

DOE PROGRESS REPORT

“Lubricated Transport of Viscous Materials”

Daniel D. Joseph, P.I.

June 1997

Since last year's report we completed the first direct numerical simulation of axisymmetric core flow. We showed that the pressure at the front of the wave is large (the fluid enters a converging region) and it pushes the interface in, steepening the wave at its front. At the backside of the wave, behind the crest, the pressure is low (diverging flow) and it pulls the interface to the wall, smoothing the backside of the wave. The steepening of the wave can be regarded as a shock up by inertia and it shows that dynamics works against the formation of long waves which are often assumed but not justified in the analysis of such problems. We showed that the steep wave persists even as the gap between the core and the wall decreases to zero. The wave length also decreases in proportion, so that the wave shape is preserved in this limit. This leads to the first mathematical solution giving rise sharkskin. The analysis also showed that there is a threshold Reynolds number below which the total force reckoned relative to a zero at the wave crest 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. This work is reported in the paper by Bai, Kelkar and Joseph, “Direct simulation of interfacial waves in a high viscosity ratio axisymmetric core flow,” *Journal of Fluid Mechanics*, **327**, 1-34 (1996).

Our work on lubricated pipelining, core-annular flow, has achieved the status of a recognized topic of fluid mechanics which is defined in the invited review paper by Joseph, Bai, Chen and Renardy, “Core-Annular flow”, *Annual Review of Fluid Mechanics*, **29**, 65-90 (1997).

The most important results obtained since our last report comes from work which we did for Syncrude Canada Ltd on the self-lubrication of bitumen froth. This work was funded by Syncrude, and the funding has been renewed, but it falls squarely in the domain of the DOE grant and we are going to continue the work. Syncrude built a 24" \times 1 km pilot pipeline to check our results. Their results showed the same trend and from their data I found a scale-up law which is presently proprietary because of patents, but will be released soon. Syncrudes' management has taken the

decision to build a 35 km large diameter pipeline from the Aurora mine to lake Mildred, at a cost of 200 million dollars based on this work.

We are continuing our studies of self-lubrication of bitumen froth. For a given froth and froth temperature we want to determine all of the flow regimes, holdup ratios, wave forms and pressure gradients as a function of froth input. The working hypothesis of self-lubrication is that water is released at a critical shear stress. This implies that there is a critical shear rate for a given froth and this shear rate prevails in the produced water used for lubrication so that for all conditions of lubricated transport U/L is a constant, where U is the superficial velocity of the froth and L is the thickness of the lubrication layer. This idea is being tested.

We have proposed a new mechanism for the stabiliation of annular gas liquid flows based on our DOE studies of lubricated pipeline. The idea is that annular flow stabilizes when the gas core gets more viscous than the water outside, due to turbulent eddy viscosity in the gas. The criterion that comes out of this is in excellent agreement with experimental observation. The paper “Stability of Annular Flow and Slugging” by Joseph, Bannwart and Liu will appear in the *International Journal of Multiphase Flow*.

During the last reporting period Joseph received two awards.

- (1) Timoshenko Medalist of the ASME,
- (2) Thomas Baron Fluid-Particle Systems Award of the AIChE and Shell.
(Nov. 1996)

Papers acknowledging DOE support which were written or appeared in the years 1995 - 1996 are listed bellow. Numbers 233, 236, 237, 238, 243 and 244 are the ones most relevant to the two phase lubricated flow problem for which we are funded.

220. “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).
221. “Stability of eccentric core-annular flow” (with A. Huang). *J. Fluid Mech.* **282**, 233-245 (1995).
222. “Dynamic simulation of the motion of capsules in pipelines” (with J. Feng). *J. Fluid Mech.* **286**, 201-207 (1995).
223. “Dynamics of fluidized suspensions of spheres of finite size” (with P. Singh). *International Journal of Multiphase Flow* **21**, 1-26 (1995).
224. “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).
225. “The negative wake in a second order fluid” (with J. Feng). *J. Non-Newtonian Fluids* **57**, 313-320 (1995).
226. “A Maxwell memory model for the delayed weather reponse to solar heating” (with K.R. Sreenivasan). Submitted to *Proc. Roy. Soc. A* (1995).

227. "Boundary layer flow of air over water on flat plate" (with J. Nelson and A. Alving). *J. Fluid Mech.* **284**, 159-169 (1995).
228. "Cavitation in a flowing liquid." *Physical Review E* **51**(3), R1649 (1995).
229. "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.
230. "Two-dimensional cusp at the trailing edge of an air bubble rising in a viscoelastic liquid" (with Y.J. Liu and T.Y. Liao). *J. Fluid Mech.* **304**, 321-342 (1995).
231. "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).
232. "Non-solenoidal velocity effects in the smoothing of an initial discontinuity of concentration" (with T.Y. Liao) Submitted to *J. Fluid Mech.* (1995).
233. "The effective density and viscosity of a suspension" (with M. Poletto). *J. Rheology* **39**(2), 323-343 (1995).
234. "The unsteady motion of solid particles in creeping flows" (with J. Feng). *J. Fluid Mech.* **303**, 83-102 (1995).
235. "Vaporization of a liquid drop suddenly exposed to a high-speed air stream" (with A. Huang and G.V. Candler), *J. Fluid Mech.* **318**, 223-236 (1996).
236. "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).
237. "Flow characteristics of concentrated emulsions of very viscous oil in water" (with G. Núñez, Maria Briceño, Clara Mata, and Hercilio Rivás). *J. Rheology* **40**(3), 405-423 (1996).
238. "A note on the forces that move particles in a second-order fluid" (with J. Feng). Accepted for publication in *J. Non-Newtonian Fluid Mech.* (1996).
239. "Core-annular flows" (with R. Bai, K.P. Chen, and Y.Y. Renardy). To appear in *Annual Reviews of Fluid Mech.*, Jan. 1997.
240. "Dynamic simulation of sedimentation of solid particles in an Oldroyd-B fluid" (with J. Feng and P.Y. Huang). *J. Non-Newtonian Fluid Mech.* **63**(1), 63-89 (1996).
241. "The motion of solid particles suspended in viscoelastic liquids under torsional shear" (with J. Feng). Accepted for Publication in *J. Fluid Mech.* (1996).
242. "The motion of a solid sphere suspended by a Newtonian or viscoelastic jet" (with J. Feng). Accepted for publication in *J. Fluid Mech.* (1996).
243. "Stability of Annular flow and slugging" (with Antonio Bannwart and J. Lui). To appear in *Int. J. of Multiphase Flow*.
244. "Flow induced microstructure in Newtonian and Viscoelastic fluids" Keynote presentation (paper no. 95a) at the 5th World Congress of Chemical Eng. Particle Technology Track. San Diego. July 14-18, 1996.

Graduate Students supported under this grant: 2