Direct Numerical Simulation of Slurry Transport Focusing on Engineering Correlations

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National Science Foundation GOALI Program

World Wide Web: *http://www.aem.umn.edu/Solid-Liquid_Flows*

A. Project Summary

This GOALI proposal is for University based support for partnering between the fluid mechanics laboratory at the University of Minnesota and STIMLAB, which is a research laboratory in Duncan, OK supported by a consortium of oil production and oil service companies interested in reservoir stimulation. The proposal is to develop and apply direct numerical simulation (DNS) to problems of slurry transport in general and to proppant transport into reservoir fractures in particular. We aim to deliver a practical product to the fracturing industry in the form of (1) formulas for lift and drag on particles to be used by PC-based models of slurry transport and (2) correlations based on the processing of numerical experiments and real experiments using the same dimensionless parameters in log-log plots.

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C. Project Description

Direct numerical simulation (DNS) is a way of solving the initial value problem for the motion of particles in fluids on a computer exactly without approximation. The particles are moved by Newton's laws under the action of hydrodynamic forces from the numerical solution of the fluid equations. Computer codes for moving particles in fluids by DNS have been developed by us under successive NSF Grand Challenge (HPCC) and KDI/NCC grants. The collaborations established under these grants are presently active and are a valuable resource for the implementation of advances sought in this proposal

Broadly speaking our goals for this GOALI proposal are: (1) flow diagnosis aiming at modeling of lift and drag on single particles and slurries of many particles in conduits, and (2) to deliver engineering correlations of the variables controlling these flows by processing data from numerical experiments. We call this the *method of correlations*; it is the same method that is used to get correlations from real experiments. The results of simulation plotted in log-log plots of the relevant dimensionless parameters map to straight lines from which power laws emerge. From a modest number of calculations we find a continuum of results extending even beyond where we can compute. The existence of ubiquitous power laws in solid-liquid flow is a hidden self-similar property not evident from the equations of motion. Since we gain so much from so little, it can be said that even very expensive calculations are cheap when they give rise to correlations.

Flow diagnosis is a many faceted activity in which DNS is interrogated for guidance in understanding the principles of particulate flow, in deriving formulas [14,16] and in the building and testing of models [7,9,13,15]. Microstructural interactions between pairs of sedimenting and fluidized particles were studied: drafting, kissing and tumbling in Newtonian fluids, and drafting, kissing and chaining in viscoelastic fluids. Pair interactions lead to anistropic structures in the flow of many particles: horizontal arrays in Newtonian fluids and vertical chains in viscoelastic fluids [1,2,3,4,8].

The lift off and levitation to equilibrium of single heavy circular particles in Poiseuille flow in horizontal channels revealed the existence of critical values for lift-off and levitation to equilibrium of steady flow [6,8,11,14,16]. The effects of controlled rather then free (no torque) rotation of particles was studied [14,16]; the free particle rotates at an angular velocity Ω_p. This value is a little less than the rotation rate $\dot{\gamma}/2$ of the fluid at the point in the Poiseuille flow, where the particle center is at the place where the shear rate is $\dot{\gamma}$ when no particle is present. Suppression of particle rotation overpredicts lift. The angular slip velocity discrepancy is the difference between the angular slip velocity of a migrating free particle and its unique value at equilibrium; the discrepancy changes sign across the unique position of equilibrium. The proposition was advanced that the angular slip velocity discrepancy is the shear flow equivalent of circulation in the theory of aerodynamic lift, and that the lift is proportional to the linear slip velocity $U_s = \dot{\gamma}\, y - U_p$ at *y,* times this circulation. This lift formula is the only one so far advanced that is consistent with migration to a unique equilibrium between the center and wall [16].

An analytical formula for the particle velocity U_p of a circular particle was derived from a long particle model and shown to be in surprisingly good agreement with computed values of U_p for circular particles by DNS [12,16].

DNS revealed the existence of previously unknown turning point bifurcations in the equilibrium height and velocities in Newtonian and even in viscoelastic fluids [11,14]. The implications of these bifurcations for the fluidization of slurries will be studied.

A DNS study of the forces controlling the lateral migration of spherical particles in a vertical tube was constructed [19]. Much more extensive 3D simulations that extend the 2D results already achieved to real flows are a high priority for future work.

Projects to extend the range of applications we can do with DNS are: (1) to determine the dependence of correlations on the number or number density of particles. We did correlations of 300 circular particle in Poiseuille flow; it is necessary to see if the correlations depend in an important way on the number of particles in a computational cell. (2) Develop a simulation method that allows for accumulation of particles in a computational cell, such as would be the case when particles are injected into a fluid flow or a transient problem in which the injection rate of particles and fluid are increased. (3) The way that collisions are handled in our simulations needs to be improved. At present we initiate a repelling force when the particles are closer than a preassigned value; we don't let them touch. This has the unfortunate consequence that particles cannot close pack. Though this does not seem to effect fluidized flows greatly, we must be able to generate close packing if we are to model the immobile part of beds of slurries of particles such as occur when proppants are injected into fractured reservoir.

To achieve credibility for the method of correlations for proppant transport we are going to set up simulations that model STIMLAB's experiments. We want to process our numerical experiments and their real experiments for correlations in exactly the same way. The correlations are power laws in the relevant dimensionless parameters. It is surprising that the list of dimensionless parameters that control solid-liquid flow is unknown to modelers in the fracturing industry and appear not to have been so clearly set out in academic studies. We believe that a careful examination of experimental data from DNS and real experiments from STIMLAB will become intelligible when viewed in a frame of values of the dimensionless parameters.

Results form prior NSF support. This proposal builds on our previous GOALI award "Academic industrial partnerships for studies of reservoir stipulations, drilling, transportation, emulsion stability, and foaming reactors," NSF/CTS 96100595, 05/01/97-04/30/00 for $341,084. We have also had two successive NSF HPCC Grand Challenge awards ESC-95-2713 10/01/95 to 09/30/98 and KDI /NCC award CIS-9873236, 9/15/98 to 8/31/01 that targeted the direct numerical simulation of solid-liquid flows. We rely on these simulations to achieve the goals of the projects proposed here. The simulation projects that are most relevant to this proposal are discussed in the next section and at places where they come up in this proposal. The other projects that were funded were:

(1) Pipeline transport of concentrated oil in water emulsions. A collaborative study with personnel from an industrial partner INTEVEP SA was carried out in Venezuela [22]. Different flow regimes were identified, depending on the size of the pipe and flow rate, suggesting lubrication in small pipes and fouling in large pipes with turbulent flow.

(2) Studies of suppression of foams in foaming bubble columns by fluidized particles. A new method [US Patents 5,922,190 and 5,922,191, described under Joseph's bio] for controlling the evolution of foams in foaming systems was developed in the Ph.D. work of two students from INTEVEP SA under GOALI. Foaming may be strongly suppressed by fluidizing hydrophobic particles in the bubbly mixture below the foam [23]. This suppression is achieved by increasing the liquid hold-up by bed expansion; by increasing the wetted solid surface (by adding particles); and by decreasing gas hold-up (by increasing the effective density of the mixture by weighting it with solids.) In Mata's [24] study we found that hydrophobic sands reduce the amount of foam more than hydrophilic sands because they actually break the existing foams whilst suppressing the formation of new foam.

In another type of foam study [25] we set up a flow cell [length,height,width] = [43",1",1.4"] to collect volume flow vs. pressure gradient data while monitoring flow regimes as a function of foam wetness. Lubricating regimes are typical for stable foams. When the gas input is too large the foam breaks under shear and the lubrication stops.

(3) The third project on self-lubricated transport of bitumen froth was brought to us by Syncrude Canada at a time when they were evaluating options for transporting bitumen froth from a newly opened Aurora mine 35 kilometers to the upgrading facility at Lake Mildred. Bitumen froth is a stable water in oil emulsion which is created from the oil sands by a steam process in which most of the dirt and stones are removed. It is extremely important that the natural water left in this emulsion is a colloidal dispersion of clay particles. We found that the clay particles are crucial to the success of the technology since they stick to the bitumen yet are hydrophilic, thus giving rise to a surfactant action that acts to keep the clay-covered bitumen from sticking to itself. After the water coalesces into a lubricating film under shear, the oil on the wall is protected from the buildup of fouling by the clay covering.

Very interesting fundamental problems came out of our NSF/Syncrude studies. We discovered a scale up law in which the friction factor vs. Reynolds number follows the Blasius turbulence relation in which the pressure gradient is proportional to the ratio of the $7/4^{th}$ power of the velocity to the $5/4^{th}$ power of the pipe radius at a cost of ten to 20 times greater than water alone. These results were shown to hold 1", 2" and 24" pipes in the paper by Joseph, Bai, Mata, Grant and Sury, "Self-lubricated transport of bitumen froth", *J. Fluid Mech.* **386**, pp 127-149 1999. Grant and Sury are from Syncrude. Sanders at Syncrude research in Edmonton confirmed the scale up law; together we developed a froth rheometer to determine critical stress for self-lubrication and we found that cement lined pipes promote self-lubrication of bitumen froth because the clay in the natural water promotes a strong wetting of cement by colloidal clay.

The Blasius scale up seems to be universal for lubricated flows in which the lubricating water layer is turbulent. The increased friction is apparently due to waves. The source of the increased friction is a topic of research because unlike roughness which increases the exponent from 7/4 toward 2, the increase of friction in lubricated flows does not change the exponent.

Based on our joint works with Syncrude people, Syncrude's management authorized a 76 million dollar investment for the construction of a 36" pipeline to run 35 kilometers from the Aurora mine to the upgrading facility at Lake Mildred. The engineering of this pipeline follows our scale up, since no tests were done in such a large pipeline. This line was put into operation in August of 2000; it is a total success and transports froth at a cost 6 times more than water alone, better than expected.

In their press release of August 17, 2000 titled, "**Syncrude's Aurora Mine Heralds New Era of Energy Production for Canada**, *New technology lowers cost and improves environmental performance*," they coin the words "natural froth lubricity":

> Long distance pipelining of bitumen froth is enabled by Natural Froth Lubricity. This technology uses the water that is naturally evident in the froth to form a lubricating 'sleeve,' thus allowing the froth to travel via pipeline without adding a diluent such as naphtha.

A letter of recognition of the importance of our contribution to the Aurora project appears at right.

Syncrude
Strategic Projects

September 27, 2000

Dr. Daniel D. Joseph
Dept. of Aerospace Engineering and Mechanics
University of Minnesota
110 Union Street
107 Akerman Hall
MINNEAPOLIS, MN 55455

Dear Dr. Joseph:

This letter is to recognize the excellent collaborative work between Syncrude and yourself at the University of Minnesota on bitumen froth pumping that has occurred over the last several years.

With the start-up of the Aurora mine project in July of this year Syncrude has introduced the new technology of long distance pumping of bitumen froth on a commercial scale using "Natural Froth Lubricity" without the need for added hydrocarbon diluent.

Your work at the laboratory scale and your presence at field trial work at Syncrude in 1996 contributed to our having sufficient confidence to move forward with this significant technology advancement for Syncrude and for the Oilsands Industry in Canada.

Our collaborative work has been published (1) and I enclose a recent presentation paper, which outlines the significance of this technology to Syncrude's growth plans and to the Oilsands Industry.

Thank you for your contribution to our latest success.

Yours truly,

SYNCRUDE CANADA LTD.

Derrick Kershaw

Derrick Kershaw
General Manager
Aurora Mine Project

(1) "Self-lubricated transport of bitumen froth"
By Daniel D. Joseph, Runyan Bai, Clara Mata, Ken Sury, Chris Grant
J. Fluid Mech. (1999), vol. 386, pp. 127-148. Copyright 1999 Cambridge University Press

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Syncrude Canada Ltd.
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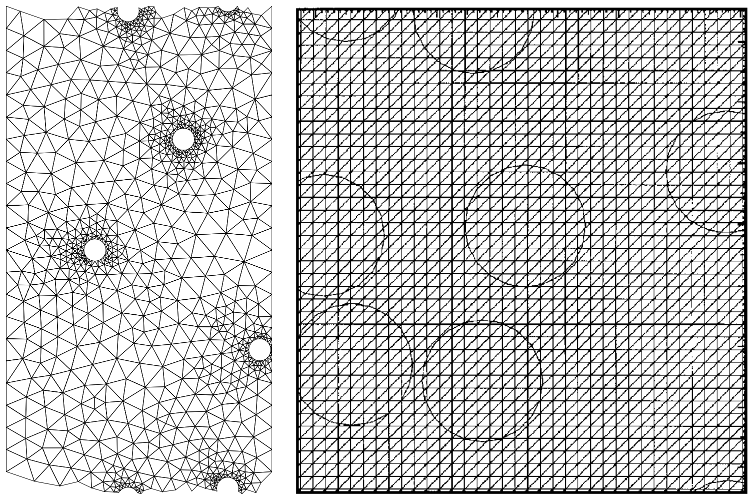
Recycled paper

Direct numerical simulation (DNS) of solid-liquid flow. The current popularity of computational fluid dynamics is rooted in the perception that information implicit in the equations of fluid motion can be extracted without approximation using direct numerical simulation (DNS). A similar potential for solid-liquid flows, and multiphase flows generally, has yet to be fully exploited, even though such flows are of crucial importance in a large number of industries.

We have taken a major step toward the realization of this potential by developing two highly efficient parallel finite-element codes called *particle movers* for the direct numerical simulation of the motions of large numbers of solid particles in flows of Newtonian and viscoelastic fluids. One of the *particle movers* is based on moving unstructured meshes (arbitrary Lagranian-Eulerian or ALE) and the other on a structured mesh (distributed Lagrange multiplier or DLM) using a new method involving a distribution of Lagrange multipliers to ensure that the regions of space occupied by solids are in a rigid motion (figure 1 below). Both methods use a new combined weak formulation in which the fluid and particle equations of motion are combined into a single weak equation of motion from which the hydrodynamic forces and torques on the particles have been eliminated. Several different kinds of code have been developed and tried on a variety of applications. See the project Web site, *http://aem.umn.edu/Solid-Liquid_Flows/*.

ALE Particle Mover. The ALE particle mover uses a generalization of the standard Galerkin finite-element method on an unstructured body-fitted mesh, together with an Arbitrary Lagrangian-Eulerian (ALE) moving mesh technique to deal with the movement of particles. In our implementation, the nodes on a particle surface are assumed to move with the particle. The movement of the nodes in the interior of the fluid is computed using a modified Laplace's equation, to ensure that they are smoothly distributed. At each time step, the grid is updated according to the motion of the particles. A new grid is generated whenever the elements of the mesh get too distorted, and the flow fields are projected onto the new grid.



(a) (b)

Figure 1. ALE body-fitted, unstructured grid (a) compared with the fixed triangular grid (b) used in the DLM particle mover in which the bodies are filled with fluid and constrained to move as a rigid body by a distribution of Lagrange multipliers. The Lagrange multiplier fields and the associated variational rigid body constraint are analogous to the pressure field and the associated variational constraint of incompressibility. The DLM is as useful as it is elegant; fast solvers can be used and run matrix-free on the fixed grid and the problems of remeshing, projection and so on which plague methods based on unstructured grids, like ALE, have been circumvented. On the other hand, the DLM grids are not locally adaptive and they may not be as flexible for applications in irregular domains.

DLM Particle Mover. The DLM particle mover uses a new Distributed-Lagrange-Multiplier-based fictitious-domain method. The basic idea is to imagine that fluid fills the space inside as well as outside the particle boundaries. The fluid-flow problem is then posed on a larger domain (the "fictitious domain"). This larger domain is simpler, allowing a simple regular mesh to be used. This in turn allows specialized fast solution techniques. The larger domain is also time-independent, so the same mesh can be used for the entire simulation, eliminating the need for repeated remeshing and projection. This is a great advantage, since for three-dimensional particulate flow the automatic generation of unstructured body-fitted meshes in the region outside a large number of closely spaced particles is a difficult problem. In addition, the entire computation is performed matrix-free, resulting in significant savings.

The velocity on each particle boundary must be constrained to match the rigid-body motion of the particle. In fact, in order to obtain a combined weak formulation with the hydrodynamic forces and torques eliminated, the velocity *inside* the particle boundary must also be a rigid-body motion. This constraint is enforced using a distributed Lagrange multiplier, which represents the additional body force per unit volume needed to maintain the rigid-body motion inside the particle boundary, much like the pressure in incompressible fluid flow whose gradient is the force required to maintain the constraint of incompressibility. DLM has been implemented [18] for viscoelastic fluids.

Prior Literature. This proposal is to process results of numerical simulations of particulate flow in log-log plots in a search for power laws. As far as we know, we are the only group of researchers to carry out this program; in fact, this approach has only evolved in the past year and our main papers have not yet appeared. There is no prior literature, other than that produced by us, in which power laws are obtained form numerical experiments. On the other hand, there are a number of numerical packages for particles in fluids that might be used in this way. The methods of Stokesian dynamics [27] can be recommended for problems in which inertia is absent. Hofler, Muller, Schwarzer and Wachmann [28] introduced two approximate ALE simulation methods for particles in fluids. In one method, the particle surface is discretetized in grid topology; spheres are polygons on flat places between nodes. In the second method a volume force term is introduced to emulate rigid body motions; this method is similar to the force coupling methods introduced by Maxey *et al* [29].

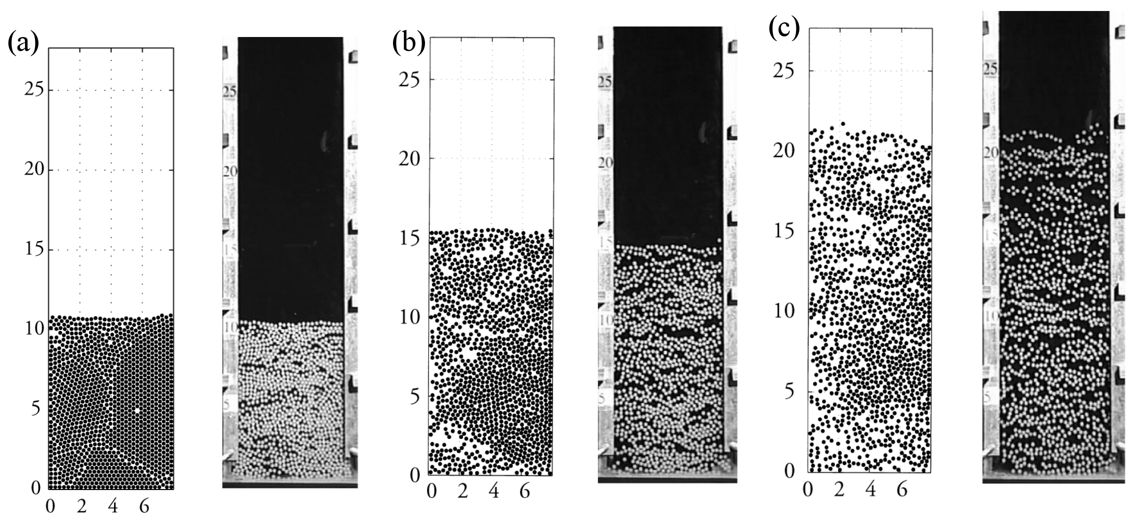
Hofler *et al* [28] calculated sedimentation of 65,000 spheres but at Reynolds numbers so small that it is essentially Stokes flow. Johnson and Tezduyar [30] used a fully resolved DNS/ALE method to compute sedimentation of 1,000 spheres at Reynolds numbers not larger than 10.

To our knowledge we are the only group to compute fully resolved particulate flow at Reynolds numbers in the thousands occurring in the applications. The problem of particulates in turbulent flows has been considered by a few authors [31,32,33]; these approaches use point particle approximations because fully resolved computations in turbulent flow are not presently possible.

Richardson and Zaki (RZ) correlations. The correlations of Richardson and Zaki [20,21] are an empirical foundation for fluidized bed practice. They did very many experiments with different liquids, gases, particles and fluidization velocities. They plotted their data in log-log plots; miraculously this data fell on straight lines whose slope and intercept could be determined. This showed that the variables follow power laws; a theoretical explanation for this outstanding result has not been proposed. After processing the data Richardson and Zaki found that

$$V(\phi) = V(0)\,(1-\phi)^n$$

where $V(\phi)$ is the composite velocity which is the volume flow rate divided by the cross-section area at the distributor when spheres of volume fraction f are fluidized by drag. $V(0)$ is the "blow out" velocity, when $\phi = 0$; when $V > V(0)$ all the particles are blown out of the bed. Clearly $V(\phi) < V(0)$. The Richardson-Zaki (RZ) exponent $n(R)$ depends on the Reynolds number $R = V(0)\, d/\nu$, in a complicated but prescribed way.



- V = 2 : Particle position at t = 5.625.
- The maximal particle Reynolds number is 1383.
- The maximal averaged particle Reynolds number is 130.

- V = 3.5 : Particle position at t = 17.238
- The maximal particle Reynolds number is 1671.
- The maximal avaraged particle Reynolds number is 236.

- V = 4.5 : Particle position at t = 31.
- The maximal particle Reynolds number is 1859.
- The maximal averaged particle Reynolds number is 292.

Figure 2. Snapshots of fluidization of 1204 spheres comparing experiment (right) and simulation (left) (a) V = 2, (b) V = 3.5, (c) V = 4.5.

Fluidization of 1204 spheres. Pan, Sarin, Joseph, Glowinski and Bai 2000 [20] have carried out DNS simulations of 1204 balls in a slit bed whose dimensions exactly match a real experiment. The simulation is compared with a matched real experiment and they give rise to essentially the same results (see figure 2). This simulation is presently at the frontier of DNS; it is a 3D computation of 1204 spheres at Reynolds numbers based on the sphere diameter of the order of 10^3 and the agreement with experiment is excellent. The details and animation of the computation [20] can be found at *http://www.aem.umn.edu/Solid-Liquid_Flows*.

The simulation of 1204 spheres was carried out in the bed [depth, width, height] = [0.686, 20.30, 70.22] cm. Snapshots comparing the animation with the experiment, in a frontal view are shown in figure 2. Figure 3 shows the rise curve vs. fluidizing velocity. Using all the data [20] we found from regression that

$$V(\phi) = V(0)\varepsilon^{n(R)} = 8.28^{2.33} \text{ cm}$$

The literature RZ value is 2.39 compared with our 2.33.

The computation shows that accurate direct simulation of real fluidized beds is possible and that the details of the particulate flow can be post processed and analyzed in ways not possible in real experiments. It shows that engineering correlations, here the RZ correlation, can be obtained from data generated from DNS.

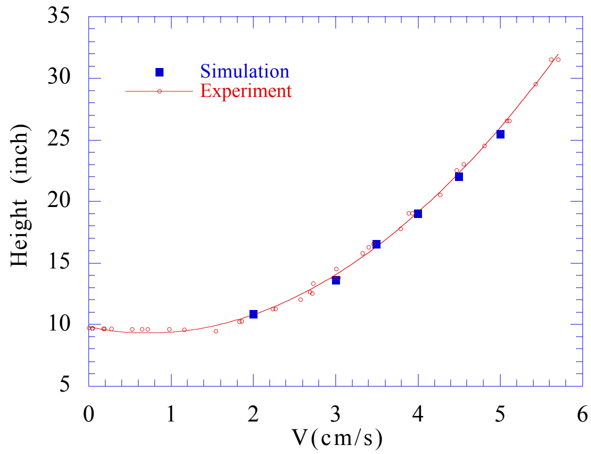


Figure 3. Final bed height H *vs. fluidizing velocity. The simulations give essentially the same height of rise as the experiments.*

Single particle lift off and levitation to equilibrium. The problem of lift off and levitation to equilibrium of a single circular particle in a plane Poiseuille flow was simulated using an ALE particle mover in [14]. The principal features of lift off and levitation to equilibrium are listed in the caption of figure 6. Heavier particles are harder to lift off. The critical lift off Reynolds number increases strongly with the density ratio (see table 1). The height, velocity and angular velocity of the particle at equilibrium is given as a function of prescribed parameters in tables and trajectories from lift-off to equilibrium in graphs shown in [14].

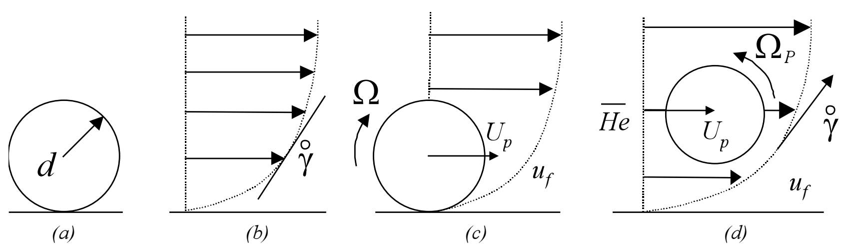


Figure 4. Lift off and levitation to equilibrium. The pressure gradient in the flow and on the particle is increased. The heavier than liquid particle slides and rolls on the bottom of the channel. At a critical speed the particle lifts off. It rises to a height in which the lift balances the buoyant weight. It moves forward without acceleration at a steady velocity and angular velocity.

The channel height is W, particle diameter d, density of fluid ρ_f and particle ρ_p, viscosity η, kinematic viscosity η/ρ_f. The equation of motion of fluid and particles made dimensionless with $[d, w, d/v, \eta\dot{\gamma}_w]$ where $\dot{\gamma}_w$ is the wall shear rate and $\overline{p}$ is the applied pressure gradient that drives the flow, are in the form

$$R\left[\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right] = -\nabla p + 2\frac{d}{w}\mathbf{e}_x + \nabla^2 \mathbf{u}, \qquad (1)$$

Solid

$$\frac{\rho_p}{\rho_f} R \frac{d\mathbf{U}}{dt} = -\frac{R_G}{R} e_y + 2\frac{d}{w}\mathbf{e}_x + \frac{4}{\pi}\int_0^{2\pi} (-p + 2\mathbf{D}[\mathbf{u}]) \cdot \mathbf{n}\, d\theta \qquad (2)$$

$$\frac{\rho_p}{\rho_f} R \frac{d\mathbf{U}}{dt} = -\frac{R_G}{R} e_y + 2\frac{d}{w}\mathbf{e}_x + \frac{4}{\pi}\int_0^{2\pi} (-p + 2\mathbf{D}[\mathbf{u}]) \cdot \mathbf{n}\, d\theta\,. \qquad (3)$$

The flow is determined by four dimensionless groups,

$$\frac{\rho_p}{\rho_f},\ \frac{2d}{w},\ R = \frac{\rho_f \overset{\circ}{\gamma}_w d^2}{\eta},\ R_G = \frac{\rho_f(\rho_p - \rho_f)gd^2}{\eta^2} \tag{4}$$

where R is the shear Reynolds number and R_G is a Reynolds number based on the sedimentation velocity in Stokes flow. The terms with the factor $\mathbf{e}_x$ come from the pressure gradient; the pressure gradient ($2d\mathbf{e}_x/w$ in (2)) drives the particle forward and the forward motion is resisted by the integral of the shear tractions.

Freely moving particles in steady flow have zero acceleration. The density ratio ρ_p/ρ_f vanishes when the particle accelerations are zero.

The critical value of the Reynolds number for lift-off increases with density of the particle from zero for neutrally buoyant $\rho_p = \rho_p$ circular particles to $R = 25$ for particles 1.4 times heavier than water $\rho_p = 1.4\,\rho_f$. After the particle lifts off it rises to an equilibrium height in which the buoyant weight equals the hydrodynamic lift. The equilibrium height for neutrally buoyant particles is called a "Segré-Silberberg" radius; it is determined by a balance of wall and shear gradient effects. The equilibrium height for heavy particles is lower than the Segré-Silberberg height. The rise to equilibrium is shown in figure 5.

DNS results given in [14] show that a circular particle will rise higher when the rotation of the particle is suppressed and least when the slip angular velocity is put to zero; the freely rotating zero torque case lies between. DNS allows such a comparison, which would be difficult or impossible to carry out in an experiment.

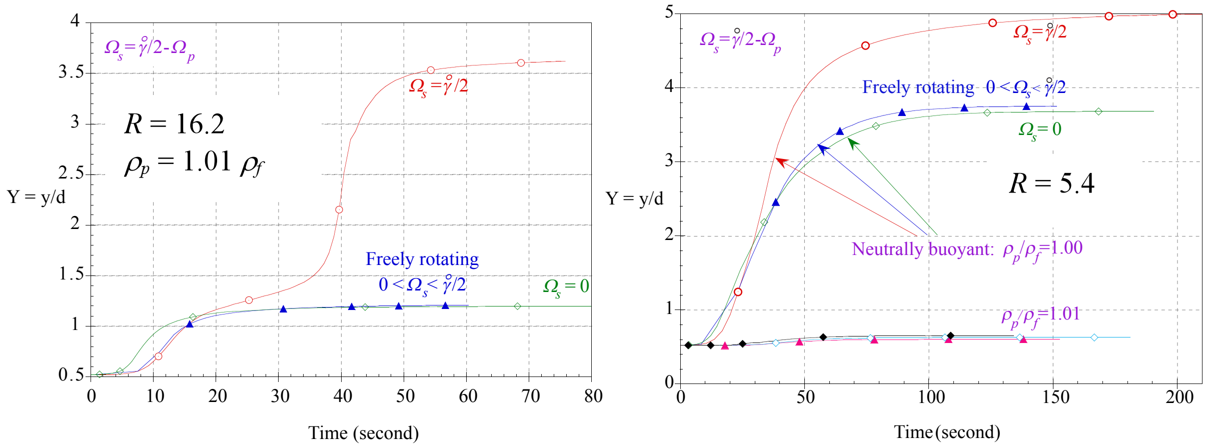


Figure 5. Rise vs. time for R_w = 16.2 and 5.4. Compare rise of freely rotating and nonrotating particles. Nonrotating ones rise more. A neutrally buoyant, freely rotating particle rises closer to the center line than the "Segré-Silberberg" experiment; the nonrotating one rises even more. Models which ignore particle rotation overestimate lift. A yet smaller lift is obtained when the slip velocity is entirely suppressed (Ω_s = 0), but the particle does rise. The greater the slip angular velocity, the higher the particle will rise.

Slip velocities, circulation and lift. In commercial packages for slurry flow in pipes, conduits and fractured oil and gas reservoirs, lift forces are not modeled, and in academic studies they are not modeled well. Possibly the best known and most used formula for lift is the Rayleigh Formula $L = \rho_f U\Gamma$ for aerodynamic lift. Here U is the forward velocity in still air that is produced by an external agent like a rocket engine, and Γ is the circulation, which is a complicated quantity determined by boundary layer separation. The lift on a free body in a shear flow is analogous and the lift formulas that have been proposed are in the form of U_s, the slip velocity, times $\rho_f \Gamma$, where Γ is a different quantity for different modelers. The slip velocity is the fluid velocity at the particle center when there is no particle minus the particle velocity. Since it is the fluid motion rather than an external agent which drives the motion of the particle, it might be expected that $U_s > 0$. Since free particles in shear flow migrate to an equilibrium radius, the associated Γ ought to change sign at this radius; in fact none of the lift formulas that have been proposed do change sign; if they are right at one side of the equilibrium they are wrong on the other. The slip angular velocity discrepancy defined as the difference between the slip angular velocity of a migrating particle and the slip angular velocity at its equilibrium position is positive below the position of equilibrium and negative above it. This discrepancy is the quantity that changes sign above and below the equilibrium position for neutrally buoyant particles, and also above and below the lower equilibrium position for heavy particles. On the other hand the slip velocity discrepancy U_s - U_{se} does not change sign [16].

Future work on slip velocities, correlations and lift

(1) Study the proposition that the lift on a circular particle in a plane Poiseuille flow is given by $CU_s\Gamma$ where $\Gamma = \Omega_s - \Omega_{se}$ is the slip angular velocity discrepancy and C is a to-be-determined function of particle radius, fluid viscosity and density. We propose to determine C by numerical simulation.

(2) Repeat the analysis of the effects on the lateral migration of circular particles in 2D of the slip and angular slip velocity for spheres in 3D.

(3) Test the hypothesis that the direction of lateral migration of circular particles is controlled by the sign of angular velocity discrepancy in the case of plane Couette flow and general flows with shear gradients.

(4) Test the hypothesis that the direction of lateral migration of circular particles in a slurry follow the same migration rules qualitatively as single particles.

(5) Attempt to formulate rules governing lateral migration and lift based on the analysis of slip and angular slip that can be implemented in continuum models used in commercial proppant transport models.

Model of slip velocity. A long particle model was proposed in [16] which leads to an explicit expression for the particle velocity U_p of a circular particle in a Poiseuille flow. Referring to figure 6 we find that

$$U_A = \phi + \psi h_A d, \quad U_B = \phi + \psi h_B d \tag{6}$$

where

$$\phi = \frac{\bar{b}}{\eta}(2d + h_A + h_B)h_A h_B / 2(h_A + h_B)$$

$$\psi = \mathring{\gamma}(h_B + d/2)\big/2(h_A + h_B)$$

and the particle velocity U_p is given by

$$U_p = \mathring{\gamma}\ (U_A + U_B)/2.$$

The slip velocity U_s is given by

$$U_s = \frac{\bar{p}}{2\eta}\left(h_B + \frac{d}{2}\right)\left(h_A + \frac{d}{2}\right) - U_p > 0 \quad \text{and} \quad U_s = 0 \quad \text{when} \quad d = 0. \tag{7}$$

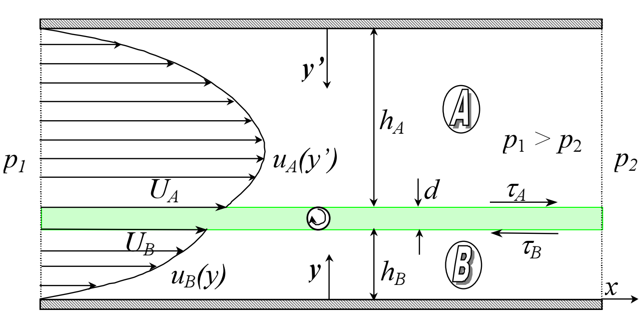


Figure 6. The circular particle is replaced with a long rectangle where short side is d. The rectangle is so long that we may neglect the effects of the ends of the rectangle at sections near the rectangle's center. The rectangle is sheared at the shear rate of the circular particle $\Omega_p \cong \dot{\gamma}/2$ (see figure 5). The velocity profile is Poiseuille flow on either side of the particle and U_A and U_B determined by requiring that the pressure gradient $\bar{p}$ balance the shear stress.

A comparison of the velocity profile of the long particle model with the velocity profile through the center of the circular particle computed by direct numerical simulation is given in figure 7. Such a good agreement is surprising.

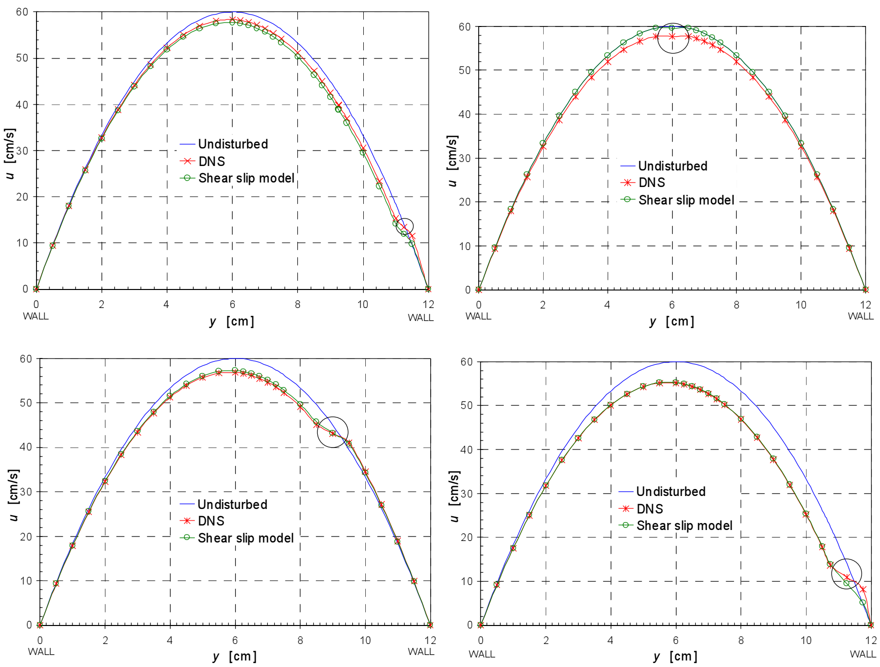


Figure 7. Comparison of the velocity profiles (figure 6.) for the long particle model with the velocity profile on a line through the circular particle center computed by DNS for constrained motion at R = *20. In a constrained motion the* y *position of the particle is fixed, lateral motion is suppressed, but the particle is otherwise free to translate and rotate under the action of the hydrodynamic forces and torques.*

Future work on long particle models. Explicit approximations of particle velocity and slip velocity in shear flows ought to have applications in the modeling of flows of particulates. Such models can be created for Poiseuille, Couette, combined Poiseuille-Couette flows, and possibly for general shear flows in 2D and 3D. The application of such approximations to the flow of slurries is not so direct since our understanding of hindered motions is as yet incomplete. Further studies of long particle models in other shear flows to slurry flows and extensions to 3D are proposed for further study.

Bifurcation. A turning point bifurcation of steady forward flow of a single particle at equilibrium was found in direct simulations of rise trajectories reported in [12]; the height and particle velocity change strongly at such a point. A computational method advanced in [14] looks for the points on lift vs. height curve at which lift balances buoyant weight. This gives both stable and unstable solutions and leads to the "bifurcation" diagram shown in figure 8, which shows there are two turning points, hysteresis, but no new branch points.

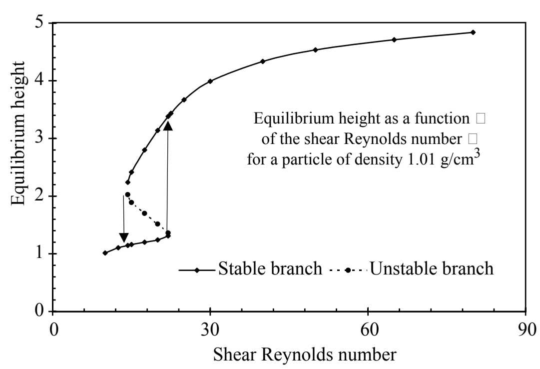


Figure 8. Turning point "bifurcations" shown in the height vs. Reynolds number curve. There are two stable branches separated by an unstable branch.

Similar turning point bifurcations have been found also in computations of levitation to equilibrium of viscoelastic fluids of Oldroyd-B type. Similar instabilities have been found at yet higher Reynolds numbers. Bifurcations of sedimenting particles, including Hopf bifurcations to periodic motions, have been reported in the literature. It is probable that all the phenomena known for general dynamic systems occur also for particulate flows.

Future work on bifurcations of slurry flows. Though many directions for study might be taken, we are most interested in the implications of instability and bifurcation of single particles for the flow of many particles. The problems we propose to study are:

(1) Compute the bifurcations of single spherical particles (3D) in a channel and then in a pipe. There is no reported evidence of bifurcations of the type so far computed in the flow of single particles in pipes; no sudden change in the Segré-Silberberg radius.

(2) Study the instability and bifurcations of two singular circular particles to determine whether and how such instabilities might appear in the case of Poiseuille flow of three and many particles.

Levitation to equilibrium of 300 circular particles. The transport of a slurry of 300 heavier than liquid particles in a plane pressure driven flow was studied using DNS in [12]. Time histories of fluidization of the particles for three viscous fluids with viscosities η = 1, 0.2 and 0.01 (water) were computed at different pressure gradients. The study leads to the concept of fluidization by lift in which all the particles are suspended by lift forces against gravity perpendicular to the flow.

The time history of the rise of the mean height of particles at a given pressure gradient is monitored and the rise eventually levels off when the bed is fully inflated. The time taken for full inflation decreases as the pressure gradient (or shear Reynolds number) increases (see figure 9). At early times, particles are wedged out of the top layer by high pressure at the front and low pressure at the back of the particle in the top row (t = 1 in figure 9a, t = 0.9 in figure 9b).

The dynamic pressure at early times basically balances the weight of the particles in the rows defining the initial cubic array. This vertical stratification evolves into a horizontally stratified propagating wave of pressure, which tracks waves of volume fraction. The pressure wave is strongly involved in the lifting of particles. For low viscosity fluids like water where R_G is large the particle-laden region supports an "interfacial" wave corresponding to the wave of pressure. If R^2/R_G is large the interface collapses since the stronger lift forces push wave crests into the top of the channel, but the pressure waves persist (figure 10).

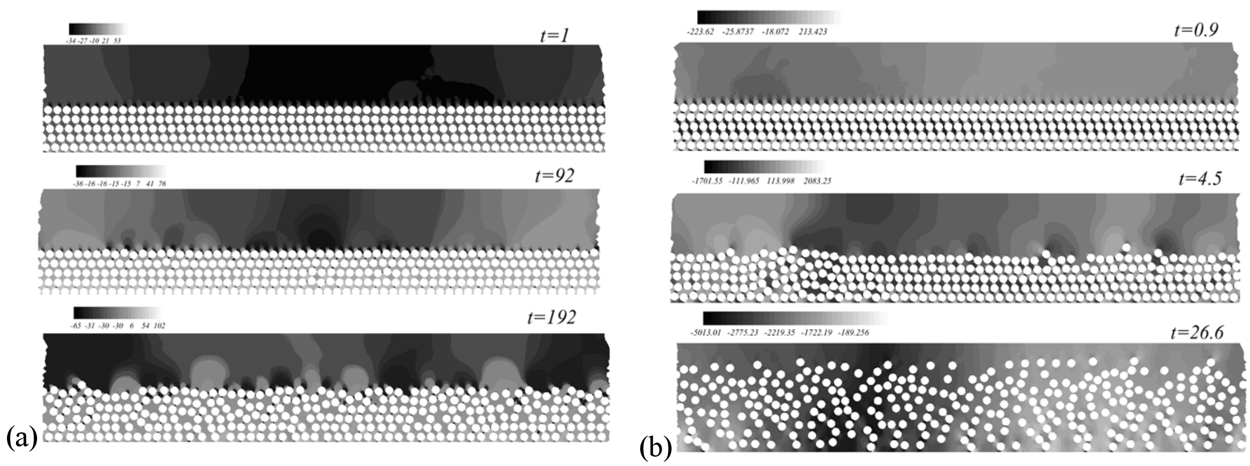


*Figure 9. (a) Snapshots of the fluidization of lift of 300 circular particles ρ_p = 1.01 g/cm^3 when η = 1 poise (*R *= 5.4,* R^2/R_G *= 1.82). The flow is from left to right. The gray scale gives the pressure intensity and dark is for low pressure. At early times particles are wedged out of the top layer by high pressure at the front and low pressure at the back of each and every circle in the top row. The vertical stratification of pressure at early times develops into a "periodic" horizontal stratification, a propagating pressure wave. The final inflated bed has eroded, rather tightly packed at the bottom with fluidized particles at the top. (b) Fluidization of 300 particles (*R *= 120,* R^2/R_G *= 0.08). The conditions are the same as in 9(a) but the ratio of lift to buoyant weight is greater and the fluidization is faster and the particle mass center rises higher than in the previous figures.*

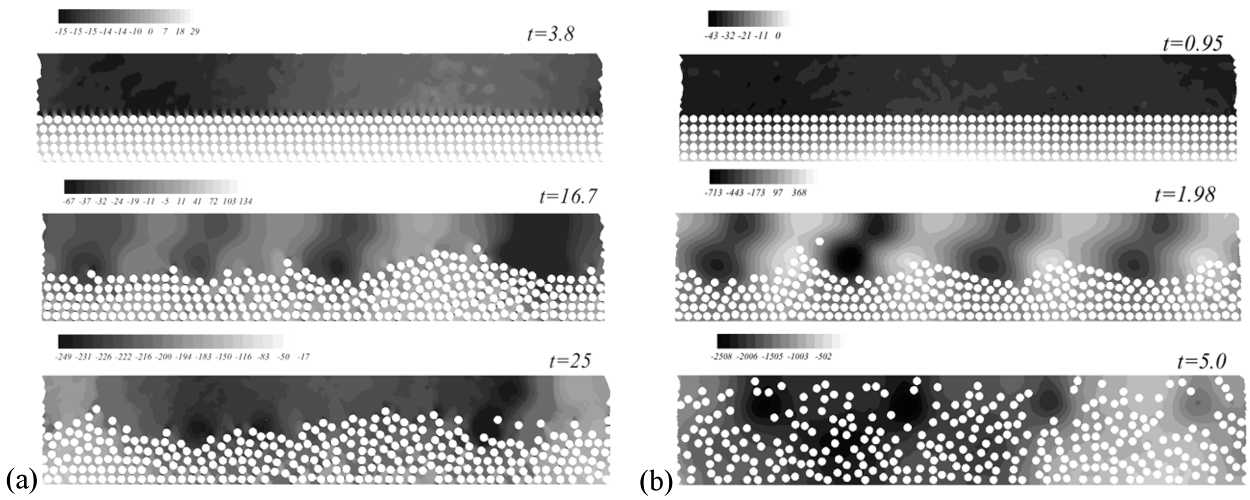


Figure 10. (a) Fluidization of 300 particles (η = 0.2 poise, R *= 150,* R^2/R_G *= 1.63). The final state of the fluidization at* t *= 25 sec has not fully eroded. The particles that lift out of the bed can be described as saltating. A propagating "interfacial" wave is associated with the propagating pressure wave at* t *= 25. (b). Fluidization of 300 particles (η = 0.2 poise,* R *= 450,* R^2/R_G *=0.54). The flow is from left to right. The particles can be lifted to the top of the channel.*

Correlations are expressions relating variables that are derived from experiments; RZ correlations for fluidization and sedimentation are well known. The correlations are obtained from experiments by plotting data in log-log plots. These come up as straight lines when the underlying physics admits power laws. It is remarkable how well this works.

The processing of the data from the simulation of fluidization of 1204 spheres [20], which was validated by experiment, gave rise to a correlation for the fluidizing velocity as a function of the solids fraction ϕ

$$V(\phi) = 8.28\,(1 - \phi)^{2.33} \text{ cm/s.}$$

The value of the power from the RZ correlation is 2.39 compared to our 2.33. This computation shows that accurate direct simulation of real fluidized beds is possible and that the details of the particulate flow can be post-processed and analyzed in ways not possible in real experiments. It also shows that engineering correlations, here the RZ correlation, can be obtained from data generated from DNS.

We did correlations in numerical experiments in 2D. Correlations work. We studied the levitation of 300 particles in a Poiseuille flow [10,12] and created a data bank which when plotted on a log-log plot give rise to straight lines; this is to say that lift results for fluidized slurries are power laws in appropriate dimensionless parameters. This shows that fluidization of slurries by lift also falls into enabling correlations of the RZ type. The method of correlations is a link between direct simulation and engineering application.

Correlations allow generalizations from 20 or 30 data points into a continuum of points reaching even beyond where we can compute. Because you get so much from correlations even expensive calculations are cheap.

The correlation we found for lift-off of a single particle is in the form

$$R_G = aR^n, \quad a = 2.36, \qquad n = 1.39 \tag{8}$$

where R and R_G are defined by (4); a and n are obtained by plotting about 25 data points in a log R vs. log R_G plane ([14], figure 11). The straight lines that come out are amazing; they show that self-similarity lies at the foundation of solid-liquid flows. Similar correlations were found for lift-off in viscoelastic fluids [11,14].

For 300 particles in Poiseuille flow we processed simulation data for the rise of the center of gravity of particles in the slurry; from the height rise we can compute the solid fraction ϕ. Processing data in log-log plots (figure 12) we got

$$R_G = 3.27 \times 10^{-4}\,(1-\phi)^{-9.05}\,R^{1.249} \tag{9}$$

This could be called a Richardson-Zaki type of correlation for fluidization by lift [10].

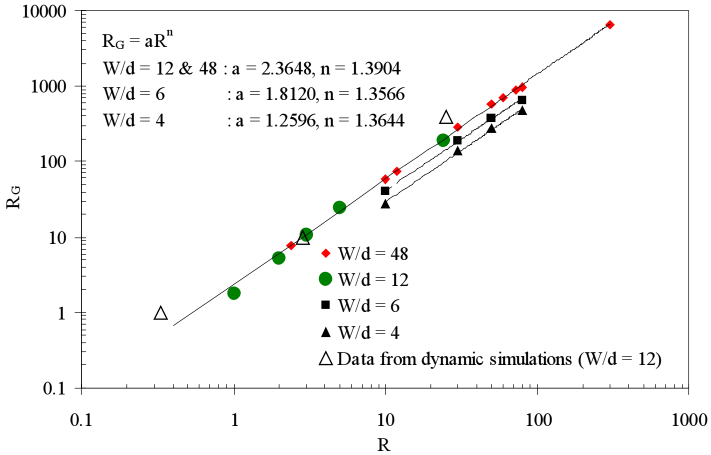


Figure 11. The plot of R_G *vs. the critical shear Reynolds number* R *for lift-off on a logarithmic scale at different values of* W/d.

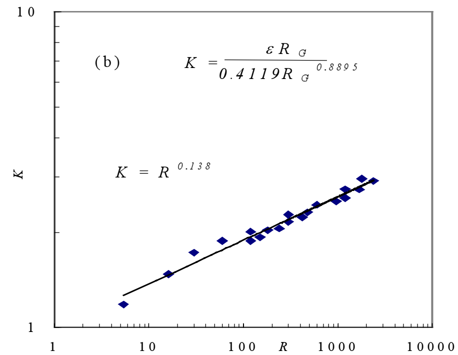


*Figure 12. An engineering correlation (9) for lift-off from numerical simulations of 300 circular particles in plane Poiseuille flows of Newtonian fluids (*W/d *= 12).*

Future work on correlations. We probably have seen only a hint of what can be done by processing simulations in log-log plots. Some possible ways to learn more are to create correlations for functionals of the solutions like particle velocities and angular velocities, slip velocities and other quantities.

The main goal is to carry out simulations in 3D, just like those in 2D, which can be processed for correlations that can be validated against real experiments.

We are especially interested in deriving and formatting correlations for applications in industry. Correlations for Newtonian, shear thinning and viscoelastic fluids could, for example, be created for applications in drill cutting, removal and sand transport in fractured oil and gas reservoirs.

Sand transport in fractured reservoirs. The problem of transport of particles by fluids in horizontal conduits and pipes is of considerable scientific and industrial importance and is the focus of this paper. This problem arises in the transport of coal-water slurries, in the removal of drill cuttings in drilling of horizontal oil wells and in proppant transport in hydraulically fractured rock in oil and gas bearing reservoirs, to name a few. The central unsolved fluid dynamics problem arising in these applications is the problem of fluidization by lift. The problem of fluidization by lift can be well framed in the problem of hydraulic fracturing.

Hydraulic fracturing is a process often used to increase the productivity of a hydrocarbon well. A slurry of sand in a 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 well bore far into the pay zone. When the pumping pressure is removed, the sand acts to prop the fracture open. Productivity is enhanced because the sand-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 be a continuous sand-filled path from great distances in the reservoir to the well, and that the sand is placed within productive, rather than non-productive, formations.

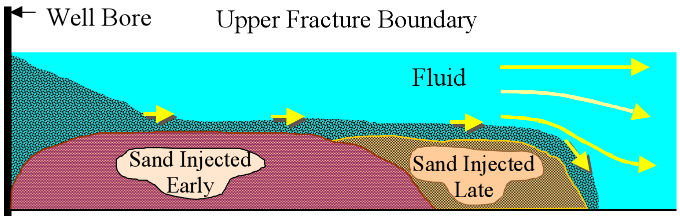


Figure 13. Sand transport in a fractured reservoir [26] is different than the eroded bed of 300 particles in figure 9(a) and 10(a) because particles are injected. The creation of algorithms to simulate continuous injection is one of our simulation projects.

In a slot problem a particle laden (say 20% solids) fluid is driven by a pressure gradient and the particles settle to the bottom as they are dragged forward. Sand deposits on the bottom of the slot; a mound of sand develops and grows until the gap between the top of the slot and the mound of sand reaches an equilibrium value; this value is associated with a critical velocity. The velocity in the gap between the mound and the top of the slot increases as the gap above the mound decreases. For velocities below critical the mound gets higher and spreads laterally; for larger velocities sand will be washed out until the equilibrium height and velocity are reestablished (see figure 13). The physical processes mentioned here are *settling* and *washout*. Washout could be by sliding and slipping; however, a more efficient transport mechanism is by *advection after suspension* which we studied by direct simulation.

The fracturing industry makes extensive use of models and correlations programmed for PCs to guide field operations. These models are developed to predict how the fracture crack opens and closes and how proppant is transported in the crack. Commercial packages dealing with these problems and proprietary packages developed by oil service companies are used extensively. None of these packages model the all-important levitation of proppants by hydrodynamic lift.

STIMLAB. Despite many years of practice and experiments many of the most essential fluid dynamic properties of proppant transport, other than fluidization by lift are not well understood. To help our studies of these properties focused and practical, we have partnered with 11 companies that support research on ways to stimulate the production of oil and gas from fractured reservoirs. These companies form a consortium, which funds a research laboratory (STIMLAB) in Duncan, OK. The participating companies are:

Aqualon Company	*Baker*	*Halliburton Energy Services*	*OSCA Shell*
BJ Services	*Dowell Schlumberger*	*KELCO*	*Texaco*
BP Amoco	*Gas Research Institute*	*Marathon Oil Company*	

The collaboration between this consortium and our multidisciplinary team is through STIMLAB. The consortium funds STIMLAB and STIMLAB funds us.

STIMLAB does experiments. They have laboratories in Duncan, OK and Edinburgh, Scotland and sales offices in many cities worldwide. They were recently absorbed by a bigger company, Core Laboratories, but they continue to operate independently. They have been collecting data on sand transport in large and small slots for fifteen years. They have a huge data bank, ripe for exploitation, which can be used for modeling and simulation. The interest of the consortium and STIMLAB in our work has drifted from experiments, which they can do themselves to simulation, which they cannot do.

Proppant transport model. The simulations of slurry flow we have done so far are set in a periodically extended channel in which the number of particles in each periodic cell is fixed. This model is not a faithful image of the proppant transport experiments that have been done over the years at STIMLAB; in all cases though it may be used to approximate steady transport of solids in liquid across the cell (see figure 13). To process our numerical experiments and their real experiments for correlations in the general case, we must compute with a model that is closer to what is observed and measured.

Typical experiments in STIMLAB are done in a fixed rectangular cell, [width,length,height] = [5/16",8',1'], [5/16",16',4'] and [5/16",6',6'].The nominal size of particles is 1mm and density 2.65 g/cc. Fluid and particles are injected through ports and ejected at an open exit without ports. Since the particles are heavy, they settle as they move forward and the state of fluidization is determined by a balance between buoyant weight and lift. Of course proppant sand particles are not round although round particles are often used in experiments.

It is not hard to pose numerical simulation problems that mimic the experiments. We would use the particle diameter as a dimensionless length and then scale the channel dimensions in terms of this length. The width of these channels is most important because the frictional resistance of close walls is greatest. On the other hand it is the shear rates in the height dimension that are most relevant for lift. The numerical model that we are proposing for comparative study with experimental is an initial value problem in which the flow in the cell is suddenly started by prescribing a distribution of flow rate of particle and fluid at its extremes; thereafter the injection rates are held constant. After a transient evolution to steady state a solids "hold up" and a distribution of particles in various states of fluidization emerge as a steady state. At steady state there is no further accumulation of particles; the ejection rates equal the injection rates.

The evolution of the proppant bed in the experiments is well described in the diagram of figure 13 with the caveat that experimental cell has a finite length. In the steady state there is an initial development length followed by a flat bed that is divided into zones shown in figure 14. The bottom of the bed is immobile, it is a stationary porous media that supports liquid throughput that might be modeled by Darcy's law. Above the immobile bed is a mobile bed in which particle slide and roll but do not lift. The traction carpet is a fully fluidized bed in which particles move forward in free motion under a balance of buoyant weight and lift. The lift off region lies between the stationary and fluidized bed.

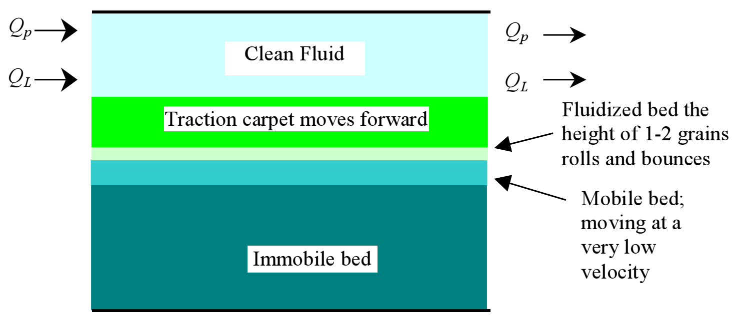


Figure 14. Proppant transport in thin fluid at steady state conditions.

In steady state the injection rates for solids and liquids is the same as the ejection rate; the number of particles in the cell does not change. If the flow development region at the entrance of the cell is neglected so that the mean height is flat and constant, then a periodic extension could be appropriate and lead to useful correlation. In fact periodically extended beds with properties similar to those just described are shown in figure 8a and 9a.

Possibly the greatest impediment to good simulation processing of the periodic model of the bed in figure 6 is the security zone we use to keep the particles from touching and from close packing. Close packing should immobilize the bottom parts of the bed as in the experiments.

Collisions. The statement that DNS fully resolves the solid-liquid flow should be qualified to say resolved up to the treatment of collisions. We prevent collisions by invoking a force in a security zone to force nearly-touching particles apart. This force does not belong to the problem's description; it is invoked to keep the particles apart. Smooth particles should not collide, there is always a liquid film if we do not provide for film rupture, and the repulsive lubrication forces get larger and larger as the film gets smaller.

Fortunately the artificial repulsive force does not seem to have a big effect on the global motion. We have tested this by doing simulations with different sizes for the security zone and if this zone is small the simulations are insensitive to large changes in the small size of the zone. Another way to test this is by comparing the simulation with an exact solution in the case in which a sphere falls against a wall under gravity. The numerical method could possibly solve the lubrication force properly within a measure of coarseness of the mesh.

The implementation of a security zone has the unfortunate consequence that particles cannot close pack. Though this does not seem to effect fluidized flows greatly, we must be able to generate close packing if we are to model the immobile part of beds of slurries of particles such as occur when proppants are injected into a fractured reservoir.

We may consider putting the security zone where we activate artificial forces to push the particle apart inside the particle; we would allow particles to overlap and only introduce artificial forces in the artificial overlap situation. When the particles are close, but not overlapping, only hydrodynamic forces will act. This strategy, unlike the ones we use now, will allow particles at rest to close pack, to touch.

Glowinski's group at Houston is looking at another approach based on adapting the Kuhn-Tucker multiplier based methods, which are used in the treatment of unilateral constraints encountered in contact problems to the treatment of collisions. In effect, with this method one can reduce the size of the security zone to zero.

Processing of experimental data. It is probable that progress toward obtaining correlations can be obtained from STIMLAB's data bank even before solving the problem of the immobile bed. The top of this bed could be regarded as defining the border of a fluidized slurry and a fixed porous bed. The fluidized slurry above the fixed bed could then be treated by the method of correlations. STIMLAB's data bank has not yet been expressed in terms of the underlying dimensionless parameters but if $\dot{\gamma}_w d$ is replaced by a typical velocity V, then $R = Vd/\nu$ and R_G may be readily obtained. We would then seek power laws from plots of log R vs. log R_G for a fixed volume fraction. This method of processing data from proppant transport experiments has not been tried before and apparently it has not been tried for any other experiment on slurry transport in horizontal conduits.

We believe that research leading to optimal techniques of processing data for correlations from real and numerical experiments is founded on the far from obvious property of self similarity (power laws) in the flow of dispersions. The bases for this belief are the excellent correlations of experiments on fluidization and sedimentation done by Richardson and Zaki and the correlations for lifting of slurries in horizontal conduits obtained form numerical experiments described here. The method of correlations is a new link between DNS and engineering practice.

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E. Biographical sketch

a. Vitae

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US Patent 5,988,198, Process for pumping bitumen froth through a pipeline, 1999, O. Nieman, K. Sury, D.D. Joseph, R. Bai, C. Grant.

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G.I. Taylor Lecturer, Cambridge Phil. Soc., Jan 1992
Aris Phillips Lecturer, Yale University, April 1992
American Academy of Arts and Sciences, April 1993
Schlumberger Foundation Award, July 1993
Bingham Medalist of the Society of Rheology, Oct 1993
Croco Lecturer, Princeton University, Mechanical Engineering, Oct 1995
Fellow of the American Physical Society, Nov 1993
Thomas Baron Fluid-Particle Systems Award of the AIChE and Shell, 1996
Timoshenko Medalist of the ASME, May 1995
Illinois Institute of Technology Professional Achievement Award 1997
Fluid Dynamics Prize of the APS, Nov 1999
University of Illinois Professional Achievement Award 1999
Kovasznay Lecturer, University of Houston, Mechanical Engineering, April 1999
Professional Achievement Citation of the University of Chicago, June 1999

Selected Publications
The papers most relevant to this project are recent and not yet published; they are listed with a ♦ under references and may be downloaded from our web page *http://www.aem.umn.edu/Solid-Liquid_Flows/references.html*. The five papers below are relevant and also have been published.

b. Five papers closely related to the proposed project

1. P.Y. Huang, H. Hu, D.D. Joseph 1998.
Direct simulation of the sedimentation of elliptic particles in Oldroyd-B Fluids, *J. Fluid Mech.*, **362**, 297-326.

2. P. Glowinski, T. Pan, T. Hesla, D.D. Joseph 1998.
A Distributed Lagrange Multiplier fictitious-domain method for flow, *Int. J. Multiphase Flow,* **91**, 165-188.

3. P. Singh, D.D. Joseph 2000.
Sedimentation of a sphere near a vertical wall in an Oldroyd-B fluid, *J. Non-Newtonian Fluid Mech.* **94**, 179-203.

4. N. Patankar, P. Singh, D.D. Joseph, R. Glowinski, T.W. Pan 2000.
A new formulation of distributed Lagrange multiplier/fictitious domain method for particulate flows, *Int. J. Multiphase Flow*, **26**, 1509-1524.

5. D.D. Joseph, P.Y. Huang 2000.
Effects of shear thinning on migration of neutrally buoyant particles in pressure driven flow of Newtonian and viscoelastic fluids, *Journal of Non-Newtonian Fluid Mechanic*s, **90,** 159-185.

Five other publications

1. D.D. Joseph and Y. Renardy 1992. *Fundamentals of Two-Fluid Dynamics,* Vol. I: Mathematical Theory and Applications, Vol. II: Lubricated Transport, Drops and Miscible Liquids, Springer Interdisciplinary Applied Mathematics Volumes 3 and 4.

2. D.D. Joseph, L. Preziosi, 1989. Heat waves, *Reviews of Modern Physics* **61**, 41–73.

3. D.D. Joseph, T. Liao, March 1994. Potential flows of viscous and viscoelastic fluids, *J. Fluid Mech.* **265**, 1-23.

4. D.D. Joseph, 1998. Cavitation and the state of stress in a flowing liquid, *J. Fluid Mech.,* **366**, 367-378.

5. D.D. Joseph, J. Belanger, G.S. Beavers, 1999. Breakup of a liquid drop suddenly exposed to a high-speed airstream, *Int. J. Multiphase Flow* **25**, 1263-1303.

Synergetic Activities

Professor Joseph's career has focused on knowledge creation but possibly he has stressed more than some others the integration of the pieces to present a conceptual structure integrating knowledge. This kind of scholarly activity has been well acknowledged by his peers with many honors and awards including election to all relevant academies, medals and prizes from engineering and physics communities. The main service component of Joseph's career has been as an editorial responsibility for about a dozen mathematical journals. Possibly the most important aspect of the transfer of knowledge in Joseph's work is the transfer to industrial applications. Joseph has consulted with many firms especially in the oil industry. The work with Syncrude Canada on self-lubrication of bitumen froth led to the construction of a 36" pipeline of 30 km from the Aurora mine to the upgrading station at Lake Mildred. This pipeline cost $70M; it is in service and runs well. The present research is also dedicated to synergies, this time between direct numerical simulation to problems of proppant transport that arise in oil and gas reservoir engineering.

c. List of Collaborators

G. Beavers (Univ. Minnesota)
H. Choi (Seoul National Univ.)
T. Funada (Numazu College of Technology, Ooka, Japan)
R. Glowinski (Univ. Houston)
C. Grant (Syncrude, Canada)
J. Guittian (Intevep S.A.)
T. Hesla (Univ. Minnesota)
H. Hu (Univ. Pennsylvania)
P. Huang (Univ. Minnesota)
T. Ko (Univ. Minnesota)
T. Lundgren (Univ. Minnesota)
C. Mata (Intevep S.A.)
G. McGrath (Intevep S.A.)
G. Núñez (Intevep S.A.)
T.-W. Pan (Univ. Houston)
A. Pereira (Intevep S.A.)
V. Sarin (Texas A&M)
P. Singh (New Jersey Inst. Tech.)
K. Sury (Imperial Oil, Canada)

d. List of Postdoctoral scholars & students

Postdoctoral scholars

H. Choi (Seoul National Univ.)
N. Patankar (Northwestern Univ.)
P. Huang (Univ. Minnesota)

Ph.D. Students since 1995

Geraldo Ribeiro 1995
Jungtav Feng 1996
Runyan Bai 1996
Yaoqi Lui 1996
Jose Guiltian Lopez 1996
Peter Huang 1997
Harry Vinagre1998
Clara Mata 1998