Lubricated Pipelining

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Abstract

This paper gives a brief overview of the issues posed by the science and technology for transporting heavy oils in a sheath of lubricating water. It touches on measures of energy efficiency, industrial experience, fouling, models of levitation and future directions.

1. Introduction

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 viscosity ratio can be achieved in lubricated flows. Lubricated flow in an oil core is called core annular flow, CAF for short.

Various arrangements of oil and water occur in experiments. The arrangements which appear in horizontal pipes are: stratified flow with heavy fluid below, oil bubbles and slugs in water, concentrated oil in water in emulsions (stabilized by surfactants), continuous cores of oil in water and water in oil emulsions. The flows are lubricated whenever the bulk of the oil does not adhere to the wall. Any of these arrangements can be lubricated. A light oil may be levitated off the top wall by pressure forces which are generated in the water by waves on the oil. Water in oil emulsions are an oil continuous phase of an "effective" oil which can be lubricated with water. The most comprehensive classification of flow types in horizontal CAF was given by Charles, Govier and Hodgson [i] for the case in which the oil density was increased to that of water by an additive. Effective oils, continuous emulsions of water in oil, can be made to approach the density matched case (see Ho and Li [ii]). Different, but similar, flow types appear in CAF in vertical pipes (Bai, Chen and Joseph [iii]).

Typically, waves appear on the surface of oil core and they appear to be necessary for levitation of the core off the wall when the densities are different and for centering the core when the densities are matched. We call these flows wavy core annular flow (WCAF). Perfectly centered core flows (PCAF) of density matched fluids in horizontal pipes and, generally in vertical pipes, are possible but are rarely stable (Joseph and Renardy [iv] hereafter called JR; Preziosi, Chen and Joseph [v]; Chen, Bai and Joseph [vi]).

The science behind the technology of CAF has given rise to a large literature which has been reviewed by Oliemans and Ooms [vii] and more recently by Joseph and Renardy [iv]. This literature has many facets which include models for levitation, empirical studies of energy efficiency of different flow types, empirical correlations giving the pressure drop vs. mass flux, stability studies and reports of industrial experience.

2. Industrial Experience

It is best to start this review with industrial experience since the potential of lubricated lines for energy efficient transport of heavy oil gives this interesting subject an even greater urgency. 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. Isaacs and Speed [viii] in U.S. Patent #759374 were the first to discuss water lubrication of lighter oils which they proposed to stabilize by centripetal acceleration created by rifling the pipe. For stratified flow, Looman [ix] patented a method of conveying oils by passing them over an array of water traps at the bottom of the pipe. An extended history of patents is presented in JR. The patent history of the subject as it is presently understood starts with application Clark and Shapiro [x] of Socony Vacuum Oil Company who used additives to reduce the density differences between the oil and water and anionic surfactants to reduce emulsification of water into oil. Clifton and Handley [xi] of Shell Development proposed to prevent the emulsification of oil at pumps by removing the water before and inserting the oil after the pumps. In fact, water-in-oil emulsions can be pumped in a sheath of water despite the fact that the viscosity of the emulsion can be orders of magnitude larger than the oil alone. 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 [xii] 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 and Li [ii] of Exxon produced a *concentrated* water in oil emulsion with 7 to 11 time more water than oil, which they successfully transported in CAF.

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 and Simpson [xiii] 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, Briceño, Mata and Joseph [xiv]).

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 CAF was stable as long as the flow velocity was at least 3 ft/s.
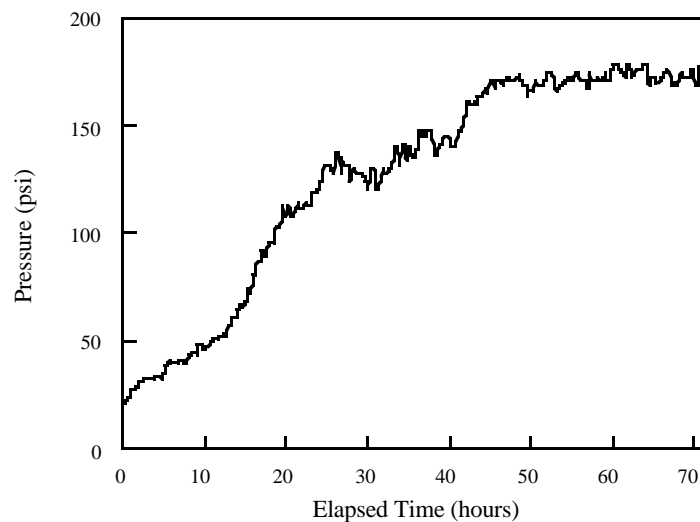
3. Fouling

Even though lubricated flows are hydrodynamically stable, oil can foul the wall. This is an adhesion rather than a hydrodynamic effect and is not taken into account in the equations used to study stability. The hydrodynamic stability of lubricated flow is very robust even when oil wets the wall. A water annulus can lubricate an oil core even in a pipe whose walls are spotted with oil. Sometimes, however, the fouling builds up, leading to rapidly increasing pressure drops even blocking the flow. An example taken from an experiment in which Zuata crude oil (ρ = 0.996 g/cm^3, η = 1,150 poise at 25°C) from the Orinoco belt was pumped through an 8" (20 cm) ID, 1-km pipeline

with input fraction of 4% water and superficial oil velocity of 1.5 m/s as shown in Figure 1. The pressure gradient increased monotonically from about 29 psi up to 174 psi due to the gradual fouling of the pipes. If allowed to continue, the Zuata would completely foul and block the pipeline.

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

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

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

Remedial strategies to prevent fouling naturally alter the adhesive properties of the wall which depend on the solid surface and the oil used. The different strategies that have been tried were discussed by Ribeiro, Rivero, Arney, Hall and Joseph [xv] and by Arney, Ribeiro, Guevera, Bai and Joseph [xvi]. The addition of sodium silicate to the water will inhibit fouling of carbon steel pipes. It does so by increasing the negative charge density of the steel surface through the absorption of SiO_3^{-2} ions. But the flowing water constantly washes the silicate ions from the steel pipe walls, so a continuous supply is needed. The continuous addition of sodium m-silicate did not completely suppress the fouling of Maraven's 54 km San Diego-Budare line by Zuata crude. Sodium m-silicate also helps to make normally hydrophobic quartz glass hydrophilic. Although the effect lasts longer on glass than carbon steel, it does not appear to be permanent. A very substantial increase in the hydrophilicity of quartz can be achieved by hydration in sodium m-silicate and a surface gel may actually form there. Desirable aggregates in mortars of Portland cement are principally quartz or silicates so that these treatments should be studied further.

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

Cement linings may offer a practical solution to the problem of fouling because they not only have good oleophobic properties but are commercially available at prices not greatly in excess of unlined pipes. In the experiments reported by Arney et al. [xvi] a pilot scale cement-lined core-annular flow pipeline using No. 6 fuel oil never fouled in over 1000 hours of operation. Repeated and determined attempts to soil properly hydrated cement-lined pipes with heavy Venezuelan crudes under conditions modeling restart always failed.

4. Levitation

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 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 leavings at low Reynolds numbers. Ooms, Segal, Van der Wees, Meerhoff and Oliemans [xvii] and Oliemans and Ooms [vii] 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 2 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.
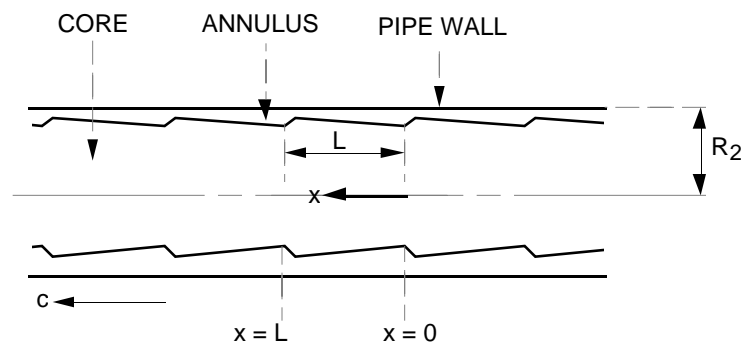
Figure 2. The core is at rest and the pipe wall moves to the left.

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 3. To get a lift from this kind of wave it appears that we need inertia, as in flying. Liu's [xviii] 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 CAF 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.


(c)
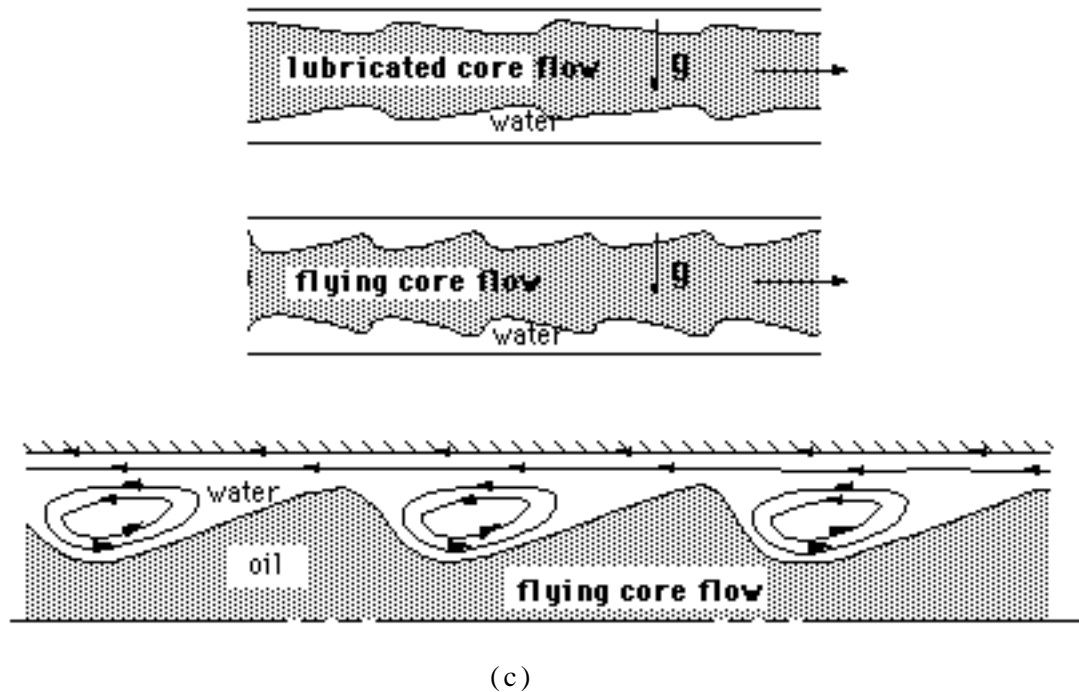
Figure 3. (After Feng, Huang & Joseph [xix]) (a) The interface resembles a slipper bearing with the gentle slope propagating into the water. (b) The high pressure at the front of the wave crest steepens the interface and the low pressure at the back makes the interface less steep. (c) The pressure distribution in the trough drives one eddy in each trough.

Bai, Kelkar and Joseph [xx] did a direct numerical simulation of steady axisymmetric CAF, assuming that the core viscosity was so large that secondary motions could be neglected in the core. They found that shapes like those in Figure 3 always arise from the simulation (see Figure 4). They also found a threshold Reynolds number corresponding to a change in the sign of the pressure force 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 (see Figure 5). Their work suggests that a positive pressure force is required to levitate the core when the densities are not matched and to center the core when they are not (references from the paper by Bai et al. [xx] are in the list below). A further conjecture is that the principal features which govern wavy core flows cannot be obained from any theory in which inertia is neglected.
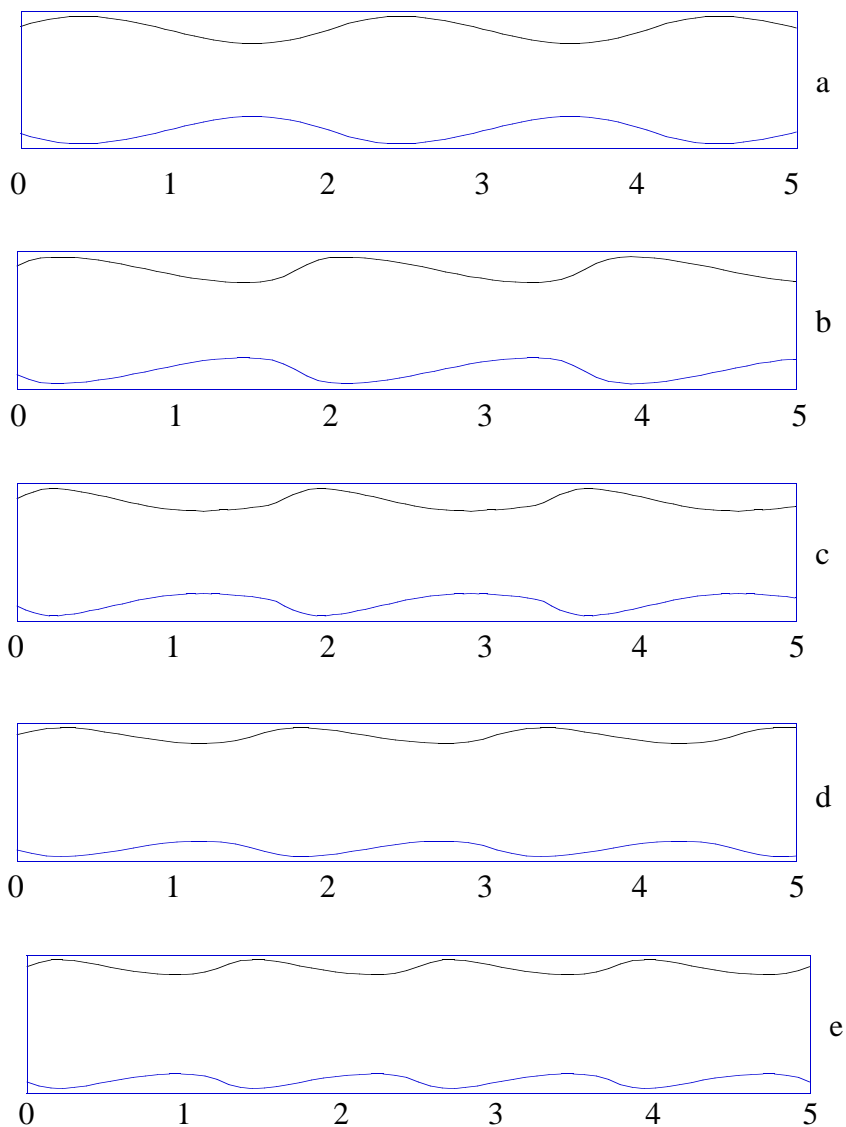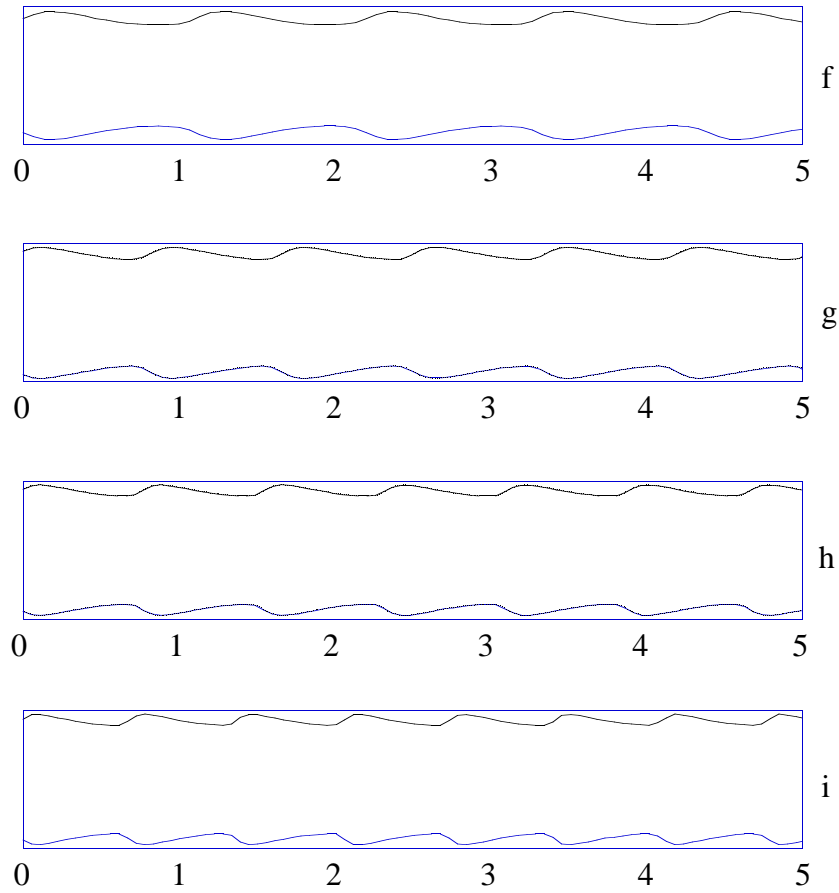
Figure 4. Selected wave shapes for water lubricated axisymmetric flow of oil and water with the same density $\rho = 1.0$ g/cm^3, $\mu_2 = 0.01$ poise and $\sigma = 26$ dyne/cm for oil and water. The pipe diameter is $R_2 = 1.0$cm. Q_o and Q_w are in cm^3/sec. The data for each frame is given as the triplet (R_1, Q_o, Q_w), a (0.37, 4.30, 2.73), b (0.37, 8.6, 5.47), c (0.37, 17.2, 10.93), d (0.41, 10.56, 3.67), e (0.41, 18.48, 6.43), f (0.41, 26.41, 9.19), g (0.43, 34.85, 8.76), h (0.43, 43.57, 10.96) and i (0.43, 69.71, 17.53). The core is stationary and the wall moves to the right.
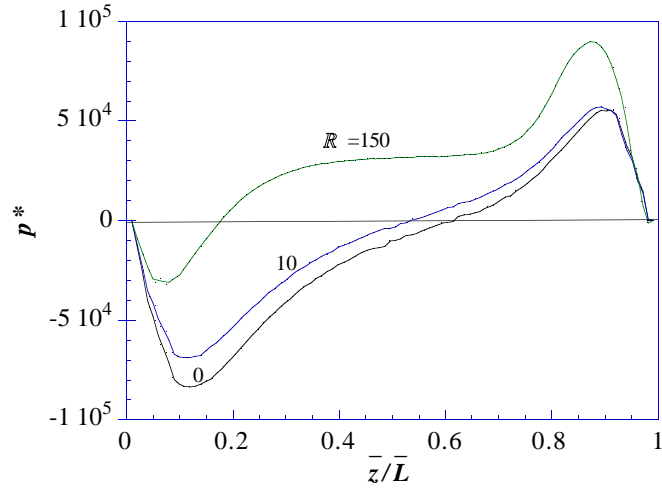
(a)
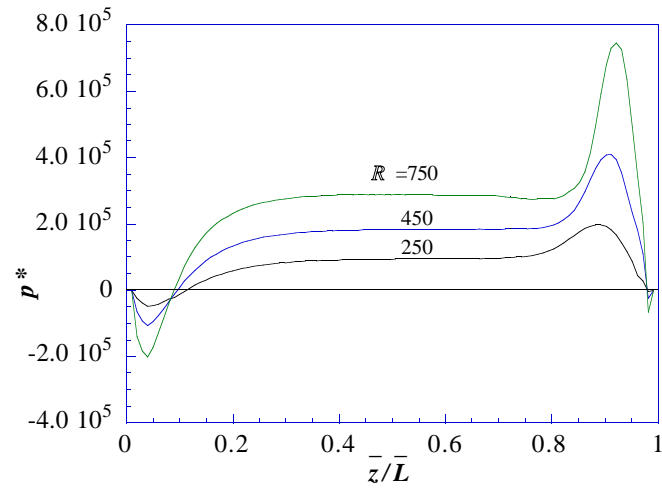
(b)

Figure 5. (a) Pressure distributions on the interface $p*(\bar{z}/\bar{L})$ for $\mathbb{R} = 0, 10, 150$ when $[\eta, h, J] = [0.8, 1.4, 13\times10^4]$. Note that the pressure force, the area under the pressure curve, is negative for $\mathbb{R} = 0, 10$ and is positive when $\mathbb{R} = 150$. (b) Pressure distributions on the interface for $\mathbb{R} = 250, 450, 750$ when $[\eta, h, J] = [0.8, 1.4, 13\times10^4]$. All the pressure forces are positive with the greatest pressure at the forward points of stagnation. Here $\eta = R_1/R_2$ is radius ratio, R_1 is the mean interface position, $\mathbb{R} = \rho_2(R_2 - R_1)/\mu_2$ is a Reynolds number based on water properties, h is the holdup ratio (the ratio of average velocity of oil to water) and J is a surface tension parameter.

Looking forward, the main scientific issue is the role of inertia in levitation and the main technology issue is the remediation of fouling.

Acknowledgement

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