A Project Summary

This GOALI proposal is for University-based support for partnering between the rheological fluid mechanics laboratory at the University of Minnesota, Dowell-Schlumberger, Intevep, Stimlab and Syncrude Canada for research bearing on the stimulation of reservoirs, drilling, production, transportation of hydrocarbons and hydrodynamic products, emulsion stability and the suppression of foam in reactors used to refine heavy crudes, including joint graduate student advising. The proposal formalizes and extends collaborations presently active. All the problems posed here relate to problems of complex rheology of fracturing fluids, drilling muds, concentrated emulsions of bitumen in water and foam to particle migrations in flow and lubrication and self-lubrication of heavy oils, froths, foams, emulsions and particles. We approach such problems in a standard empirical tradition emphasizing experiments, analysis and numerical computations.

The goal of the research is to provide the fluid mechanics foundations for a variety of closely related technologies in the oil industry. Of particular interest for this proposal are the forces which drive the migration of particles in the shear flows of the viscoelastic fluids used in drilling and fracturing; it is necessary to extend the excellent understanding we have of the way that these forces drive sedimenting particles to the case of shear flows driven by pressure gradients. The research will focus entirely on the analysis of principles behind the applications of interest to the industrial partners. For this kind of analysis it is essential to rely on modeling of thoughtful experiments designed to isolate the main mechanisms underway in each application. The type of large scale testing for useful correlations which is done in industrial laboratories will be avoided, favoring instead model and numerical studies and small modular experiments which require only limited amounts of fluid and are such that the configurations of the flow apparatus and fluids can be easily and cheaply changed.

The Minnesota lab is well funded under an NSF Grand Challenge, HPCC grant to develop highly efficient methods for computing three-dimensional motions of large numbers of particles in solid-liquid flows, under the action of the hydrodynamic forces and torques exerted by the suspending fluid, and to use these methods to elucidate the fundamental dynamics of particulate flows and solve problems of engineering interest. The goal is to develop high-performance, state-of-the-art software packages called *particle movers*, capable of simulating the motions of hundreds of particles; 400 particles were moved in a 2D simulation [17] of various shear flows of Newtonian fluids at Reynolds numbers in the hundreds and the sedimentation of 6 particles in direct two-dimensional simulation of a viscoelastic fluid (Oldroyd B) gives rise to the chains of spheres seen in experiments [35][36]. The grand challenge is already far enough advanced to predict the cross migrations of particles and the turning couples on long bodies which determine microstructural properties observed in fluidized suspensions and slurries [37]. The first and only direct simulations of core-annular has also been developed in the Minnesota lab [34], [23]. Though the focus of this GOALI proposal is not on direct simulations, the numerical packages for studying the migrations of particles and the lubrication of core flows are definitely a value added.

The partners in this GOALI proposal agree that the utility and intellectual value of fundamental studies gain by focusing on practical problems which are here taken from production, processing and transportation of hydrocarbons and hydrocarbon products.

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C Project Description

Rheology, particulate and two-phase flows at the University of Minnesota

The particular niche strengths of Joseph's lab are rheological fluid mechanics, particulate flow and lubricated transport. The lab is, or is among, the world leaders in problems of lubricated pipelining of heavy oil[*], self-lubrication of bitumen froth, flow-induced microstructure in Newtonian and viscoelastic fluid[‡], the role of inertia and normal stresses in particle migration in viscoelastic fluids and the fluid physics associated with the fact that shear waves propogate in viscoelastic fluids[†]. These topics are fundamental for the applications in the industrial collaboration being proposed here.

Laboratory at the University of Minnesota. Professor Joseph's laboratory has a 25 year track record on problems of fluid mechanics, rheology, particulate and two phase flows. Professor Beavers has worked with Joseph for 30 years and he was a cofounder of the lab. Runyan Bai is the lab manager. Bai came to the lab 11 years ago as a China Scholar and he received his Ph.D. in 1995 and will be promoted from post doc to research associate in 1997. He is an exceptionally talented experimenter with the deepest understanding of the elements needed for the successful experiments of the kind needed in the applications. The laboratory is also engaged in high performance computational studies of particle migrations and core-annular flows. The lab itself is equipped with networked computers, high speed and high resolution video systems, microscopes for studies of contact angles and spreading rates, a unique patented shear wave speed meter for measuring the shear wave speeds, a patented spinning drop interfacial tensiometer with an oven for studying emulsions, foams and polymer blends having both high and ultralow tensions, sedimentation columns, fluidized beds, bubbling columns for studying the suppression of foaming, a $1''$ pipeline for studying horizontal core-annular flow, a $1''$ pipeline connected to a heating and froth mixing system for studies of self-lubrication of bitumen froth, a $\frac{1}{2}''$ vertical U loop for studying vertical core-annular flow and several rheometers for viscosity and normal stresses. We routinely use the rheometrics rheometers in Professor Macosko's polymer lab for conventional studies of rheology. Our lab is blessed by the presence of an extraordinarily creative technician and machinist, Dave Hultman, who runs a well equipped machine shop next to Joseph's lab. The most important asset of the lab is its tradition of success in empirically based but fundamental studies of problems of rheology and two-phase flow.

Fluid Mechanics Foundations

A summary of some of the main ideas behind lubricated pipelines are set down under Topic 4 below and the references there. Here we present an abreviated account of some of the fluid mechanics fundamentals underlying the migrations of cuttings in drilling muds and particles in fracturing fluids.

Turning Couples on Long Bodies. It is surprising at first sight that turning couples on long bodies determine the stable configurations of suspensions of spherical bodies. A long body is an ellipsoid or a cylinder; a broad body is a flat plate. When such bodies are dropped in Newtonian fluids, they turn and put their long or broadside perpendicular to the stream. This is an effect of inertia which is usually explained by turning couples at points of stagnation. The mechanism is the same one that causes an aircraft at a high angle of attack to stall.

It is not possible to get long particles to turn broadside in a Stokes flow; bodies with fore-aft symmetry do not experience torques. The settling orientation is indeterminate in Stokes flow; however, no matter how small the Reynolds number may be, the body will turn its broadside to the stream; inertia will eventually have its way. When the same long bodies fall slowly in a viscoelastic liquid, they do not put their broadside

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[*] Joseph was elected a fellow of the American Physical Society (1993) for this; [‡]he received the Thomas Baron Fluid-Particle Systems of the AIChE and Shell (1996); [†]he was elected to the National Academy of Science (1991) and received the Bingham Medal of the Society of Rheology (1993) for this work.

perpendicular to the stream; they do the opposite, aligning the long side parallel to the stream. The difference in the orientation of long bodies falling in Newtonian and viscoelastic fluids is very dramatic; basically the flow orientations in the two fluids are orthogonal. Of course, in very dilute polymeric liquids, the effects of inertia and viscoelasticity will compete and the competition will be resolved by a tilt angle away along the stream. For cylinders with sharp corners, normal stress effects produce the "shape tilting" observed by Liu and Joseph [37] and explained here. Another, much more dramatic change in the tilting of a long cylinder or flat plate is associated with the way that inertia comes to dominate high-speed flows of viscoelastic fluids.

Particle-Particle Interactions. The flow-induced anisotropy of a sedimenting or fluidized suspension of spheres is determined by the pair interactions between neighboring spheres. The principal interactions can be described as *drafting, kissing* and *tumbling* in Newtonian liquids and as *drafting, kissing* and *chaining* in viscoelastic liquids. The drafting and kissing scenarios are surely different, despite appearances. Kissing spheres align with the stream; they are then momentarily long bodies.

The long bodies momentarily formed by kissing spheres are unstable in Newtonian liquids to the same turning couples that turn long bodies broadside-on. Therefore, they tumble. This is a local mechanism which implies that globally, the only stable configuration is the one in which the most probable orientation between any pair of neighboring spheres is across the stream. The consequence of this microstructural property is a flow-induced anisotropy, which leads ubiquitously to lines of spheres across the stream; these are always in evidence in two-dimensional fluidized beds of finite size spheres. Though they are less stable, planes of spheres in three-dimensional beds can also be found by anyone who cares to look.

The drafting of spheres in a Newtonian liquid is governed by the same mechanism by which one cyclist is aided by the low pressure in the wake of another. The spheres certainly do not follow streamlines since they are big and heavy. If a part of one sphere enters in the wake of another, there will be a pressure difference to impel the second sphere all the way into the wake where it experiences a reduced pressure at its front and not so reduced pressure at the rear. This increased pressure difference impels the trailing sphere into kissing contact with the leading sphere. The motion of the trailing sphere relative to the leading one is in the same sense as in the undisturbed case, into the rear pole of the leading sphere.

Riddle, Navarez and Bird [53] presented an experimental investigation in which the distance between the two identical spheres falling along their line of centers in a viscoelastic fluid was a function of time. They found that for all five fluids used in the experiments that the spheres attract if they are initially close and separate if they are not close; there is a critical separation distance. This looks like a competition between normal stresses and inertia, which is decided by a critical distance which may vary with latitude. Competition of normal stresses and inertia is more typical than rare, and for flows slow enough to enter into the second order region the critical distance scales with $\sqrt{\psi_1/\rho}$, where ψ_1 is the coefficient of the first normal stress difference and ρ is the density. The property that chaining tensions are short range is also put in evidence in Figure lb, which shows that spheres can also detach from the trailing end of a chain when the distance between the last two spheres exceeds a critical value, as in the experiments of Riddle et al. [53].

On the other hand, if the same two spheres are launched from an initial side-by-side configuration in which the two spheres are separated by a smaller than critical gap, as in figure 2b, the spheres will attract, turn and chain. One might say that we get dispersion in the Newtonian liquid and aggregation in the viscoelastic liquid.

If two touching spheres are launched side-by-side in a Newtonian fluid, they will be pushed apart until a stable separation distance between centers across the stream is established; then the spheres fall together without further lateral migrations (see Figure 2a).

On the other hand, if the same two spheres are launched from an initial side-by-side configuration in which the two spheres are separated by a smaller than critical gap, as in figure 2b, the spheres will attract, turn and chain. One might say that we get dispersion in the Newtonian liquid and aggregation in the viscoelastic liquid.

Sphere-Wall Interactions. If a sphere is launched near a vertical wall in a Newtonian liquid, it will be forced away from the wall to an equilibrium distance at which lateral migrations stop (see figure 3a); in the course of its migration it will acquire a counter-clockwise rotation (see Figure 7) which appears to stop when the sphere stops migrating. The rotation is anomalous in that clockwise rotation would be induced from shear at the wall. The anomalous rotation seems to be generated by blockage in which high stagnation

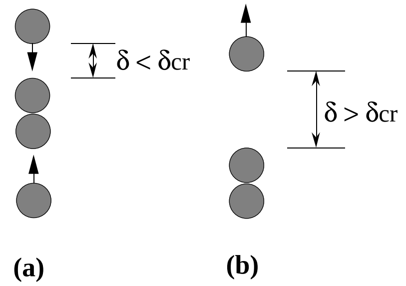

Figure 1

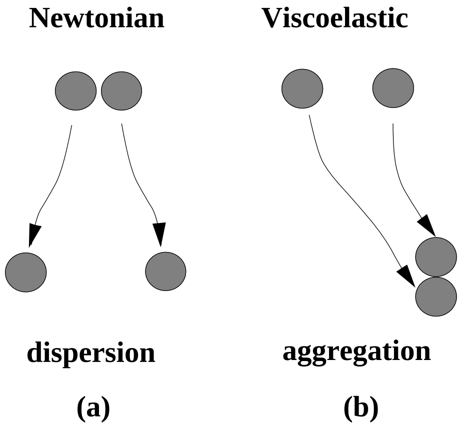

Figure 2

Figure 1: The falling chained spheres are viewed in a frame in which they are at rest. Particles may link to the chain from the bottom or top. If $\delta > \delta_{\chi\rho}$ the chained spheres will fall away faster than the trailing sphere. Figure 2: Side-by-side sphere-sphere interactions.

pressures force the fluid to flow around the outside of the sphere, as shown in figure 7.

If the same sphere is launched near a vertical wall in a viscoelastic liquid, it will be sucked all the way to the wall (see Figure 3b). It rotates anomalously as it falls. This is very strange since the sphere appears to touch the wall where friction would make it rotate in the other sense. Closer consideration shows that there is a gap between the sphere and the wall. The anomalous rotation is again due to blocking which forces liquid to flow around the outside of the sphere (see figure 7).

The pulling action of the wall can be so strong that even if the wall is slightly tilted from the vertical so that the sphere should fall away, it will still be sucked to the wall (see Figure 4).

If the launching distance between the sphere and a vertical wall is large enough, the wall will not attract a sphere falling in a viscoelastic fluid. This means that there is a critical distance S for attraction. Of course, this distance is smaller when the wall is tilted as in Figure 4. In this case, if the sphere is launched at a distance greater than the critical one, it will fall away from the wall.

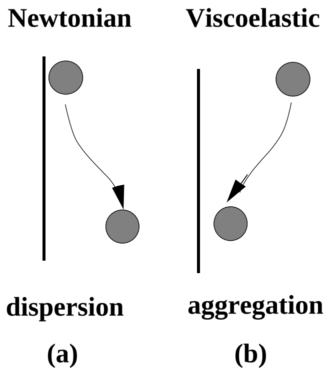

Figure 3

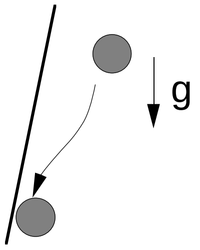

Figure 4

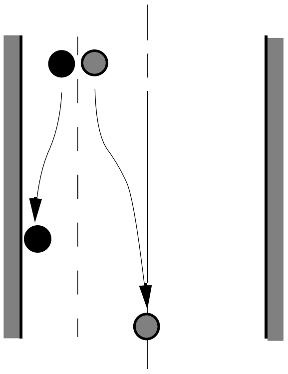

Figure 5

Figure 3: Sphere-wall interactions. Figure 4: A sphere in viscoelastic liquid is sucked to a tilted wall. Figure 5: Spheres dropped between widely-spaced walls. The dotted line is the critical distance d_{cr} for wall-sphere interaction. When $d < d_{cr}$, the sphere goes to the wall. When $d > d_{cr}$, the sphere seeks the center.

The effect of two closely-spaced walls on the migration of particles is not completely understood. We have just said that spheres which fall near a wall in a viscoelastic liquid will be pulled to the wall, but not if the launching distance from the wall is larger than a critical one. On the other hand, we noted that spheres and cylinders dropped between closely-spaced walls do center. We may think that if a sphere is launched between widely-spaced walls at a distance farther than the critical one, it will not be attracted to the near wall and certainly not to the far one. So the equilibrium position will depend on the initial distance, or it is more likely from symmetry to seek the center, as shown in Figure 5. We do not know the answer yet.

If the walls are so closely spaced that the distance d between walls is equal to or smaller than the critical one for migration, then both walls will attract the sphere, though perhaps not equally. Experiments suggest centering in this case.

Forces and Torques in Viscoelastic Fluids. The role of inertia in turning long bodies has already been discussed. The pressure is the only normal stress that can act on a solid particle in a Newtonian fluid. The nature of stresses which act in slow flow of a viscoelastic fluid was given in [24]; the main result is that the viscoelastic contribution to the normal stress on the body is always compressive and equal to $-\psi_1(0)\overset{\circ}{\gamma}^2/4$ where $\psi_1(0) > 0$ is the coefficient of the first normal stress difference and $\overset{\circ}{\gamma}$ is the shear rate. This informs intuition about how particles move and turn in a slow flow of a viscoelastic liquid; one has only to look for crowded streamlines in the Stokes flow near the body to see how the normal stresses are distributed over the body. If the particle has fore-aft symmetry, the Stokes pressure and viscous shear stress each yield a zero torque on the body; thus the normal stresses will turn the body into the stream ,[13],[37] as in figure 6(a). The argument just given suggests that the longest line of less regular bodies ought to align parallel to the stream; a cube actually does fall slowly with the line through opposite vertices parallel to gravity. For two identical spheres or circular cylinders settling side by side (figure 6b), strong shears occur on the outside and the resulting compressive stresses push the particles together; they then act like a long body and are turned into the stream by torques like those in figure 6(a). Two particles settling in tandem experience imbalanced compressive normal stresses at the bottom of the leading particle and the top of the trailing particle, causing them to chain as in figure 6(c). The lateral attraction of a particle to a nearby wall can be explained by a similar mechanism (figure 6b). Experimental evidence of particle-particle and particle-wall interactions has been documented in [28].

The compressive stresses which are generated by the motion of particles in plane flow of a second-order fluid produce aggregation rather than dispersion; they align long bodies with the stream and produce chains of particles aligned with the stream.

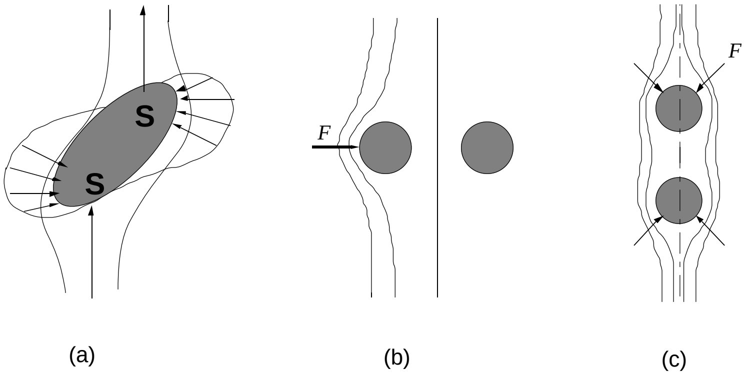

Figure 6: Cartoons of streamlines around bodies settling in Stokes flow. The normal stresses are negative and proportional to $\dot{\gamma}^2$; they are large and compressive where the streamlines are crowded, basically where the flow is fast. Inertial pressures are large at stagnation point $\dot{\gamma} = 0$, where normal stresses vanish. (a) Normal stresses turn the major axis of the ellipse into the stream. For slow flows inertial forces are small than normal stresses. (b) The normal stresses force side by side particles together and they urge particles to the wall. (c) Compressive forces cause particles in tandem to chain.

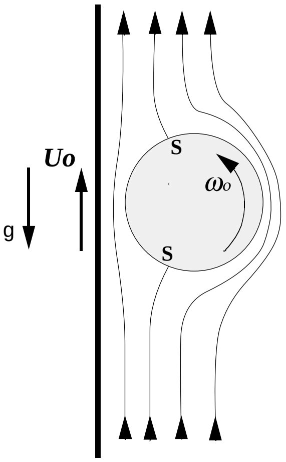

Figure 7

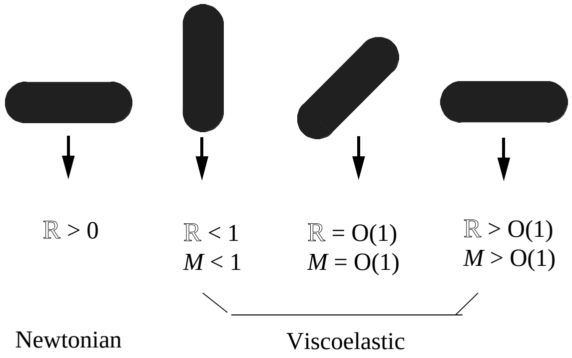

Figure 8

Figure 7: Cartoon of the settling of a circular particle in a Newtonian fluid at a vertical wall in a coordinate system in which the center of the particle is at rest, so the wall moves up with speed U_0. If the particle is dropped at the wall, the fluid will go around the outside and turn the particle in the anamalous sense as shown. There are two "stagnation" points S on the circle where the shear stress vanishes associated with high positive pressure on the bottom and a smaller negative pressure near the top. The positive pressure "lifts" the particle away from the wall and it seeks an equiligrium in the channel center. Normal stress effects are greatest at the outside of the cylinder where the streamlines are crowded and the shear rates are large. The effect of shear thinning is to increase these shear rates and the forces which now push the cylinder closer to the wall. Figure 8: Orientation of cylinders falling in Newtonian and viscoelastic liquids.

Shear Thinning. Now I give a heuristic argument which suggests that the effects of compressive normal stresses are intensified by shear thinning because larger values of $\dot{\gamma}$ are produced where the streamlines are crowded. In the case of an Oldroyd B fluid

$$\psi_1 = \eta(\lambda_1 - \lambda_2) \tag{1}$$

where λ_1 and λ_2 are the relaxation and retardation times. Shear thinning does not appear at second-order in the asymptotic analysis leading to the second-order form of the Oldroyd-B model. Therefore we are taking liberties with mathematical rigor by writing $\eta = \eta(\dot{\gamma})$ where $\eta(\dot{\gamma})$ decreases with $\dot{\gamma}$. The effect of shear thinning is to decrease the viscosity and increase the shear rate at places of high $\dot{\gamma}$ on the body. In a pipe flow with a prescribed pressure gradient, the pressure force balances the shear force at the wall so the shear stress $\tau_w = \eta(\dot{\gamma})\dot{\gamma}$ is the same for all viscosity functions. If the fluid thins in shear, the viscosity η goes down and the shear-rate $\dot{\gamma}$ goes up, keeping the product constant. Then $\eta(\dot{\gamma})\dot{\gamma}^2 = \tau_w\dot{\gamma}$ is larger than what it would be if the fluid did not shear thin because $\dot{\gamma}$ is larger.

The increase in the intensity of compressive normal stresses means that the turning couples which turn long bodies into the stream and the pushing stresses which cause spherical particles to aggregate are all increased. For example, the standoff distance of circular cylinder sedimenting near a wall (figure 7) will be much less in the shear thinning form of the Oldroyd B fluid as is shown by direct numerical simulation [12].

Reversal of the Extensional Stress at a Point of Stagnation. A point of stagnation on a stationary body in potential flow is a unique point at the end of a dividing streamline at which the velocity vanishes. In a viscous fluid all the points on the boundary of a stationary body have a zero velocity but the dividing streamline can be found and it marks the place of zero stress near which the velocity is small. The stagnation pressure makes sense even in a viscous fluid where the high pressure of the potential flow outside the boundary

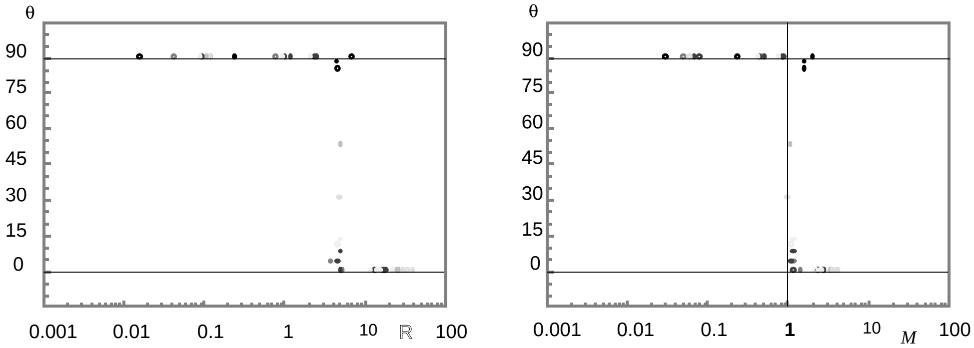

Figure 9: Tilt angle vs. Reynolds number and Mach number. Cylinders (length 0.8 in., diameters 0.1 – 0.4 in.) falling in 2% polyacrylamide/water solution. The data are taken from cylinders with round ends only. (Reproduced from *J. Fluid Mech.* 255, 1993, with permission.)

layer is transmitted right through the boundary layer to the body. It is a good idea to look for the dividing streamlines where the shear stress vanishes in any analysis of the flow pattern around the body.

The points marked S on Figure 7 are points of stagnation for a real no-slip fluid marking the place where $\dot{\gamma} = 0$. In the slow flow analysis just given, these points where $\dot{\gamma} = 0$ have no viscoelastic normal stress. For faster subcritical flows which are still dominated by viscoelastic stresses, we can imagine viscoelastic effects to be transmitted through a boundary layer which will reverse the sign of the normal stress there. Some of the principal causes for the reversal can be seen in the equations governing the potential flow of a second order fluid given in [20]. Not all models of a viscoelastic fluid admit potential flow as a solution irrespective of the boundary conditions [26], but a second order fluid does, and for these, there is a Bernoulli equation which is in the form

$$\rho\phi_{,t} + \frac{\rho|\mathbf{u}|^2}{2} + p - \hat{\beta}\nabla\mathbf{u} : \nabla\mathbf{u} = c \tag{2}$$

where $\hat{\beta}$ is the climbing constant which is positive in nearly all viscoelastic liquids and can even be large. Obviously there is a competition between inertia $\rho|\mathbf{u}|^2$ and normal stresses $\hat{\beta}|\nabla\mathbf{u}|^2$ with the latter dominating for slow speeds and large gradients. *Inertia scales with the square of the velocity and normal stresses scale with the square U^2/L^2 of the rate of shear or extension.* Carrying out analysis of potential flow a little further, we find that at a stagnation point, the stress σ_{11} in the direction x_1 of stretching is given by

$$\sigma_{11} = -\frac{\rho}{2}U^2 + 4\eta\frac{U}{L}\dot{s} + \hat{\gamma}\frac{U^2}{L^2}\dot{s}^2 \tag{3}$$

where $\hat{\gamma}$ is a positive combination of first and second normal stress coefficients and $\dot{s}$ is a dimensionless rate of stretching [29]. Equation 3 shows clearly how the sign of the normal stress at a point of stagnation can be re- versed by high rates of stretching in a viscoelastic fluid.

The reversal of the extensional normal stresses at points of stagnation would pull long bodies into the stream, reversing the tendency of inertia to push them across the stream. In this case the turning couples of high compressive normal stresses due to shear compete with high tension at points of stagnation due to extension.

Tilt Transition and Shear Waves. Liu and Joseph [37] have done experiments on the settling of long cylinders in aqueous solutions of polyox and polyacrylamide, and in solutions of polyox in glycerin and water. The tilt angles of long cylinders and flat plates falling in these viscoelastic liquids were measured. The effects of particle length, particle weight, particle shape, liquid properties and liquid temperature were determined. In some experiments, the cylinders fall under gravity in a bed with closely-spaced walls. No matter how or where a cylinder is released, the axis of the cylinder centers itself between the close walls and falls steadily at a fixed angle of tilt with the horizontal. A discussion of the tilt angle may be framed in terms of competition between viscous effects, viscoelastic effects and inertia. When inertia is small, viscoelasticity dominates and the particles settle with their broadside parallel or nearly parallel to the direction of fall. When inertia is large, the particles settle with their broadside perpendicular to the direction of fall. The tilt angle varies continuously form 90°, when viscoelasticity dominates, to 0°, when inertia dominates. The balance between inertia and viscoelasticity was controlled by systematic variation of the weight of the particles and the composition and the temperature of the solution. Particles will turn broadside-on when the inertia forces are larger than viscous and viscoelastic forces. This orientation occurred when the Reynolds number $\mathbb{R}$ was greater than some number not much greater than one in any case, and less than 0.1 in Newtonian liquids and very dilute solutions. In principle, a long particle will eventually turn its broadside perpendicular to the stream in a Newtonian liquid for any $\mathbb{R} > 0$, but in a viscoelastic liquid this turning cannot occur unless $\mathbb{R} > 1$. Another condition for inertial tilting is that the elastic length λU should be longer than the viscous length ν/U where U is the terminal velocity, ν is the kinematic viscosity and $\lambda = \nu/c^2$ is a relaxation time where c is the shear wave speed measured with the shear wave speed meter (Joseph [48]). The condition $M = U/c > 1$ was provisionally interpreted by Liu and Joseph [37] as a hyperbolic transition of solution of the vorticity equation analogous to transonic flow. They showed that strong departures of the tilt angle from $\sigma = 90°$ begin at about $M = 1$ and end with $\sigma = O°$ when $1 < M < 4$ (see figures 8 and 9 for some representative results).

It is perhaps helpful to frame the criteria for the tilt transition in terms of a comparison between the fall speed U and the other speeds which depend on material and not on U; long and broad objects falling in a viscoelastic liquid will turn broadside to the stream when the fall velocity U is greater than the diffusion speed ν/d and the shear wave speed c. The reason is that under these conditions, signals cannot reach the fluid before the falling body and the body feels the pressures of potential flow at its front side. Such pressures turn the body broadside-on.

Research Description

Topic 1: Particle Migrations in Shear Flows of Fracturing Fluids.

We seek strategies to control how particles are positioned by flow in fractured formations opened by hydraulic pressure. The aim is to increase the productivity of the reservoir by holding the cracks open after the fracturing fluid is withdrawn.

Nolte [44] has noted that “Significant progress has been made ... in the understanding of rock failure and deformation during hydraulic fracturing ... To bring the level of understanding for fluid flow to that of rock mechanics, and provide the basis for another major advance in fracturing technology, significant and focused investigations of fluid flow are required.” We want to study the migration and settling of proppant particles flowing in slit channels, using extensive diagnostic experiments which rely heavily on flow visualization. Already in our grand challenge HPCC grant we are able to do numerical simulations of many particles in shear-flows of Newtonian and viscoelastic fluids.

Proppant Migration During Hydraulic Fracturing of Hydrocarbon Wells. Hydraulic fracturing is a process often used to increase the productivity of a hydrocarbon well. A slurry of sand or ceramic particles (proppant) in highly viscous, usually elastic, fluid is pumped into the well to be stimulated at sufficient pressure to exceed the horizontal stresses in the rock at reservoir depth. This opens a vertical fracture, some hundreds of feet long, tens of feet high, and perhaps an inch in width, penetrating from the wellbore far into the pay zone. When pumping pressure is removed, the proppant acts to prop the fracture open. Productivity is enhanced because the proppant-filled fracture offers a higher conductivity path for fluids to enter the well than through the bulk reservoir rock, and because the area of contact for flow out from the productive formation is increased. It follows that a successful stimulation job requires that there is a continuous proppant-filled path from great distances in the reservoir to the well, and that the proppant is placed within productive, rather than non-productive, formations.

It has been suspected for some time [44], and recent experiments have demonstrated [55], that the suspended proppant does not remain uniformly distributed during pumping of these slurries. It is found that under the flow conditions expected within the fracture during pumping, the proppant particles migrate rapidly towards the center plane of the fracture, leaving a clear fluid layer at the fracture walls. This clear layer lubricates the motion of the slurry, and so increases the rate of gravity driven settling and density currents. The net result of these processes is to cause proppant to accumulate at the bottom of the fracture and good vertical filling can be lost [57]. This can reduce well productivity.

It is sometimes suggested that migration of proppant occurs while the slurry is being pumped down the tubing to reservoir depth. This may cause preferential injection of solids rich fluid at the bottom of the reservoir and of solids poor fluid at the top. While it is not known if this process actually occurs, if it did, the consequences on final fracture productivity would be similar to those described above.

The phenomenon of proppant migration is not currently controlled or exploited in the fracturing industry. One reason for this is that the relationship between migration and fluid properties has only recently become better understood [21] (there is some indication from experiments [55], [22] and direct numerical simulation [16] that the combination of fluid elasticity and non-uniform shear flow are necessary for rapid migration). It may therefore be possible to design fluids which, for example, suppress migration.

The results of a careful theoretical and experimental investigation of the phenomenon of migration during flow of moderately concentrated suspensions of heavy particles in viscoelastic fluids, in particular the identification of the fluid properties and flow conditions responsible for migration, and of those which can be controlled to suppress it, would benefit the hydrocarbon industry by permitting the development of more effective fracturing fluid systems.

Proppant Settling in Fracturing Fluids. The industrial process is as described above. The settling of particles within the fracture after pumping has stopped, but before the fracture closes, also impacts final fracture productivity; loosely speaking, the more settling, the more non-uniform the coverage of the productive formation and the lower the productivity. Settling rates are influenced in a poorly understood way by suspending fluid visco-elasticity.

The current trend in the industry is towards the use of fracturing fluids with lower concentrations of polymer; this brings cost savings, and productivity and environmental benefits, through the use of less material. However there is a lower limit on polymer concentrations set, among other factors, by the need to ensure good particle carrying and suspending properties. A better understanding of the fluid properties controlling settling of solids in visco-elastic fluids could permit further reductions in polymer concentration to be achieved.

Foams. Foams have a yield stress and can trap small particles that are not too heavy. Foams are used to carry proppant in fracturing applications and to cary cuttings in underbalanced drilling. They are also of interest for acid diversion into all prospective zones at a wellbore.

A different kind of application is to refining (Topic 6) and other foaming chemical reactors in which high gas hold ups which characterize foams are undesirable. Here, one seeks to destroy foam or to suppress foam formation so as to maximize the contact between the liquid and particles (catalysts).

We have done experiments in a foaming bubble reactor which allows one to visualize and measures properties of moving foam, foam formation and foam suppression. This reactor can be used to study foam for applications in fracturing and drilling as well as refining (Topic 3).

Topic 2: Cuttings Transport in Drilling Fluids.

We seek to understand the fundamental mechanisms governing cuttings transport and hole cleaning in vertical, horizontal and deviated well bores. We also plan to do rheological modeling of drilling fluids, emphasizing the viscoelastic and thixotropic properties not presently understood by our industrial partners. Typically, a horizontal drilling hole will have to start with deviated or vertical segments before it turns horizontal. In fact, the drilling of such holes five miles laterally from the surface location is a miracle of modern technology in which drilling fluids play an the critical role. Five functions of a drilling fluid are: (1) cooling and lubricating the bit, (2) cleaning the bottom of the borehole of drilled cuttings, (3) transporting cuttings to the surface, (4) stabilizing the wellbore, and (5) allowing adequate formation evaluation. Even though the technology of drilling and drilling fluids is well advanced, all will agree that many problems of great economic and environmental consequence remain and fundamental understandings are lacking. Here we propose to fill a gap in understanding of the fluid mechanics and rheology of drilling fluids.

Cuttings Transport. A cutting generated at the drill bit may be transported to the surface of a well in flowing mud by different mechanisms at different angles of wellbore inclination. For nearly horizontal wells the cuttings, which are even heavier than the weighted mud, roll and slide along the bottom. In deviated wells, say 40° from the horizontal, churning motions produce unwanted (Barite sag) effects which may interfere with the lifting mechanisms needed for effective cuttings transport. Transport in nearly vertical wells is determined by the settling velocity which depends on the size, weight and shape of cuttings, fluid rheology and the effective composite density of the weighted liquid and the configuration of hole and the pipe which contains the drill string.

Recent transport studies focus on empirical correlations for horizontal and deviated wells where one of the main issues is the minimum mud velocity for transporting cuttings without the formulation of a bed; the smallest velocity for which all the cuttings will be fluidized. The industry relies on these correlations for operations and though some reasonably successful models of cuttings transport have been developed, fundamental studies have not been carried far. The problem of cuttings transport ought to be studied from the microstructural properties of cuttings in muds, as well as from the correlations which are needed for operations.

The technology of hole cleaning is essentially a matter of correcting for situations of inefficient cuttings transport. Polymeric muds, using biopolymers like Xanthan, are used as viscosifiers with improved performance capabilities for suspending particles in flow. For example, Xanthan and Whelan viscosifiers are used preferentially in Alaskan high angle and horizontal drilling and workover operations. Their unique rheology and flow profiles minimize the formation of cutting beds, decreased bed compaction, and promote erosion and removal of existing beds, particularly when used at or above a certain critical polymer concentration [49]. Polymeric muds cannot be described by the conventional shear thinning, yield stress models, like the Herschel-Buckley model, because the migration of particles is so radically different in viscoelastic fluids. The effects of normal stresses and other viscoelastic properties on the migration of sand and cuttings in polymeric muds would be of definite value to drilling technology and operations.

Barite Sag. Muds weighted with barite and other heavy particles are prey to unwanted effects due to sedimentation of the particles. These effects are particularly severe in deviated wells with angles $30° - 60°$ from the vertical. The phenomenon of barite sag is closely related to the enhanced sedimentation in an inclined cylinder known as the Boycott effect. Predictions of empirical codes and correlation for hole cleaning are adversely affected by barite sag. The problem of barite sag is not well understood; it is a complicated fluid mechanics problem.

People dealing with barite sag in the oil industry have not used the fluid mechanics literature on the Boycott effect. Most of this literature is for batch systems of particles rather than for the continuous systems generated by transport of mud and cuttings in continuous drilling operations. It is not known if and in what sense the literature on the Boycott effect can be made to apply to Barite sag.

The Boycott effect has not been studied in weighted polymeric liquids. It is probable that the inward migration of barite or sand used to weight the fluid off the walls which may occur in a viscoelastic liquid will greatly alter the nature of both the Boycott effect in conventional settlers and barite sag in drilling operations.

Rheology. The demands of drilling practice require the least complicated description of a fluids rheology which can guide operations. This results in a sort of reduced description in which the fluids viscosity, power law index and yield point are recognized, but elasticity, normal stresses and thixotropy are totally neglected. This approach is not compatible with successful operations in the case of polymeric drilling muds or fluids exhibiting marked viscoelastic and thixotropic effects.

The study of rheology of polymeric drilling muds is complicated by the presence of clay, barite and other particles. We think rheology of weighted polymeric muds has to be understood to predict their performance in operations. The study of the effects of particulates could be particularly useful as a control opportunity to alter the effective density of the mud and its structural and gel properties which control the suspension and migrations of cuttings.

The *drilling* fluids to be studied are aqueous solutions of bentonite, Xanthan and foams. The foams will be studied in the foaming bubble reactor described under Topic 6.

Composite drilling fluids are weighted with sand (barite or substitutes) in typical concentrations. *Cuttings Surrogates* are particles of any shape or density which are heavier and will fall in a composite drilling fluid.

We will measure *rheological properties* of drilling and composite drilling fluids: yield stress and elastic modules in creep, τ vs. $\overset{\circ}{\gamma}$ (for viscosity $\eta = \tau/\overset{\circ}{\gamma}$), G', G'' vs. ω (for linear viscoelasticity), the climbing constant (normal stress) and shear wave speed.

The shear wave speed gives the value of the relaxation time for elastic effects and a measure of the speed at which inertia dominates elastic effects. The free surface on a fluid near a rotating rod will sink in a Newtonian fluid and climb in a viscoelastic fluid with the amount of climb controlled by normal stresses and measured by the climbing constant. Rod climbing devices are robust, cheap, and easy to use and interpret, and perfectly suited to the needs of industrial laboratories and field practice.

Batch tests of composite fluids and cutting surrogates will be done in sedimentation columns and used to determine the effective density of mixtures, segregation of polydisperse mixtures, migration, orientation, rolling, sliding and lift off of interacting cutting surrogates. Many of these robust properties of cuttings response in motion were mentioned in the section on fluid mechanics foundations and they appear not to be known even to experts in the drilling industry. We can make an impact here. Weighting of muds is used for overbalanced drilling, but the weighted mud can segregate when the barite is polydisperse and this has an important effect on the way the composite moves the cuttings. Batch sedimentation of particles in tilted channels leads to enhanced settling known as the Boycott effects which is related to Barite sag in continuous systems.

Flow tests pump fluid and cutting surrogates through slit channels. The flow tests are to be carried out with continuous injection of drilling fluid, sand and cutting surrogates at most, and continuous injection of the fluid, batch in sand and cuttings, at least. We seek information on the migrations of sand and cuttings in shear flows produced by pumping, on the flow types which arise as the inputs of liquid, sand or cuttings are varied, and on the pressure drop vs. flow rate and hold up of sand and cuttings for different flow types in horizontal deviated and vertical slits.

Rheological properties of many of the fluids used in the oil industry are time dependent even when the fluids are at rest. Such time dependent effects are associated with evolutionary changes in the microstructure of fluids in which different additives, like particles or particulates, interact. Such fluids are said to be thixotropic; a more specific definition [40] of thixotropy is "the continuous decrease of apparent viscosity with time under shear and the subsequent recovery of viscosity when the flow is discontinued." It is probably more useful to think of fluids which have a microstructure which may be associated with damage and healing, leading to a healing time which is typically much greater than the relaxation time for the stress. It is well known that water-based muds with suspended clay and other additives are strongly thixotropic. Xanthan and Whelan muds are said [49] to be thixotropic at low shears. In fact, any compostie fluid with clay colloids which can flocculate, cement slurries and drilling muds, is apt to exhibit time dependent structure changes. Mewis [40] remarks that "...about a thousand papers in the field have not resulted in a satisfactory picture of the mechanisms governing thixotropy."

One of the outstanding manifestation of thixotropy is the memory of shear-thinning. Some shear-thinning fluids appear to remember the places where the fluid was thinned for a long time. The locus of these places form evanescent corridors of reduced viscosity. A slow recovery of viscosity seems to be associated with a slow healing of molecular conformations in the sheared state to those which prevail in the rest state where the fluid response is viscoelastic with a well defined shear wave speed and storage modulus. At least two times, a short relaxation time and a long time of healing, are required to model the behavior of such fluids. The existence of relaxing corridors of reduced viscosity, marked in the fluid by the shear-thinning induced by a falling ball, is consistent with the observations of Cho, Hartnett [7] and Cho et al [8]. They studied falling ball rheometry, measuring the drag on balls that were dropped in the test liquid in specified and definite intervals of time. They found memory effects in a 10^4 ppm by weight solution of aqueous polyacrylamide (Separan, AP-273), a highly viscoelastic and highly shear-thinning liquid. The measured terminal velocity depends strongly on the time interval between the dropping of successive balls into the test fluid. Balls launched after only a short wait period would fall up to nearly twice as fast as the speed of the initial ball, and it took intervals of 30 minutes or more for the memory of the corridor of reduced viscosity to relax.

In recent work on the settling of particles Joseph and Liu [27] discussed corridors of reduced viscosity in which the effects of shear-thinning are remembered for a time. A very excellent comparison between 1.5% and 2% solutions of aqueous polyacrylamide (Magnaflox E10 supplied by Allied Colloids) and 2% and 3% solutions of aqueous Xanthan gum Keltrol F (supplied by Kelco) was made by Walters, Bhatti, and Mori [58]. They arranged solutions with nearly the same viscosity values over a large range of shear rates and compared different measures of elasticity. They found that the Xanthan solutions had much lower normal stresses than the polyacrylamide, but had larger values of the storage modulus. They noted that Xanthan is a semi-rigid molecule and polyacrylamide is a flexible molecule. They reasoned that Xanthan solutions are highly elastic near the rest state with a gel-like structure but this structure is easily broken down by shear. This is consistent with the observation that the dynamic properties of Xanthan solutions can be significantly affected by pre-shearing. The effect of such pre-shearing does relax but recovery can take a day. They noted that the Xanthan solutions are extensional thinning for shear rates which are apparently in excess of a value near 3 $\sec^{-1}$ but the polyacrylamide is strongly extensional thickening.

The aforementioned effects of preshearing mentioned by Walters et al [58] and the falling ball experiments of Cho et. al. [7], [8] are different manifestations of the same underlying memory of shear thinning physics.

We have already noted that the physics of the memory of shear thinning in viscoelastic fluids requires at a minimum two characteristic times; a short time (say, milliseconds) for the relaxation of the stress and a much longer "healing" time (say, hours) for the repair of damage. We can imagine a constitutive equation for the stress with material parameters that depend on the structure and an evolution equation for the structure. A theory of this type, inspired by a theory of clay pastes [42], has recently been presented by Coussot, Leonev and Piau [11]. They present a fully three-dimensional model but study only one-dimensional spatially homogeneous unsteady motions described by an "Oldroyd B" model for the shear τ with a "viscosity function" $\eta^*(\xi)$ depending on the evolution of a structure parameter ξ, $0 \le \xi \le 1$, governing the creation and destruction of clay flows. In this case, they get one equation for τ and another for ξ.

$$\begin{aligned} \frac{d\tau}{dt} + \frac{G}{\eta^*}\tau &= G\left(1 + \frac{\eta_m}{\eta^*}\right)\mathring{\gamma} + \eta_m \frac{d\mathring{\gamma}}{dt}, \\ \frac{d\xi}{dt} + \frac{1}{\sigma^*}\xi &= \frac{(1-\xi)}{\sigma^*}\frac{\eta_p}{\Upsilon}|\mathring{\gamma}| \end{aligned}$$

Here G is the elastic modulus, $\eta^*(\xi)/G$ is a relaxation time for the stress (typically milliseconds) and σ^* is a healing time for repair of broken floes (typically hours). The other parameters and some one-dimensional analysis of homogeneous states which give rise to yield stress behavior, without yield criterion in the theory and non-monotonic flow with transitions between solid-like and fluid, are discussed in the original paper. Here it serves our purpose only to say that we hope that this model, or another like it, can be made to fit the thixotropic behavior observed in some polymeric solutions and drilling muds.

We are pursuing this work as one part of a collaborative project with the drilling group of Mayella Rivero, Intevep S.A., and the University of Minnesota. The modeling part of the project is presently being carried forward by Douglas Ocando in Venezuela. He will continue his work at Minnesota next year as Ph.D. student, funded by Intevep, working under Joseph for a Ph.D. in fluid mechanics, and Rivero in Intevep.

Foam Muds for Underbalanced Drilling. Underbalanced drilling is increasingly used in shallow wells where the excess pressure due to the overburden outside is not so severe as to collapse the well. When the overburden pressure is too great, say in deep wells, the mud is weighted to produce overbalance. Underbalancing prevents formation damage because the fluid in the well will not be driven into the formation; underbalanced gas wells can produce gas even in drilling because the gas pressure in the rock is greater than the pressure in the well. Generally, the pressure is not smaller than the weight of brine at the same height and it is not easy to find liquids of lesser density which can also carry away heavy cuttings; foam muds do this. The particle carrying capacity of the foam and its law of flow can be studied in a foaming bubble column which is described just below. This column is very convenient for studying foam flow for fracture and drilling operations, though it was originally designed for studies of foam suppression.

Topic 3: Flow Loops for Fracturing Fluids, Drilling Muds and Foams

The Minnesota lab is presently equipped with 3 pipelines to study lubricated transport and a foaming bubble reactor which is designed for continuous injection of gas and liquid plus surfactant. The bubble reactor can be adapted to accept also a continuous injection of particles and it can be used as a device for studying the motion of foams for understanding proppant transport in fracturing and underbalanced drilling. We are developing concepts and hardware for diagnostic studies of fracturing and drilling, following the idea that, unlike industrial practice, for understanding foundations, smaller is better.

Foaming Bubble Columns. A schematic is shown in figure 10. The water plus surfactant begins to foam at the top of the reactor when the gas velocity exceeds a critical value. More and more of the reactor is consumed by foam as the gas velocity is increased. In each steady state foam is created at a fixed interface between the bubbly mixture and foam, and this foam must move steadily through the reactor.

Nine highly accurate pressure transducers were installed. The output of each pressure transducer is in mV range and is amplified to the 0-10V range. The signal is fed into a PC where the signal is converted to pressure and a time average is constructed. The total and local average gas hold-up in the column is calculated using the pressure obtained at different times. A typical frequency for taking measurements is 30 1/s for a period of 3 minutes after reaching a stable state. The time required for transients to decay depends on the operating conditions and foam formation capability of the surfactant mixtures. Steady states are recognized in foaming systems by the stabilization in the pressure values in the column and by visual observation of the foam interface. The time required to reach steady state is between 30 min. and 60 min. depending basically on the liquid and gas velocities.

The superficial gas velocity U_g and liquid velocity U_l are prescribed data which we control in our bubble column. The total average gas fraction $\varepsilon_g = 1 - V_l/V$ in steady flow determined by direct measurement of the liquid volume V_l after the gas and liquid flows were stopped simultaneously and by a second method based on the pressure drop $(\triangle P_t)$ which is the sum of the static pressure drop $(\triangle P_s)$ and the pressure drop due to friction between two points separated by a distance $(\triangle H)$

$$\varepsilon_g = 1 - \frac{\triangle P_s}{g\rho_l \triangle H}$$

The two methods agree when $\triangle H = L$ showing that the pressure drop due to friction is negligible.

We did some experiments in which particles are placed in a batch mode in the reactor. Some particles are carried out of the reactor by the foam. The device is very convenient for studying the transport of particles in foam and the laws governing the flow of foams. The bubble column can be used for our foam studies of fracturing and drilling. It could be useful to use even smaller columns, which allow for continuous injection of particles but otherwise work by the same principle.

Flow Loops for Fracturing and Drilling. These loops have not yet been constructed. The goal is to understand the principles which control the motion of large particles (cuttings) in shear flow of weighted and non-weighted Newtonian and viscoelastic fluids. We also need to know how sand settles and is transported in the shear flow of these fluids. For the study of principles it is necessary to see how particles migrate, settle and roll and slide in horizontal, deviated and vertical flow lops. Moreover, since many different fluids are to be studied in the experiments we cannot deal with large volumes. For these reasons, we will look to small modular experiments in which the flow configurations, the inclination angles, the lengths and other dimensions, and the fluids used can be readily changed at small cost. We also want to enhance the potential for direct flow visualization wherever possible.

To meet the aforementioned requirements, we are going to construct plane slit channels with narrow slits to enhance flow visualization. We are seeking loops which are as small as possible, consistent with the requirement that we can monitor particle motions in the flowing liquid. Ours is a fundamental study of sand and particle transport, cross-stream migration settling and barite sag, sliding and rolling of cuttings in different liquids.

Brandt & Bugliaro [5] used a $\frac{1}{16}'' \times 1'' \times 84''$ rectangular channel with only one layer of beads and a continuous injection of stirred beads slightly smaller than $\frac{1}{16}''$ to study slurry flow types in water. We would like an even smaller apparatus of roughly the same relative dimensions, devices that can be used with a microscope. In such devices there is a shearing flow across the slit. The continuous injection of particles and fluids can be done with the sine pump on loan to us from Intevep. This excellent pump uses a gentle motion of constant volume chambers which do not compress the liquid or create large shears. This feature is valuable for polymeric liquids which are easily degradable.

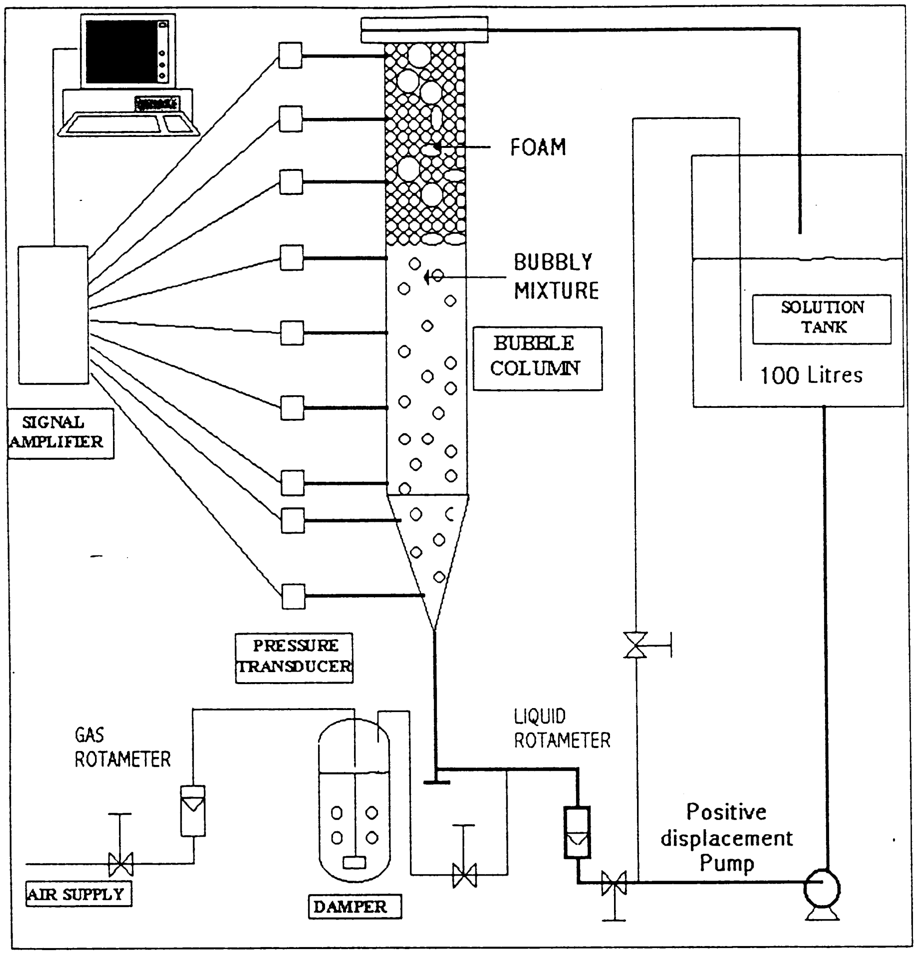

Figure 10: Diagram of the bubble column: height 170 cm, width 26 cm and depth 1.3 cm. Flow lines are clearly visible through the thin Plexiglas column. Metal screens at the top of the column are used to hold solid particles in the reactor.

Particle paths, velocity and accumulation within the slits can be monitored using a high speed video camera and a microscope. We can process the obtained images to get the hold up ratio, once we know the associated flow rates. Finally, pressure measurement devices can be installed along the slits. We patented a buffer chamber assembly which can be mounted between the slit and pressure gauges. This device allows only fluid to get into the chamber and thus prevents particles from reaching the pressure gauges.

Topic 4: Lubricated Pipelining of Bitumen Froth, Concentrated Oil in Water Emulsions and Heavy Oil in Core-Annular Flow.

The goal here is to deepen understanding, improve technology and evolve operating procedures for lubricated pipelines.

Core-Annular Flow of Heavy Oil. 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. Lubricated flow in an oil core is called core annular flow, CAF for short.

Typically, waves appear on the surface of the 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 & Renardy [30]; Preziosi et al [50]; Chen et al [6]).

The science behind the technology of CAF has given rise to a large literature which has been reviewed by Oliemans & Ooms [46] and more recently by Joseph & Renardy [30]. 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 versus mass flux, stability studies and reports of industrial experience.

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.

Industrial Interest in Lubricated Flow of Heavy Oil, Bitumen Froth and Emulsions. Oil companies have had an intermittent interest in the technology of water-lubricated transport of heavy oil since 1904. Isaacs & Speed [19] 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 [38] 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 Joseph & Renardy [30]. The patent history of the subject as it is presently understood starts with the application of Clark & Shapiro [9] 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 & Handley [10] 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 [33] 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 [15] 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 [43] and recent studies at the University of Minnesota have shown that the produced bitumen froth will self lubricate in a pipe flow. A similar self-lubrication of water in oil emulsions (5 to 60% water by weight) at a certain shear rate for a certain period of time is claimed and supported by data for tests by V. Kruka [35] using 10% water in 3 different Midway-Sunset crudes flowing in a $\frac{1}{2}$ inch pipe.

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 [36] 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 [45]).

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. Industrial experience suggests that inertia is necessary for successful CAF.

Fouling and Restart. 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 ($\rho = 0.996$ g/cm^3, h = 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. 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.

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 et al [52] and by Arney et al [2]. The addition of sodium silicate to the water will inhibit but not prevent fouling of carbon steel pipes. 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. 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. However, if the pipe is not well hydrated, it will foul; clean up procedures for fouled cement pipes should be developed.

Obviously, the restart of a fouled pipe will be easier if the oil does not strongly stick to the pipe wall.

The restart is also easier if there is an open channel through which water may flow. Such a channel can be opened by stratification under gravity in a large diameter horizontal line. The flowing water will produce a propagating solitary wave near the pump, which tends to partially block the flow of water in such a way that the high local pressure fingers water between the oil and pipe wall in an unzipping motion which restores core flow as the wave moves forward. The open channel may be closed at places where the pipe goes over a hill since the lighter oil will fill the pipe at high places and make restart more difficult. In small pipes, in which capillarity may dominate gravity, the oil will stratify in slugs separated by water lenses in which water is trapped. A comparison of pipelining in a single large diameter pipe to parallel pipelining in many small pipes is given in Joseph et al [25].

Self Lubrication of Bitumen Froth. The bitumen froth produced at the Alberta tar sands contains about 30% water as a dispersed phase. The water takes form as a colloidal dispersion of clay particles. The clay water promotes self-lubrication of the froth by covering froth-water interfaces with a layer of clay particles which prevents the bitumen from sticking to itself. When sheared, the water drops in the froth coalesce and form a lubricating layer. This is a self-lubricating system which works well with the clay water produced on site. The lubrication of the froth with clay water worked well, with pressure gradients of the same magnitude as water alone and no evidence of fouling after 4 days of continuous running. The start up and restart procedures are an issue which should be resolved by future research, but they seem manageable. As a result of this research, Syncrude's management have decided to build a pilot line, 24″ diameter by 1 km length. If no unforeseen problems occur in the pilot, Syncrude will build a commercial line of 25km to the upgrading center.

Here we are proposing research to determine the fundamental and engineering parameters for self-lubrication of Syncrudes' bitumen froth; for a given froth and froth temperature determine all of the flow regimes, holdup ratios, wave forms and pressure gradients as a function of froth input. We seek also to determine the physical mechanisms leading to water release and self lubrication under shear.

Topic 5: Rheology, Flow and Stability of Concentrated Emulsions.

This research focuses on highly concentrated emulsions of a very viscous dispersed phase in water for which the maximum packing geometry and direct contact forces are an issue. An example is the coal-substitute fuel, "Ormulsion®", which is a highly concentrated emulsion of over 70% bitumen (1,000 poise or more) in water plus surfactant. Other examples are asphalt, fuel, food and cosmetic emulsions.

The research proposed here should be viewed in the frame established in our article "Flow characteristics of concentrated emulsions of very viscous oil in water" by Núñez, Briceño, Mata, Rivas and Joseph [45].

In that article we considered three topics related to the flow characteristics of concentrated emulsions with a highly viscous dispersed phase and very small (5-50μm) drops in water. The first topic was about drop refinement of the most highly concentrated emulsion when flowing between rotating cylinders. This was observed in unimodal emulsions with bitumen fractions equal or greater than 0.7 and in a 0.8 bimodal emulsion. As the angular velocity was increased, we observed a rise followed by a sharp fall in the torque. The drop sizes were reduced near the point of maximum torque and the reduction was specially severe in the bimodal distribution where the large drop fraction is completely annihilated. We think that shearing the concentrated and viscous dispersion effectively breaks the larger drops by direct contact with other drops as in the comminution of solid rocks; in both cases the largest particles are broken and the mean effective diameter is reduced. We could not change identical size distributions in concentrated emulsions of much less viscous oil under the same dynamic conditions; these drops deform rather than fracture.

We could not change the drop distributions in pressure-driven flow in straight capillary tubes even in the more concentrated and highly viscous bitumen-in-water emulsions. Such dispersions could shear strongly only in the boundary layer, but boundary layers are effectively eliminated by the development of lubrication layers of clear water at the wall. The lubricated flows are essentially shear free.

The second topic considered there deals with the development of lubrication layers in the flow of concentrated emulsions. Lubricated flows are well known; they are enhanced by hydrophilic pipe walls and suppressed by hydrophobic counterparts. The lubrication layers require a development region with lateral migration of water to the wall and bitumen drops away from the wall. A minimum speed appears to be required suggesting that inertia is important.

The third topic is the local inversion of a concentrated emulsion testing the maximum packing fraction locally. Local inversion occurs where the fluid dynamics concentrates bitumen beyond the inversion limit set by the maximum packing fraction. Encapsulation of water in the interstices between closely packed drops is an inevitable consequence of the simultaneous coalescence of many drops. In fact, water was always found in coalesced bitumen drops. The water fraction in a totally inverted emulsion does not change, but the fraction of water encapsulated in a local inversion can be less, with some water driven off into reservoirs of free water. Local inversion are industrially important in pumps and contractions where squeezing motions further concentrate an already concentrated emulsion testing the maximum packing fraction locally.

Heavy oil in water emulsions are of potential commercial interest to all oil companies with significant reserves of heavy oils; Orimulsion's® are our paradigm. However, research on this topic could benefit a variety of emulsion-related technologies. For example, in the very important fields of asphalt and fuel emulsions, the choice of process equipment (pumps, control valves and paving hoses) is usually made on rather empirical grounds, to prevent deterioration of the emulsions. There seems to be practical evidence to suggest that the instabilities induced by pumps, for example, are closely related to the mechanism of local inversion. In the realm of food and cosmetic emulsions, the problem of handling these fluids also suggests the same difficulties, such as those encountered in the processing of thick creams and hand and body lotions.

Rheology. The rheological properties of a concentrated bitumen in water emulsion is complicated because the underlying fluid microstructure depends on the concentration, size distribution of bitumen drops and flow type. For this reason, the concept of the effective viscosity η of such an emulsion is elusive; for concentrated emulsions, the resistance to flow will depend on how the particles pack and they pack differently in different flows. A different effective viscosity can be given for each flow; we may hope that the range of values of viscosity does not vary too strongly over the range of flows of interest and we can hope to an interval of values, rather than a single one for a given emulsion.

The viscosity of a concentrated emulsion of small viscous drops with volume fractions less than the maximum packing fraction should be independent of the viscosity of the drop for large viscosities. This idea is consistent with the observation that the pressure drop in turbulent flow of emulsions tends to be independent of the oil viscosity (see Pilehvari, et al. [47]). An emulsion with very viscous disperse phase behaves like a concentrated suspension of solid spheres. The effect of the high internal phase viscosity is to inhibit relative motions and deformations of the spheres. This consequence of high viscosity of the drops allows us to use theoretical and empirical relations for the viscosity of fluidized suspensions of solid spheres to describe the viscosity of the emulsion. We may think of the analogy between the viscosity of suspensions of bitumen on the one hand and solid spheres on the other in the following way. The reduction of the drag in pipe flow of bitumen alone and bitumen in water emulsion is of the order of the ratio of the viscosities. This ratio is not relevant for the calculation of the viscosity of the suspension provided only that the viscosity of the viscous disperse phase is large enough to render the internal motion of the drop fluid nil. A solid sphere can be thought to be a bitumen drop with an infinitely great viscosity.

The determination of an effective viscosity of a suspension of solid spheres can be made reliably when the volume fractions are small, say $\phi < 0.6$, but the determination of the viscosity of more concentrated suspensions is more difficult as it depends on details of the packing and size distribution and even on the nature of flow in the viscometer as well as on the volume fraction of the spheres.

Even in the case of small volume fractions one of the main impediments to the determination of the viscosity of a fluidized suspension of solids or bitumen is polydispersity. One technique for modeling polydisperse suspensions is to treat them as if they were bimodal with the fluid and small particles treated as a single composite fluid which forms a continuous phase for larger particles. Typically the larger particles are modeled as a unimodal suspension. Segun and Probstein [56] modeled a polydisperse coal slurry as bimodal dispersion in which the fluid plus colloidal particles form the pseudo-fluid and the non-colloidal fraction is modeled as monodisperse. This theory does not require that the size ratio be large. Further developments in bimodal modeling have recently been discussed by Probstein, Sangun and Tseng [51].

An interesting recent study by Aral and Kalyon [1] of wall slip in a steady torsional flow of a concentrated suspension ($\phi = 63\%$) of glass beads in a polymeric liquid reveals dynamics analogous to the dynamics of flow of a bimodal 80% oil-in-water emulsion. In these emulsions the large drops of bitumen can be thought to be suspended in a pseudo-fluid of water and small bitumen particles with a pseudo-fluid fraction not greatly different than 37%.

The concept of a pseudo-fluid seems not to have been tried for bitumen-water emulsions, though these should be identical to solids in fluids whenever the flows are such that the structural integrity of the emulsion is left intact; that is, when there is no change in the drop size distribution and no local inversions. These conditions appear to hold for emulsions with bitumen fractions under 0.6 or even larger in the case of bimodal emulsions. The effect of fines in reducing the effective viscosity of a bimodal dispersion seems to be identical in bitumen in water and solid spheres in water. Owing to the nature of their packing, bimodal systems have greater critical packing fractions, which explains the viscosity reduction relative to a unimodal dispersion at the same disperse phase fraction. We want to evaluate the applicability of correlations for solid-fluid suspensions to bitumen-in-pseudo-fluid emulsions.

A conceptual framework for the more complicated and interesting case of a concentrated emulsion requires that we look carefully at the concept of maximum packing fraction ϕ_M which appears in nearly all correlations of the effective viscosity $\eta(\phi)$ of a concentrated suspension in a solvent of viscosity η_s; for example, with $\psi = \phi/\phi_m$ we have

$$\frac{\eta}{\eta_s} = \begin{cases} \frac{9}{8}\psi^{\frac{1}{3}}/(1-\psi^{\frac{1}{3}}) & \text{(Frankel \& Acrivos [14])} \\ \exp[\psi/(1-\psi)] & \text{(Mooney [41])} \\ (1-\psi)^{-2} & \text{(see Metzner [39]),} \\ (1-\psi)^{-[\eta]\phi_M} & \text{(Krieger \& Dougherty [34])} \end{cases}$$

where the 2nd & 4th formulas are in notations used by Wildemuth and Williams [59] and

$$[\eta] = (\eta - \eta_s)/\eta_s\psi$$

is the "intrinsic" viscosity which is said to depend on particle shape.

The formulas just given, and others which are said to hold for concentrated suspensions,

$$\psi = 1 - \epsilon, \quad \epsilon \to 0.$$

are functions only of ϵ, to leading order in ϵ. Thus, respectively,

$$\frac{\eta}{\eta_s} \to \begin{cases} \frac{9}{8\epsilon}, \\ \exp(\frac{1}{\epsilon}), \\ \epsilon^{-2}, \\ \epsilon^{(\frac{\eta}{\eta_s}-1)}. \end{cases}$$

None of these, or any of the more than 250 formulas presented by Rutgers [54], works well beyond the restricted data sets where they were derived. One problem is ϕ_M is a vague concept; the geometrical maximum packing fraction is not known for any but the simplest of polydisperse systems, and the geometric value is never actually achieved in a flowing suspension. A maximally packed bed of particles is a fixed bed. Metzner [39] says that ϵ^{-2} works well when $\phi_M = 0.68$ for monosized spheres and Wildemuth and Williams [59] like $\epsilon^{\frac{\eta}{\eta_s}-1}$ best, but they have identified the main reason that these formulas don't work; ϕ_M depends on the shear stress in the flow. These authors achieve very good agreements with different sets of data using the Krieger-Dougherty expression by manipulation of $\phi_M(\tau)$ for different τ.

In fact, ϕ_M depends rather more generally on the motion than through the shear stress. For example, in pure extension, there is no shear stress. Even in the easier case of dilute suspensions, Batchelor and Green [4] showed that the expression for the effective viscosity of a dilute suspension

$$\eta(\phi) = 1 + \frac{2}{5}\phi + K\phi^2 + O(\phi^3)$$

depends on the motion, with one value for K in shear flow and another in extensional flow.

Returning now to polydisperse concentrated emulsions of bitumen and water, we seek an interval of values for the effective viscosity η of a dispersion of large solid (bitumen) spheres in a psuedo fluid in which the maximum packing fraction depends on all the important motions which occur in practice. In this effort we acknowledge that the concept of an effective viscosity is flawed because the resistance depends on the motion, but that nevertheless something can be said about the resistance when account is taken for how the microstructural arrangements of a concentrated dispersion are changed by flow.

Lubricated Pipelining of Emulsions. This topic also falls under Topic 1. Here, we mention questions which apply to concentrated emulsions of solid-like bitumen drops. Again, we plan to see what can be learned from lubricated transport of concentrated slurries. To get lubrication, particles must migrate away from the wall and water comes out of the emulsion to replace space formerly occupied by particles, until equilibrium is reached. When in equilibrium, the emulsion moves in a core flow under a constant pressure gradient with no net lateral migration of bitumen drops. We can think that in the developing region the pressure gradient is not constant. The water responds to the gradients of the pressure gradient as it would in a porous media composed of the bitumen in the flowing emulsion. This forces water to flow relative to the bitumen drops, which takes form as an out-of-equilibrium migration of water through the bitumen drops. It is possible that the engine for development of lubrication is the levitation of particles from the wall by lubrication and inertial forces of exactly the same nature as the forces that produce lubricated slurries.

The picture just developed suggests two flow regimes: developing and developed lubricated flows. Both flow regimes appear to be amenable to simple mathematical modeling, but the modeling must be based on real data. For developed flow, we need pressure gradient versus mass flux data and hold-up ratios. For developing flow, we need to measure development length for different emulsions and pipe diameters, etc.

It is essential for practical applications to know the factors that promote or prevent lubrication. The operating conditions which require a speed fast enough to levitate bitumen (or solid) particles off the wall are know-how factors. The material of pipe construction, or surfactant-wall interaction which promote hydrophilic walls are material factors which we hope to understand.

Stability. An emulsion can lose stability in several ways: it can stratify, it can invert or it can invert locally, producing large drops of bitumen with encapsulated water. In emulsions of heavy oils, where density of the oil and water are nearly the same, stratification is not a problem.

A very concentrated emulsion of oil in water is prey to an inversion instability. Obviously, if the flow further concentrates an already concentrated emulsion, the oil fraction may test the maximum packing fraction locally. One example of a local flow-induced increase of the concentration of the dispersed oil is the ring instability of a uniform dispersion discussed below.

In a local inversion, parcels of oil-in-water invert to water-in-oil emulsions with small water fractions. This could be described as drop coalescence, but with the additional caveat that the resulting coalesced drop contains water (see Núñez, et. al [45]); it is a water in oil drop. The instability here follows from the fact that the coalescence that was produced in a region starved of water actually increases the degree of starvation by absorbing water. Total inversion arises here from local inversion so that stability is the same as a local inversion.

Local inversion occurs in devices like pumps and valves which tend to crowd bitumen drops, squeezing out the water. this is a highly practical subject which needs further study. A few such studies are described below.

The Ring Instability. Emulsions can be generated by shearing liquids between concentric rotating cylinders. This is a mechanical method of generating emulsions which does not involve surfactants. The emulsion collapses when the cylinders are stopped. Joseph, Singh and Chen [32] studied emulsions of silicone and soybean oils generated by rotating cylinders. Their observations can also be found in Chapter II of the book by Joseph and Renardy. [31].

The mechanical generation of emulsions between concentric rotating cylinder occurs in the following way. The fluids at rest are stratified by gravity. At slow speeds of rotation, a stable interface of one fluid advances into the other. The advancing interface develops scallops at its leading edge. These scallops become unstable and finger into the host fluid (see Figure 11). Bubbles form from capillary instability leading directly or eventually to emulsions. The average size of the bubbles in the emulsion decreases as the speed (shear) increases. The emulsion is maintained by shearing. It collapses to stratification when the motion is stopped.

Although such a mechanically-generated emulsion may be uniform initially, it never remains so for long. Apparently, the state of uniform emulsification is unstable, leading to a phase separation (see Figure 12).

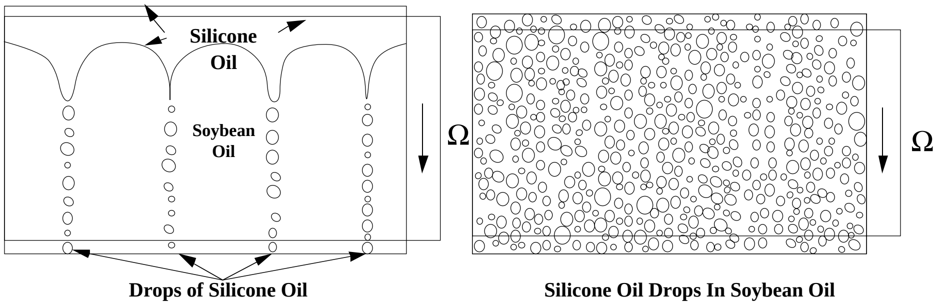

Figure 11: Fingering instability leading to emulsion

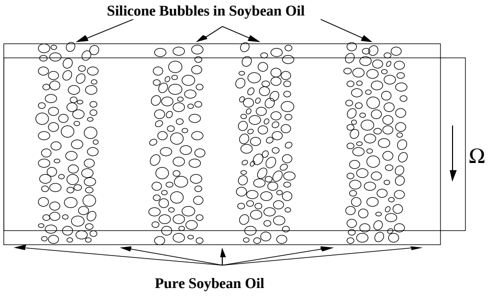

Figure 12

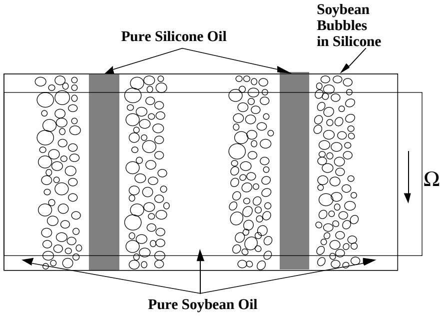

Figure 13

Figure 12: Phase separation when silicone oil fingers. Bands of emulsified silicone oil are separated by bands of pure soybean oil. Figure 13: Phase separation when soybean oil fingers.

We recently verified that this phase separation also occurs when the inner cylinder is fixed and the outer one rotates.

Referring again to Figure 11, we note that when the volume fraction ϕ of silicone oil is less than 0.6, the less viscous silicone oil fingers into the more viscous soybean oil, leading to silicone drops in soybean oil; when $\phi > 0.75$, the reverse happens: the soybean oil fingers into the silicone oil, leading to soybean-oil drops in silicone oil. This is *phase inversion*. In our experiments, the critical value of $\tilde{\phi}$ of ϕ lay in the range $0.6 < \tilde{\phi} < 0.75$. In both cases, the bubbly emulsions which exist before phase separation are uniform without structure. There is a preference for low-viscosity fingers to penetrate into the high-viscosity one when $\phi < 0.6$. Phase inversion shows that it is also possible to get a more viscous liquid to finger into a less viscous one.

When $\phi \leq 0.6$, symmetric, equally-spaced bands of an emulsion of silicone oil in soybean are separated by bands of pure soybean oil, as in Figure 12. For $\phi \approx 0.7$, instead of silicone bubbles, we get soybean-oil bubbles, again with more or less symmetric, equally-spaced bands. In this case, a narrow band of pure silicone oil is in the center of each band of emulsified soybean oil, as in Figure 13. As Ω increases, the phase boundaries disappear, leading to a foam unlike the bubbly mixture which develops after fingering. This foam is more stable and takes longer (5 to 10 minutes) to collapse when the rotation stops.

The ring instability not only shows that a uniform dispersion between rotating cylinders is unstable, but it gives rise to a mechanically-induced phase separation leading to local concentrations of emulsions and to phase inversion. The mechanisms which are associated with this instability are not understood; they need to be identified and modeled. We are going to look at the stability of a uniform dispersion between rotating cylinders using two-fluid models, in addition to methods of direct numerical simulations without modeling assumptions to the present problem. On the experimental side, it is necessary to monitor the lateral migration of particles in the apparatus which leads to the separation of the drops from the clear fluid. We have not yet been successful. Our next effort will involve streak photography using rapid laser flashes to catch the streaks formed by a single shuttering of a 35mm camera using good illumination and magnification.

Local Inversion Meter. To measure the tendency of a concentrated emulsion to invert locally we are constructing an eccentric rotating cylinder device with axial through flow (Poiseuille flow through rotating eccentric cylinders). A rotating inner cylinder is isolated inside a fixed outer cylinder and the inner cylinder can be offset to achieve any degree of eccentricity. The device will be outfitted for controlled axial throughput. Taylor cells will develop in this apparatus, but they are unimportant. The important parameters are the local pressure gradient produced in the narrow gap between eccentric cylinders and the residence time of bitumen particles which is controlled by the axial throughput speed. The circumferential pressure gradient in the narrow gap will move and squeeze the emulsion; the squeezing drives the water through the bitumen drops, forcing inversion. The device will be calibrated and we will develop a theory to interpret the calibration.

Topic 6: Suppression of Foam

In hydrocracking and other foaming reactors, the foam rises to the top because it has a higher gas fraction than the bubbly mixture from which it comes. The high gas hold-up in foams is undesirable in chemical reactors because it strongly decreases the liquid residence time and in hydrocracking reactors also promotes the formation of coke. To study foams we built a cold thin bubble reactor which when used with aqueous anionic surfactants gives rise to foam production. This reactor reproduces the foaming processes which are characteristic of the commercial system CANMET from Petrocanada. We discovered a critical condition for foaming; when the gas velocity exceeds a critical value which depends on the liquid velocity, a foam interface appears at the top of the reactor, with foam above and bubbly mixture below. The interface is very sharp and it moves down the reactor as the gas velocity is increased at a constant liquid velocity. This is the way reactors foam, with the bubbly mixture being consumed by foam.

The foam may be destroyed by increasing the liquid velocity backing up against the foaming threshold. The reactor partitions into two phase, two phase flow with foam above. The interface marks a phase change boundary which has not been studied before. We derived good constant state theories for the bubbly mixture and the foam, but the "phase change" mechanism and a theory to predict the position of the interface has not yet been given. We found that we could suppress the formation of foam by fluidizing particles in the bubbly mixture, but the mechanism and parameters (weight, size, concentration of particles) need to be systematically investigated. We are proposing to study the fluid mechanics of the bubbly mixture-foam interface and the suppression of foam by fluidizing particles in the bubbly mixture.

Foam-bubbly mixture interface

- Study the fundamental physics leading to the appearance of the foam-bubbly interface.
- Establish the conditions which determine and predict the height of the interface.

The suppression of foam can be achieved by increasing the concentration, decreasing the size or density of hydrophilic particles.

- Establish the limits of these trends with regard to extreme values of size, density, and concentration.
- Establish that hydrophilic particles are required by fluidized hydrophobic particles to which gas preferentially adheres.

Foam traps fluidized particles in the bubbly mixture.

- Search the limits of particle size, density, concentration and velocity for which the foam trap breached.
- Study the suppression of foam using particles of different shape to control the liquid hold-up.
- Study foam suppression using fluidized beds of polydisperse spheres.
- Study foam creation and suppression in hydrocarbon systems in which foaming oils replace aqueous surfactant systems. The goal is to show that foam suppression by liquid hold-up in a fluidized bed under foam is a general reactor process.
- Study foam suppression in systems in which particles are continuously injected. Since the particles must leave the reactor, the foam will be breached. The particles hold-up in the bubbly mixture may then be a critical feature in hydrocarbon reactors with continuous addition of catalyst particles.

Results from Prior NSF Support (D.D. Joseph)

1. NSF Award, CTS 9213979, for $365,000 from 10/30/92 to 2/29/96.
2. Project title: Studies of Two-Phase Flows of Liquids and Solids.
3. Summary of prior results:

Of 36 papers we published since 1993, the 25 listed below are related to the present proposal. They cover four topics: (i) experiments on the settling of particles in viscous and viscoelastic fluids [3,4,6,17,18,19,22]; (ii) direct simulation of the motion of particles in a viscous liquid [1,7,10,11,13,14,16,23]; (iii) two-phase flow modeling of solid-liquid flow [17,18,22] and (iv) studies of lubricated transport of hydrocarbons and remedial strategies against fouling [2,5,9,12,15,16,20,21,24,25].

The experiments (i) showed that the overall flow-induced anisotropy in Newtonian and viscoelastic liquids is determined by pair interactions due to wakes and turning couples on long bodies. This leads to characteristic pair interactions between particles which are maximally different in Newtonian and non-Newtonian fluids, with across-the-stream arrangements in Newtonian fluids and along-the-stream arrangements in viscoelastic fluids (see figure 2). The experiments are described in our research summary. From our direct simulations (ii) (also described in the research summary), we showed how the pressures at stagnation and separation points cause lateral migrations of particles and produce couples that control the orientation of long bodies in Newtonian and viscoelastic fluids. In modeling fluidized suspensions (iii), we proposed that the solids area fraction rather than the volume fraction is the fundamental variable controlling the dynamics and stability. A construction [17] was given relating the volume and area solids fraction and some predictions about the zeros of the area fraction were confirmed in experiments [18]. Our proposal can be fully tested by the direct simulations proposed here. The experiment in [22] showed that the values of the effective density and viscosity are close to the average density of the mixture and to the viscosity of the mixture predicted by correlation suggested by Thomas when the test particles are of the same size as the suspended particles, but not too much smaller.

In the study of the fluid dynamics of core flows (iv), we correlated all the available data on friction factors and hold-up for core flow and have shown good agreements between experimental data and k-ϵ models in turbulent flow. We analyzed the stability of eccentric core annular flow and we showed that there is no linear mechanism for centering the flow when the density is matched. The modes of instability of the eccentric core annular flow are a combination of an asymmetric mode and a first mode of azimuthal variation and it resembles cork screw waves seen in experiments. We completed the first direct numerical simulation of axisymmetric core flow, and we verified that the pressure at the front of the wave steepens the wave there while the backside is smoothed by low pressures. The steepening can be regarded as a shock up by inertia and it shows that dynamics work against the formation of long waves usually assumed in analyses. We found that there is a threshold Reynolds number below which the total force corresponding to the pressure is negative, positive above, and we conjectured, therefore, that inertia is required to center a density matched core and to levitate the core off the wall when the density is not matched [24].

Another category of study treats the problem of fouling pipe walls with oil, with undesirable increases in pressure gradients and even blocking. We found an apparent remedy for this using cement-lined pipes; over 140 cements were tested [20,21]. The best cements require hydration in sodium meta-silicate; a calcium silicate gel is formed at the surface which is extraordinarily hydrophilic and resists spotting by oil. A patented for the method of preventing fouling pipe walls for lubricated transport was obtained for cement linings (U.S. Patent No. 5,385,175).

We also considered problems of the lubricated transport of concentrated emulsions [25]. We found that concentrated emulsions of crude oil do lubricate when the pipe material is hydrophilic. In the case of very concentrated, say, 80/20, bimodal dispersions of oil in water, we showed that there is a crisis at a certain shear wherein the large drop fraction is broken into small drops by direct contact as in comminution of rocks. On the other side, we showed that bitumen drop coalescence in concentrated emulsion is, in fact, not coalescence but is a local inversion in which water appears to be the large drop. The fluid motion concentrates further an already concentrated dispersion, testing the maximum packing fraction locally. The way to total inversion is locally, in patches.

Our laboratory setting is a human resource center. It serves as a hub of activities for graduate and undergraduate students and also a kind of social center. The undergraduates are supported by programs from the University (Undergraduate Research Opportunities) and from the NSF program on Research Experiences for Undergraduates (REU). Thirteen undergraduate students, four of whom are women, have worked for us in these programs in the past five years; three students are currently working in the lab. All of these undergraduates have gone on to careers in science and engineering. These undergraduate programs are visible in the undergraduate community as opportunity programs for highly qualified students. Graduate students who participated in the research of this prior NSF grant are M. Arney, R. Bai, C. Christodoulou, K.P. Chen, J. Feng, T. Hall, H. Hu, P. Huang, A. Huang, T. Liao, J. Liu, G. Ribeiro and H. Vinagre.

Publications

1. Direct simulation of fluid-particle motions (with H. Hu and M.Crochet), AHPCRC preprint 91-43, *Journal of Theoretical and Computational Fluid Dynamics* **3**, 285-306 (1992).
2. Friction factor and holdup studies for lubricated pipelining (with M.S. Arney, R. Bai, E. Guevara, and K. Liu). *Int. J. Multiphase Flow* **19**(6), 1061-1076 (1993).
3. Orientation of long bodies falling in a viscoelastic liquid (with Y.J. Liu). *J. Rheol.* **37**(6), 961-984 (Nov/Dec 1993).
4. Anomalous rolling of spheres down an inclined plane (with Y.J. Liu, J. Nelson and J. Feng). *J. Non-Newtonian Fluid Mech.* **50**, 305-329 (1993).
5. A note on the net force and moment on a drop due to surface forces (with T. Hesla and A.Y. Huang) *J. Colloid & Interface Science* **158**, 255-257 (1993).
6. Sedimentation of particles in polymer solutions (with Y.J. Liu)*J. Fluid Mech.* **225**, 565-595 (1993).
7. Direct simulation of initial value problems for the motion of solid bodies in a Newtonian fluid (with J. Feng and H. Hu). *J. Fluid Mech.* **261**, 95-134 (1993).
8. Aggregation and dispersion of spheres falling in viscoelastic liquids (with Y.J. Liu, M. Poletto and J. Feng). *J. Non-Newtonian Fluid Mech* **54**, 45-86 (1994).
9. Friction factor and holdup studies for lubricated pipelining. Part II: laminar and k-ϵ models of eccentric core flow (with A. Huang and C. Christodoulou). *Intl. J. of Multiphase Flow* **20**(3), 481-491 (1994).
10. The turning couples on a elliptic particle settling in a vertical channel (with P.Y. Huang and J. Feng). *J. Fluid Mech.* **271**, 1-16 (1994).
11. Direct simulation of initial value problems for the motion of solid bodies in a newtonian fluid. part 2: couette and poiseuille flows (with J. Feng and H. Hu). *J. Fluid Mech* **277**, 271-301 (1994).
12. Parallel pipelining (with H. Hu, R. Bai, T.Y. Liao and A. Huang). Accepted for publication in *J. Fluids Eng.* (1994).
13. Interrogation of numerical simulations for modeling of flow induced microstructures. *ASME FED* **189** (Liquid-Solid Flows), 31-40 (1994).
14. A three-dimensional computation of the force and moment on an ellipsoid settling slowly through a viscoelastic fluid (with J. Feng, R. Glowsinski and T.W. Pan). *J. Fluid Mech.* **283**, 1-16 (1995).
15. Stability of eccentric core-annular flow (with A. Huang). *J. Fluid Mech.* **282**, 233-245 (1995).
16. Dynamic simulation of the motion of capsules in pipelines (with J. Feng). *J. Fluid Mech.* **2**86, 201-207 (1995).
17. Dynamics of fluidized suspensions of spheres of finite size (with P. Singh). *International Journal of Multiphase Flow* **21**, 1-26 (1995).
18. Propagation of voidage wave in a two-dimensional liquid-fluidized bed (with M. Poletto and R. Bai). To appear in *Int. J. Multiphase Flow* **39**, 323-344 (1995).
19. Motions of particles settling in a viscoelastic fluid. To appear in Proceedings of the Second International Conference on Multiphase Flow, Kyoto, Japan, April 3-7, 1995.
20. *Topics in the transport and rheology of heavy crude oils*, G. Ribeiro, Ph.D. Thesis, University of Minnesota, (1995).
21. Cement-lined pipe for water lubricated transport of hydrocarbons (with M. Arney, G. Ribeiro, E. Guevarra and R. Bai), *Int. J. Multiphase Flow*, **22**(2), 226–233 (1996).
22. The effective density and viscosity of a suspension (with M. Poletto). *J. Rheology* **39**(2), 323-343 (1995).

23. The unsteady motion of solid particles in creeping flows (with J. Feng). *J. Fluid Mech.*, **303**, 83–102 (1995).
24. Direct simulation of interfacial waves in a high viscosity ratio of axisymmetric core annular flow (with R. Bai and K. Kelkar). Accepted for publication in *J. Fluid Mech.*, (1995).
25. Flow characteristics of concentrated emulsions of very viscous oil in water (with G. Núñez, Maria Briceo and Clara Mata). *J. Rheology*, **40**(3), 405–423 (1996).

D References

[1] Aral, B.K. and Kalyon, D.M., Effects of temperature and surface roughness on time-dependent development of wall slip in steady torsional flow of concentrated suspensions, **38**(4):957-972, (1994).

[2] Arney, M.S., Ribeiro, G.S., Guevara, E., Bai, R. and Joseph, D.D., Cement lined pipes for water lubricated transport of heavy oil, *Int. J. Multiphase Flow.* (In press, 1995).

[3] Bai, R., Kelkar, K., and Joseph, D.D., Direct simulation of interfacial waves in a high viscosity ratio of axisymmetric core annular flow, Accepted for publication in *J. Fluid Mech.*, (1995).

[4] Batchelor, G.K. and Green, J.T., The determination of the blulk stress in a suspension of spherical particles to order c^2, *J. Fluid Mech.*, **56**:401–427, (1972).

[5] Brandt, A. and Bugliarello, G., Concentration redistribution phenomena in the shear flow of monolayers of suspended particles, *Trans Soc. Rheology*, **10**(1):229–251, (1966).

[6] Chen, K., Bai, R. and Joseph, D.D., Lubricated pipelining. Part 3. Stability of core- annular flow in vertical pipes, *J. Fluid Mech*, **214**:251–286, (1990).

[7] Cho, Y.I. and Hartnett, J.P., The falling ball viscometer – A new instrument for viscoelastic fluids, *J. Heat Mass Transfer,* **6**:335–342, (1979).

[8] Cho, Y.I., Hartnett, J.P. and Lee, W.Y., Non-Newtonian viscosity measurements in the intermediate shear rate range with the falling ball viscometer, *J. Non-Newtonian Fluid Mech*, **15**:61–74, (1984).

[9] Clark, A.F., Shapiro, A., U.S. Patent No. 2,533,878. (1949).

[10] Clifton, E.G., Handley, L.R., U.S. Patent No. 2,821,205. (1958).

[11] Coussot, P., Leonev, A.L. and Piau, J.M., Rheology of concentrated dispersive systems in a low molecular weight matrix, *J. Non-Newtonian Fluid Mech*, **46**:179–217, (1993).

[12] Feng, J., Huang, P.Y., and Joseph, D.D., Dynamic simulation of sedimentation of solid particles in an Oldroyd B fluid. *J. Non-Newtonian Fluid Mech.*, **63**(1), 63–89, (1996).

[13] Feng, J., Joseph, D.D., Glowinski, R. and Pan, T.W., A three-dimensional computation of the force moment on an ellipsoid settling slowly through a viscoelastic fluid, *J. Fluid Mech.*, **282**:1–16, (1995).

[14] Frankel, N.A. and Acrivos, A., On the viscosity of a concentrated suspension of solid spheres, *Chem. Eng. Sci*, **23**:842–853, (1967).

[15] Ho, W.S., Li, N.N., Core-annular flow of liquid membrane emulsion, *AIChE Journal,* **40**(12):1961–68, (1994).

[16] Huang, P.Y., Feng, J., Hu, H.H. and Joseph, D.D., Direct simulation of the motion of solid particles and Couette and Poiseuille flows of viscoelastic fluids, Submitted to *J. Fluid Mech*, (1996).

[17] Hu, H.H., Direct simulations of flows of solid-liquid mixtures, *Int. J. Multiphase Flow*, **22**(2):335–352, (1996).

[18] Hu, H., Huang, A. and Joseph, D.D., 6 particles sedimenting in an Oldroyd B fluid. Video Cassette.

[19] Isaacs, J.D., Speed, J.B., U.S. Patent No. 759,374. (1904).

[20] Joseph, D.D., Bournoulli equation and the competition of elastic and inertial pressure in the potential flow of a second order fluid, *J. Non-Newtonian Fluid Mech*, **42**:385–389, (1992).

[21] Joseph, D.D., “Flow induced microstructure in Newtonian and viscoelastic fluids,” Keynote presentation (paper no. 95a) at the 5th World Congress of Chemical Engineering, Particle Technology Track. Second Particle Technology Forum, San Diego, July 14–18, (1966).

[22] Joseph, D.D., “Motions of particles settling in a viscoelastic fluid,” Proceedings of the Second International Conference on Multiphase Flow. Kyoto, Japan, April 3–7, (1995). PD1(1–8).

[23] Joseph, D.D., Bai, R.,Chen, K.P. and Renardy, Y.Y, Core-annular flows, to appear in *Annual Reviews of Fluid Mech.*, Jan. 1997.

[24] Joseph, D.D. and Feng, J, The motion of a solid sphere suspended by a Newtonian or viscoelastic jet, *J. Fluid Mech.*, **315**:367-385, (1996).

[25] Joseph, D.D., Hu, H., Bai, R., Liao, T.Y. and Huang, A., Parallel pipelining, *J. Fluids Eng.*, **117**:446–449, (1995).

[26] Joseph, D.D., Liao, T., Potential flows of viscous and viscoelastic fluids, *J. Fluid Mech*, **265**:1–23, (March 1994).

[27] Joseph, D.D. and Liu, Y.J., Orientation of long bodies falling in a viscoelastic liquid, *J. Rheology,* **37**:1–22, (1993).

[28] Joseph, D.D., Liu, Y.J., Poletto, M. and Feng, J., Aggregation and dispersion of spheres falling in viscoelastic liquids, *J. Non-Newtonian Fluid Mech*, **54**:45–86, (1994).

[29] Joseph, D.D., Nelson, J., Hu, H. and Liu, Y.J., “Competition between inertial pressures in the flow induced anisotropy of solid paritcles,” in Theoretical and Applied Rheology, (eds. P. Moldenaers and R. Keunings), Elsevier, Amsterdam, 60-64, (1992).

[30] Joseph, D.D. and Renardy, Y.Y., “Fundamentals of Two-Fluid Dynamics,” New York: Springer-Verlag (1993).

[31] Joseph, D.D. and Renardy, Y.Y., “Fundamentals of Two-Fluid Dynamics. Part II: Lubrication Transport, Drops and Miscible Fluids”, New York: Springer-Verlag (1992).

[32] Joseph, D.D., Singh, P. and Chen, K., “Couette Flows, Rollers, Rmulsions, Tall Taylor Cells, Phase Separation and Inversion and a Chaotic Bubble in Taylor-Couette Flow of Two Immiscible Liquids,” in *Nonlinear Evolution of Spatio-Temporal Structures in Dissipative Continuous Systems*, (eds., F.H. Busse and L. Kramer), New York: Plenum Press (1990).

[33] Keil, OM. U.S. Patent 3,378,047. (1968).

[34] Krieger, I.M., Dougherty, T.J., Unpublished manuscript, (1959). Also, Dougherty T.J., Ph.D. thesis, Case Institute of Technology, Cleveland (1959). See remarks in: Krieger, I.M., *Adv Colloid Interface Sci*, **3**:111, (1972).

[35] Kruka, V.R., Method for establishing core-flow in water-in-oil emulsions or dispersions, Canadian patent # 1008108 granted to Shell Canada Ltd.

[36] Lamb, M.J., and Simpson, W.C., *Proc. World Petroleum Cong., 6th, Frankfurt/Main*, pp. 23–33 (1963). Published by Verein Zur Förderung Des 6. Welt–Kongresses, Hamburg.

[37] Liu, Y.J., and Joseph, D.D., Sedimentation of particles in polymer solutions, *J. Fluid Mech*, **255**:565–595, (1993).

[38] Looman, M.D., U.S. Patent No. 1,192,438. (1916).

[39] Metzner, A.B., Rheology of suspensions in polymeric liquids, *J. Rheol* **29**, 739–735 (1985).

[40] Mewis, J., Thixotropy – A General Review, *J. of Non-Newtonian Fluid Mechanics*, **6**:1–20, (1979).

[41] Mooney, J., The viscosity of a concentrated suspension of spherical particles, *J. Colloid Sci*, **6**:162–170, (1951).

[42] Moore, F., The Rheology of ceramic slips and bodies, *Trans British Ceramics Soc.*, **58**: 470–487, (1959).

[43] Neiman, O., Froth pipelining tests, *Syncrude Canada Research and Development Progress Report*, 15(1):373–407, (1986).

[44] K.G., Nolte, "Fluid Flow Considerations in Hydraulic Fracturing," SPE 18537, (1988). See also Errata submitted July 1992 for SPE 18537, available from SPE Book Order Department.

[45] Núñez, G.A., Briceño, M., Mata, C., Rivas, H. and Joseph, D.D., Flow characteristics of concentrated emulsions of very viscous oil in water, *J. Rheol.*, **40**(3): 405–423, (1996).

[46] Oliemans, R.V.A. and Ooms, G., Core-annular flow of oil and water through a pipeline. *Multiphase Science and Technology*, ed. G.F. Hewitt, J.M. Delhaye, N. Zuber, Vol. 2, Hemisphere Publishing Corporation, (1986).

[47] Pilehvari, A., Sandevandi, B., Halvaci, M., and Clark, P.E., Oil/water emulsions for pipeline transport of viscous crude oils, *SPE Paper 18218*, 393–403, (1988).

[48] Pipkin, A.C., and Tanner, R, A survey of theory and experiment in viscometric flows of viscoelastic liquids, *Mechanics Today*, 1:262–321, (1972).

[49] Powell, J.W., Parks, C.F. and Seheult, J.M., Xanthan and Welan: The Effects of Critical Polymer Concentration on Rheology and Fluid Performance, Presented at the Intl. Arctic Technology Conference, Anchorage, May 29–31,(1991). SPE 22066.

[50] Preziosi, L., Chen, K., Joseph, D.D., Lubricated pipelining: stability of core-annular flow. *J. Fluid Mech.* **201**:323–56, (1989).

[51] Probstein, R.F., Sengun, M.Z. and Tseng, T.C., Bimodal model of concentrated Suspensions viscosity for distributed particle sizes, *J. of Rheology*, **38**(4):811–829.

[52] *Topics in the transport and rheology of heavy crude oils*, G. Ribeiro, Ph.D. Thesis, University of Minnesota, (1995).

[53] Riddle, M.J., Navarez, C. and Bird, R.B., *J. Non-Newtonian Fluid Mech.*, **2**:23–25, (1977).

[54] Rutgers, R., Relative viscosity of suspensions of rigid spheresin Newtonian liquids, *Rheol. Acta* **(**2):202–210, (1962).

[55] Tehrani, A., Hammond, P.S. and Unwin, A.T., "Experimental study of particle migration in suspensions undergoing Poiseuille flow," presentation given at Society of Rheology 66th Annual Meeting, Philadelphia, October 2–6, (1994).

[56] Segun, M.Z. and Probstein, R.F., Bimodal model of slurry viscosity with application to coal slurries: Part I. Theory and experiments, *Rheol Acta*, **28**:382–393.

[57] Unwin, A.T. and Hammond, P.S., "Computer simulations of proppant transport in a hydraulic fracture," SPE 29649, presented at the Society of Petroleum Engineers Western Region Meeting, March 8–10, (1995).

[58] Walters, K., Bhatti, A.Q. and Mori, N., The influence of polymer conformation on the rheological properties of Aqueous polymer solutions, in *Recent Developments in Structured Continua*, Vol. 2, edited by DeKee, D. and Kaloni, P.N., Wiley, New York (1990).

[59] Wildemuth, C.R., and Williams, M.C., Viscosity of suspensions modeled with a shear-dependent maximum packing fraction, *Rehological Acta*, **23**:627–635, (1984).

E Biographical Sketches

F Summary Proposal Budget

G Current and Pending Support

H Facilities, Equipment and Other Resources

I Industrial Partners

This GOALI grant is to be based at the University of Minnesota with Industrial Partners:

Dowell-Schlumberger. This company is located in Sugarland, TX. It has a strong interest in reservoir stimulation and migration of particles in fracturing fluids and drilling an area of major commercial expansion with increasing emphasis on research and developement. The Schlumberger foundation gave Joseph two unrestricted grants of $20,000 each for the studies his group does in the field of particle migrations and they contributed $5,000 to support the NSF Grand Challenge Grant. Dowell-Schlumberger (DS) has expressed a very strong interest in the work proposed here and has committed to a $25,000 per/year cash contribution plus in-kind contributions of value. Ken Nolte of DS in Tulsa will be the Co-PI from Dowell and the coadvisor for Tim Hall. We will also collaborate with Yan Kuhn de Chizelle of DS in Houston and Paul Hammond of Schlumberger in Cambridge, England.

Stimlab. Stimlab in Duncan OK is a well equipped laboratory supported by a consortium of oil and oil service companies for research on reservoir stimulation and fracturing fluid dynamics. The members of the consortium are:

Acme Resin Corporation
Amoco
Aqualon Company
ARCO
BJ Services
BP Exploration
Canadian FracMaster, Ltd.
Carbo Ceramics, Inc.
Chevron
China National Petroleum Corporation
Conoco, Inc.
Dowell Schlumberger
Edinburgh Petroleum Services, Ltd.
Gas Research Institute
Halliburton Energy Services
KELCO
Knonklijke/Shell-Exploratie and Produkie Laboratium (KSEPL)
Maersk Olie Og Gas as
Marathon Oil Company
Mobil
Nowsco Well Services Ltd.
ORYX Energy Company
Pennzoil
Phillips Petroleum Company
Petrobras
Rhone-Poulenc
Santos, Ltd.
Shell
Texaco
Union Pacific Resources Company
UNOCAL
Western Company of North America

Mike Conway is Vice President of Stimlab and is a Co-PI on this GOALI proposal. After some direct discussions with Mike Conway and his coworkers in Duncan, it was decided that a proposal to partner would be best served by a lecture to members of the consortium by Joseph, which was presented on 7/16/96 at Colorado Spring. A ballot which outlines the research proposed was presented to members and is included here. The members voted unanimously to support this proposal at a level of $20,000 per year.

Intevep. Intevep is the research arm of PDVSA, the Venezuelan oil company. Citgo, an important American company is entirely owned by PDVSA. Intevep has agreed to partner with a cash contribution of $5000 per year and 3 graduate students, fully funded by Intevep, to be coadvised by Núñez & Rivero. The toal value added by these contributions is in the neighborhood of $100,000 per year. Joseph's lab has extensive contacts and a long history of collaborations with different research teams of Intevep. At present, two graduate students from Intevep, totally supported by them, are pursuring Ph.D. Programs with Joseph; José Guitian works on suppression of foam in bubbling reactors, Clara Mata works on lubricated pipelining and stability of emulsions.

Douglas Ocando, who presently works at Intevep under Mayela Rivero is supposed to come to Joseph's lab to pursue a Ph.D. degree emphasizing problems of drilling. Intevep has loaned a sine pump (20K) to Joseph's lab to use in test loop studies of drilling muds and fracturing fluids. This has specially designed constant volume chambers of great value for the gentle pumping of polymer solutions which would degrade in shear in other types of pumps. Intevep is an Industrial sponsor of our NSF grand challenge HPCC grant.

Joseph and his students have written papers on collaborative research with Gustavo Nuñez, Mayela Rivero, Emilio Guevera, Antonio Cardenas, Hercilio Rivas, Clara Mata, and Maria Brecieno, and he is presently engaged in a patent application with José Guitian and Julio Krasuk.

Syncrude. Our relation to Syncrude was recently described in a letter of Ken Sury and Chris Grant to the DOE. Excerpts from the letter are cited below.

"Syncrude Canada Limited is a joint venture operation involved in the business of mining oilsands, extracting bitumen, and then upgrading bitumen into synthetic crude oil. Currently annual production is in excess of 70 million barrels. Although this consortium is mainly owned by Canadian oil companies, U.S. companies are also involved both directly and indirectly. For example, Imperial Oil Resources which is controlled by Exxon, holds a 25% interest, Murphy Oil owns 5%, and Torch company of Houston has a 20% interest. Syncrude recognizes the importance of technology in the success of its business and pursues new technology development programs with great enthusiasm.

At present, Syncrude is evaluating the feasibility of pipelining bitumen froth using water-lubricated flow technology. The pipeline will cover a 35 kilometer distance from a remote oilsand lease to the current production site where the bitumen is upgraded into synthetic crude. For this application, the potential economic incentives for the water-lubricated flow (oil/water core-annular flow) technology are significant compared to the alternate technologies such as heating and dilution with solvents.

In-house research carried out in 1985 indicated the technical feasibility of water-lubricated flow technology, but several questions remained to be addressed prior to the commercial development of an expensive new technology. We did not know if the addition of extra lubricating water was beneficial or the fouling of pipe wall by bitumen could lead to blockage and failure. After searching the literature, we concluded that Professor Joseph was the leader in the field. We were particularly interested in his research on cement-lined pipes to reduce fouling which was supported by the D.O.E. His findings have practical significance and have been published recently in the *International Journal of Multiphase Flow* under the title "Cement lining for water-lubricated transport of hydrocarbons." Subsequently, we contracted Professor Joseph to carry out bench-scale fouling tests using bitumen froth.

Professor Joseph's research team carried out static tests on the fouling aspects of various pipeline materials and recommended further pilot tests using a 1 inch diameter pipeline in his laboratory. After visiting Dr. Joseph's laboratory, Syncrude authorized the proposed pilot test program at a cost of $100K. This research contract was arranged through the business office of the University of Minnesota.

The pilot tests were carried out during November 1995 to March 1996 and were highly successful. The results demonstrated the applicability of water -lubricated flow technology for bitumen froth. The froth self-lubricates at a high shear rate, and does not foul carbon steel pipe walls. Further, Dr. Joseph proposed mechanisms involved in water-lubrication, scale-up for commercial size pipelines, and procedures for pipeline start-up and restart following stopping. We appreciated the on-time completion of the task and the thoroughness of the test work.

As a result of Dr. Joseph's work, Syncrude is planning to test this technology at a commercial scale (24 inch diameter by 1 km pipeline loop) this summer. We anticipate the involvement of Dr. Joseph in the interpretation of the results of this testing. We think that Dr. Joseph's understanding of the fundamentals together with his appreciation of the practical elements involved in expensive engineering decisions is praiseworthy. We commend the D.O.E. for sponsoring such useful research."