smallest possible.

(b) *Eccentric core flow balanced by gravity in a round pipe resolved numerically by the level set method.*

Bai et al. (1996) did a direct simulation of steady axisymmetric, axially periodic CAF, assuming that the core viscosity was so large that the secondary motions could be neglected in the core. The numerical method they used was a modification of the SIMPLER package created to handle interface problems. We want now to work the general case with finite viscosity ratios and include the effect of gravity due to unmatched densities. We do not think that SIMPLER can be easily adapted to solve this problem. Instead, we are developing a code based on S. Osher method of level sets (1994, 1996). This level set formulation was derived for incompressible, immiscible Navier-Stokes equations separated by a free surface where the effect of surface tension is included. This numerical method have been proven to be accurate, efficient and capable of simulating incompressible multiphase flow, such as air bubbles and water drops, among others. We expect to corroborate Bai et al. results and solve the eccentric core flow balanced by gravity in a round pipe with finite viscosity ratio and ultimately prove that inertia is required for levitation of CAF.

6.2 WAVE SHAPES ON AN INFINITELY VISCOUS OIL CORE FLOWING IN TURBULENT WATER RESOLVED BY SIMPLER USING A κ–ε MODEL.

The methods of numerical analysis previously discussed do not account for turbulence in the water. Most of the data points in figure 4 belong to the branch $\lambda = 0.316 / \mathbb{R}^{1/4}$ for turbulent flow. Turbulent flow analysis for figure 4 was successfully carried out by Huang, Christodoulou and Joseph [1994] using a low Reynold's number κ-ε model under the assumption that the oil core was laminar and that there were no waves on the oil-water interface. The equations of the κ-ε model were solved with SIMPLER subject to the no-slip boundary condition on the pipe wall and the condition on the constant core radius that the turbulent energy κ, dissipation ε and eddy viscosity vanish as they must in laminar flow. This ensures that the continuity of the mean velocity and mean shear stress across the interface between the oil core and annulus can be enforced.

The formalism just described can also be applied to wavy core flow in which the position of the wavy core interface is also an unknown. The laminar flow solution in the oil core is more complicated when the core interface is wavy because the interior streamlines are not straight; Stokes flow governs and the normal stress condition must be enforced to determine the shape of the waves. The turbulence problem can be greatly simplified in the limit of infinite viscosity used by Bai et al [1996]. In this case the core moves as a rigid body, the pressure in the core is decomposed into the part with a uniform pressure gradient which is a constant term in the equation of motion and a uniform pressure which cannot drive a motion. The same conditions as before are applied on κ,ε and the eddy viscosity at the wavy surface whose shape is determined by the balance of the jump in pressure and surface tension, as in equation (1). In limit of high oil viscosity the oil velocity and pressure are uniform and all the necessary computations are done in the turbulent water using the κ-ε model.

6.3 SELF-LUBRICATION OF BITUMEN FROTH

To better understand the research issues it is useful to review the data.

(a) *Data Sorted by temperature*

Figure 5 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"(50mm) and 1"(25mm) pipelines. All the available data is shown in figure 5(a). The 2"(50mm) diameter pipeline data of Nieman (1985) is greatly scattered and will be mostly ignored in our analysis. 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 $3\text{x}10^6$). These curves are shown in figure 5(b). The parameters defining these curves are presented in table 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:

$$\tau_w = \frac{\beta R_o}{2} \tag{3}$$

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:

$$\lambda = \frac{8\tau_w}{\rho U^2} \tag{4}$$

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

$$\lambda = \frac{k}{Re^{1/4}} \tag{5}$$

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

$$Re = \frac{2R_o U}{\nu} \tag{6}$$

where ν is the kinematic viscosity of water.

Combining equations (3) to (6) 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].

$$\beta = K\frac{U^{7/4}}{R_o^{5/4}} \tag{7}$$

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

Table 1. Fitting constant K for two temperature ranges, using equation (7).

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 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 (e.i. $\frac{6}{0.316} \approx 20$). Therefore, the increase in the pressure gradient over and above the Blasius value observed in figure 5 is of the order of 10 to 20 and it is independent of velocity or pipe size. This is amazing.

(b) *Data sorted by velocity*

Figure 6 presents again all the available data, this time, parametrized by velocity rather than pressure. In figure 6(a), curves (i) and (ii) enclose most of the data, if the scatter in the 2”(50mm) 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 6(b). There, curves I and II predict the pressure gradient based on a velocity criterion, for the 24”(0.6m) and 1”(25mm) pipes, respectively. Both curves are parallel to the Blasius formula and are located between curves (i) and (ii) (see figure6(a)) until they reach a critical velocity U_C = 1.6 m/s, where they turn flat on a plateau. For the sake of argument let us assume that 1.6 m/s is a universal value of U_C for any pipe diameter. For $U > U_C$ you get much greater flow for only marginal changes of pressure gradient, “something for nothing.”

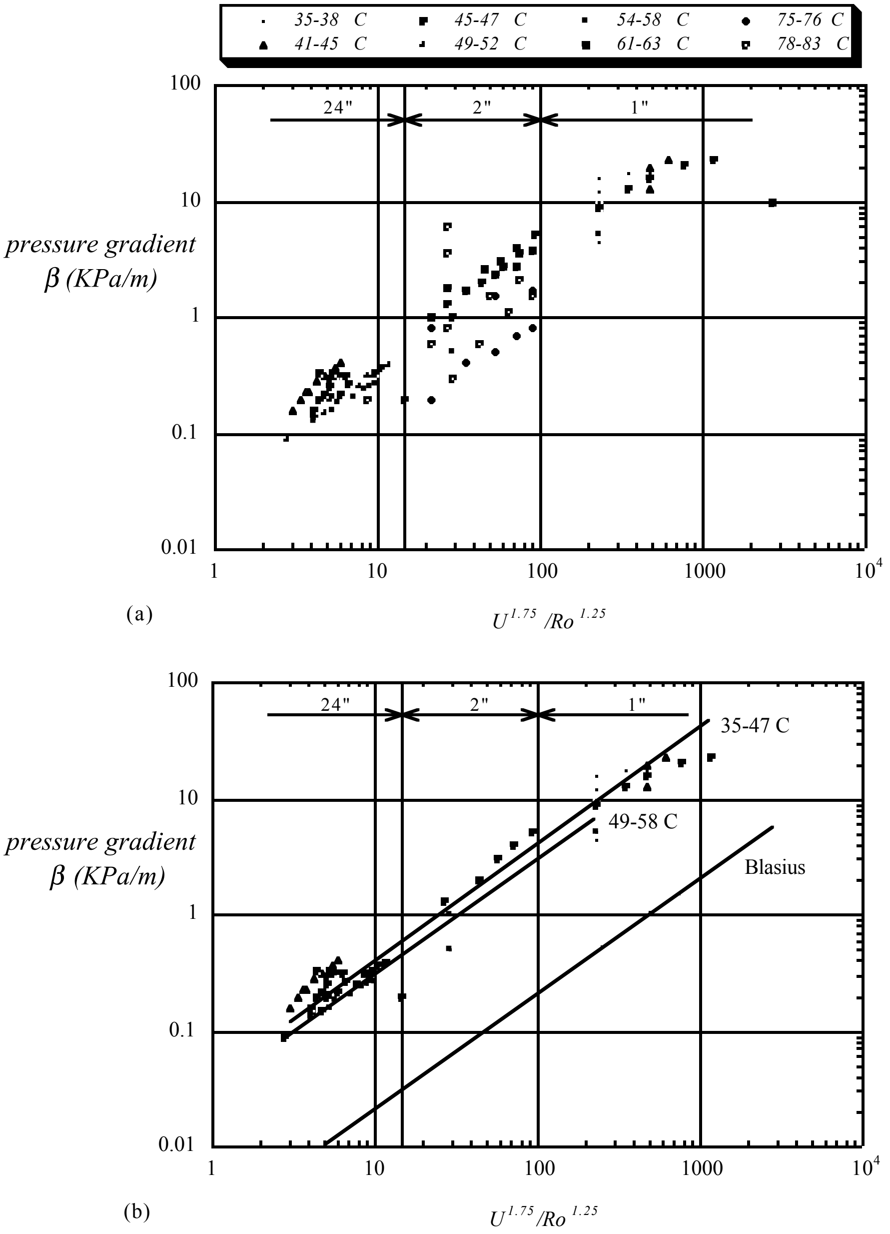

Figure 5. Pressure gradient of bitumen froth β [Kpa/m] as a function of the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe radius, parametrized by temperature. Left: 24"(0.6m) diameter pipeline; middle: 2"(50mm) diameter pipeline (Niemans' data); and right: 1"(25mm) diameter pipeline. (a) All available data. (b) Fittings parallel to the Blasius correlation for turbulent pipeflow (bottom line), for two temperature ranges: 35-47°C (top) and 49-58°C (middle). Most of the 2"(50mm) diameter pipeline data was ignored in these fits, due to its high scatter.

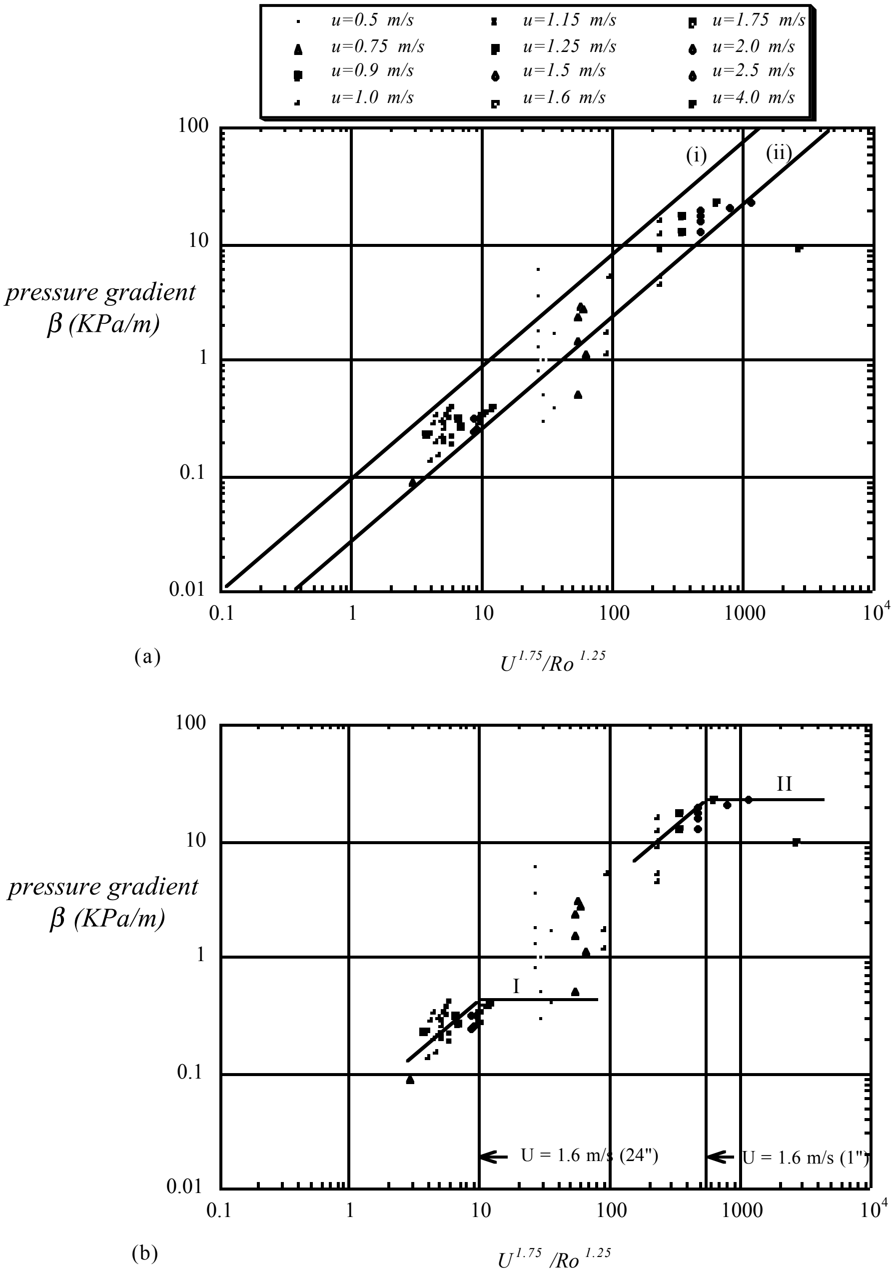

Figure 6. Pressure gradient of bitumen froth β [Kpa/m] as a function of the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe radius, parametrized by velocity. Left: 24”(0.6m) diameter pipeline; middle: 2” diameter pipeline (Niemans’ data); and right: 1” diameter pipeline. (a) All 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”(50mm) diameter pipeline data region . (b) I and II are predicted pressure gradients β, based on a velocity criterion, for the 24”(0.6m) diameter pipeline data and 1”(25mm) diameter pipeline data, respectively. Here the critical velocity is approximately $U_c = 1.6$ m/s.

(c) *Water release*

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 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.

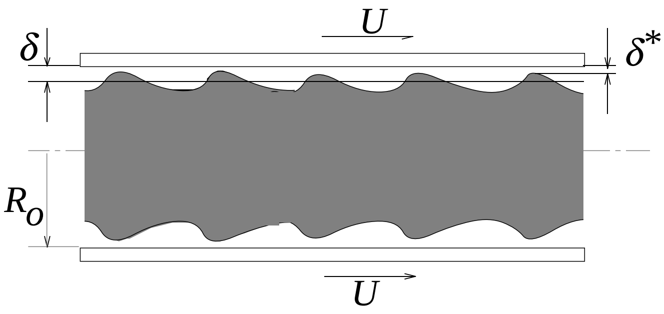

Figure 7. Released water layer thickness δ for selflubricated froth flow. R_o is the pipe radius and $\delta/R_O \ll 1$. The frame of reference has been changed. The bitumen froth core is fixed and the pipe wall moves with the measured average velocity of the froth U.

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,

$$X = \frac{R_o^2 - (R_o - \delta)^2}{R_o^2} = \frac{2\delta}{R_o} \tag{8}$$

when $\delta \ll R_O$.

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 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 9.

$$\frac{U_o}{u^*} = 2.5\ln(2\eta_r) + 5.5 \tag{9}$$

η_r is a dimensionless length, defined as follows:

$$\eta_r = \frac{ru^*}{\nu} \tag{10}$$

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

$$u^* = \sqrt{\frac{\tau_w}{\rho}} \tag{11}$$

where ρ is the water viscosity and τ_w is the shear stress on the wall, given by equation 3.

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 8(b), an expression for the released water layer thickness δ may be obtained from equation (8), as a function of U and u^*. That is

$$\delta = \frac{\nu}{u^*}\exp\left(\frac{0.5\frac{U}{u^*} - 5.5}{2.5}\right) \tag{12}$$

Equation (12) predicts values of δ of the order 10^{-3}mm for the 1"(25mm) 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"(25mm) diameter pipeline tests, which are listed on table 2. We presume that this small gap is between the pipe wall and the crests of the waves, indicated as δ^* in figure 7. However we are interested in predicting the mean gap size δ, which is much larger.

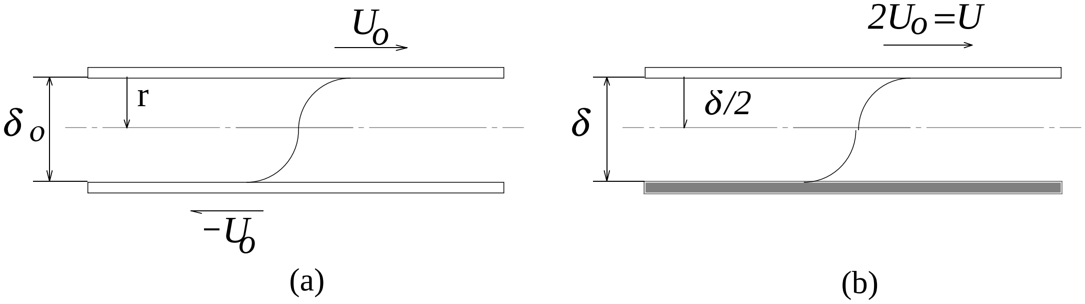

Figure 8. Turbulent Couette flow by Reichardt (1956). (a) Two parallel plates, separated by a distance δ, are moved in opposite directions with a velocity Uo. The distance from the wall to the center of the channel is denoted by r. (b) The frame of reference has been changed. Now the lower wall is fixed 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' formulal with a friction factor (*k*/0.316) times greater than the one given by equation 4, or

$$\lambda_k = \frac{k}{0.316}\lambda_{Blasius} \tag{13}$$

we can define a pseudo friction velocity as follows:

$$u*_k = \sqrt{\left(\frac{0.316}{k}\right)\frac{\tau_w}{\rho}} \tag{14}$$

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 (12) becomes

$$\delta_k = \frac{\nu}{u*_k} exp\left(\frac{0.5\frac{U}{u*_k} - 5.5}{2.5}\right) \tag{15}$$

We used equations (15) and (8) 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 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. 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"(25mm)-diameter pipe data (see table 3).

Table 2. Measured and calculated released water layer thickness δ and volume fraction for selflubricated froth flow in a 1"(25mm)-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 3. Predicted released water layer thickness δ_k and volume fraction for selflubricated froth flow in a 24"-diameter pipe.

U [m/s]	Released water layer thickness δ [mm]	Released water mass fraction X %
1.0-1.75	1-7	1-5

- Frictional heating

The effects of frictional heating in the one-inch Minnesota line are pronounced. The froth temperature increases markedly with temperature. The increase in temperature may promots reabsorption of some released water.

6.4 LIST OF PROPOSED RESEARCH PROJECTS

(a) *Experiments*

We installed a jacked around the one-inch line to circulate cooling water and control the pipe wall temperature. We are going to take data systematically for increasing values of flow velocity. At each velocity we shall measure

- Flow velocity, pressure gradient, froth temperature, water holdup
- Determine the minimum critical speed below which self-lubricated flow can not be maintained. Find how this critical value varies with temperature and water fraction.
- Find the second critical speed above which the froth flow speed may be increased greatly for only marginal increases in the pressure gradient.
- Test self-lubrication properties of cement-lined pipes. Syncrude is concerned about corrosion. Moreover, the clay water and cement can be made chemically similar and may undergo synergism which blocks fouling.
- Develop a froth rheometer to determine critical values for self-lubrication. We are trying to develop a rotating device for finding these critical values.

(b) *Numerical*

To analyze the remarkable result that the friction for froth flow scales with the Blasius law but with friction of 10 to 20 times that of water we are going to calculate the friction associated with wavy core flow of an infinitely viscous core in turbulent water. We will use the κ-ε model exactly as described under ***6.2***. In this asymptotic limit, all of the many simplifications listed in ***5.3*** apply: the flow and pressure in the core is uniform, the water flow is computed with the κ–ε model subject to no slip on the wall and the core, and the shape of the waves is determined from balancing interfacial tension against the jump in pressure as in (1).

We shall look at periodic axisymmetric waves. The core and water may be assumed to have the same density. For small gaps this problem is basically a Couette flow; the core moves forward dragging the water along. The flow due to the pressure gradient in the water goes to zero as the gap is reduced.

Using measured values of the froth velocity and the pressure gradient we may match the productions of the foregoing κ–ε asymptotic analysis with one and only one water hold-up (free water fraction). This gives the thickness of the free water layer required to match the observed gradient. We may compare the theoretical with measured values as in Table 2. If these values agree it is likely that the increased friction is associated with the small gap between the wave crests and pipe wall.

(c) ***Theoretical-Conceptual***

• Mechanism of water release

We have argued that clay covering of bitumen protects the bitumen from sticking to itself and promotes the coalescence of water drops under shear. It is well known that these clay coverings are very effective in stabilizing bitumen in clay-water emulsions [Yan and Masliyah (1994)]. We do not know the detailed mechanism of water release. One possibility is that the shear stress is constant on the bitumen-free water interface. The shear stress must increase with velocity if the thickness of the water layer does not change; the shear stress could be maintained at a constant value as the velocity increases if more free water is released.

• Frictional Heating

The froth temperature increases strongly with speed when the pipe-wall temperature is not controlled. This heating is clearly due to friction. We would like to create a scale-up theory for this which would enable us to predict the temperature rise observed in pipes of any diameter from data collected in our one-inch pipe.

• Mechanism of frictional resistance

It is necessary to explain the remarkable result that the friction for froth flow scales with the Blasius law but with friction of 10 to 20 times that of water, uniformly for pipe diameter 1” to 24”. The data suggests that the increased friction depends strongly on froth temperature. One idea is that the friction is controlled by the close approach of “tiger” waves which we hope to analyze by numerical methods previously described. The close approach could be partly determined by the creation and annihilation of fouling which are in balance, at a level determined by temperature.

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8. Biographical Sketches

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1950 M.A., Sociology, U. of Chicago
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Employment:
1962 Assistant Professor, Mechanical Engineering, Illinois Institute of Technology
1963 Assistant Professor, Aerospace Engineering and Mechanics, University of Minnesota
1965 Associate Professor, Aerospace Engineering and Mechanics, University of Minnesota
1968 Professor, Aerospace Engineering and Mechanics, University of Minnesota
1991 Russell J. Penrose Professor of Aerospace Eng & Mechanics, University of Minnesota
1994 Regents' Professor, University of Minnesota

Patents:
Wave-speed meter (US Patent No. 4,602,502); measures wave speeds, determines the effective rigidity of a liquid.
Spinning rod interfacial tensiometer (US Pat. # 4,644,782); determines the interfacial tension between immiscible liquids.
Spinning drop tensioextensiometer (US Pat. # 5,150,607); for polymer blends, & in the oil industry where temp. is important.
Device and method for determining drag on surfaces (US Patent No. 5,301,541).
Method for preventing fouling of pipewalls for lubricated transport, (US Patent No. 5,385,175).
Method and apparatus for measuring a parameter of a multiphase flow (US Patent No. 5,646,352).
Foam suppression in a bubble column reactor by fluidizing particles, 96-247 (Patent applied for).
Method for establishing self-lubricated flow of bitumen froth or heavy oil in a pipeline, (Patent applied for).
Technique to promote lubrication of bitumen through the addition of colloidal particles in the water, (Patent applied for).
Foam control using a fluidized bed of particles, 97-242 (Patent applied for).

Honors and Awards:
Guggenheim Fellow, 1969–70
G. I. Taylor Medalist, Society of Engineering Science, 1990
Distinguished Service Award, US Army CRDEC, 1992
Aris Phillips Lecturer, Yale University, April 1992
Schlumberger Foundation Award, July 1993
Fellow of the American Physical Society, November 1993
National Academy of Engineering, 1990
National Academy of Sciences, 1991
G.I. Taylor Lecturer, Cambridge Phil. Soc., Jan 1992
American Academy of Arts and Sciences, April 1993
Bingham Medalist of the Society of Rheology, October 1993
Timoshenko Medalist of the ASME, May 1995
Croco Lecturer, Princeton University, Mechanical Engineering, October 1995
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