Modeling of Sediment Bed Behavior for Critical Velocity in Horizontal Piping – 9263

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ABSTRACT

A new simulation capability has been developed for modeling the flow and thermal performance of chemical processes that involve multiphase, chemically-complex flows. A driver behind the development of this new capability was the lack of an existing tool to accurately predict (and avoid) pipeline plugging. Existing tools do not have a proven track record when it comes to this challenging problem. Our goal was to take advantage of advances in parallel computing capabilities and employ an approach with greater rigor, as compared to conventional computational fluid dynamics. This capability is applied to the transport of solid-liquid suspensions in a horizontal pipeline. Pipeline plugging has been identified as a significant issue for Hanford site's Waste Treatment and Immobilization Plant (WTP). Current modeling methods are limited to particles of uniform density, simple particle size distributions and simple geometries. The new simulation method models calculated detailed distributions for settled and suspended solids. The sediment bed is modeled using a phase-field representation. Simulation results are compared with data from experiments.

INTRODUCTION

Designing high-level waste processing facilities depends heavily on the ability to scale the fundamental processes developed during bench tests to a full sized plant. For this reason, a general simulation capability has been developed for modeling the flow and thermal performance of chemical processes that involve multiphase, chemically-complex flows of a potentially non-Newtonian nature. This capability is designed to take advantage of the new high performance computing systems with large numbers of parallel processers. This capability will ultimately be applied to a series of chemical processing applications.

An initial application of the simulation capability described above involves the modeling of the flow field and solids transport in a horizontal transfer pipeline. The treatment of high-level waste at the DOE Office of River Protection's WTP will involve the transfer of high solid content suspensions through pipelines. Pipeline plugging was identified as a significant potential issue by a panel of external experts [1]. In response to their concerns an experimental effort was initiated at PNNL to determine the critical velocities for a variety of operating conditions.

The solids concentration in a solid-liquid suspension transport pipe is relatively uniform for high flow velocity due to turbulent mixing. As the flow velocity decreases, the pressure drop decreases, solids settle toward the bottom of the pipe, and a sediment bed begins to form. The settling critical velocity occurs when further decrease in flow velocity results in an increased pressure drop due to the growth of the sediment bed.

The primary challenge in applying conventional computational fluid dynamics methods to pipeline plugging is the need for a dynamic sediment bed model that interacts with the turbulent flow field. The bed surface topography changes with particle erosion and deposition. The turbulent flow boundary conditions must continually change to account for the moving boundary.

The critical velocity for a horizontal pipe may be estimated using one of a variety of single equation correlations (Oroskar and Turian (1980) [2], Thomas (1979) [3], Gillies and Shook (1991) [4], Wasp et al. (1977) [5]) using the physical properties of the suspension (fluid viscosity, fluid and particle densities, particle size) and the pipe diameter. This approach can be extended to non-Newtonian fluids such as Bingham plastic or Casson fluid (Wasp et al. 1977 [5]). The next level in model complexity is the three-layer model by Doron and Barnea (1993) [6] where the pipe cross-section is divided into a stationary sediment bed, a moving bed and a heterogeneous flow region. Separate flow rates and solids concentrations are calculated for each of the two flow regions at a given pressure drop.

These methods are based on assumptions that limit their usefulness for complex systems. First, particle densities are assumed to be uniform, which is true for many industrial applications. Waste streams, however, generally have constituent species with a wide range of densities. Also, particle diameters are often assumed to have a relatively narrow distribution, or the fine particles are assumed to be part of the carrier fluid. The particle size distributions in waste streams are complex, typically ranging over orders of magnitude. Finally, these correlations are designed for horizontal or gradually inclined pipes. However, pipe blockage is likely to occur at pipe bends, fittings, transition to strongly inclined sections, etc.

A need exists for a predictive method that can address these complications. The approach we have taken is to develop a computational capability that models the sediment bed profile and suspended solids concentration for multiple particle sizes in any flow geometry. The next section describes the simulation methodology.

SIMULATION METHOD

A computational method has been developed to predict the flow and thermal performance of chemical processes that involve multiphase, chemically complex flows. The flow field is modeled using a lattice kinetics method, a modification of the lattice Boltzmann method [7]. Distribution functions containing information about the pressure tensor stream to adjacent lattice sites. The summation of these quantities results in equations that are solved for mass, momentum and scalar transport. The method depends only on local information and scales nearly linearly with the number of computer processors. This work is part of a larger effort to develop a process simulation capability for a wide range of chemical and nuclear processing applications.

Turbulent quantities are calculated using a k-epsilon RANS (Reynolds-averaged Navier-Stokes) model. The transport equations for the turbulent energy, k, and dissipation, ε, are

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+\tau_{ij}\frac{\partial U_i}{\partial x_j}-\varepsilon \qquad \text{(Eq. 1)}$$

$$\frac{\partial \varepsilon}{\partial t}+U_j\frac{\partial \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\nu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{\varepsilon 1}\frac{\varepsilon}{k}\tau_{ij}\frac{\partial U_i}{\partial x_j}-C_{\varepsilon 2}\frac{\varepsilon^2}{k} \qquad \text{(Eq. 2)}$$

The turbulent viscosity is given by

$$\nu_T=C_\mu\frac{k^2}{\varepsilon} \qquad \text{(Eq. 3)}$$

Solids are represented using two different continuum fields. The suspended solids are treated as passive scalars in the flow field, including terms for hindered settling and Brownian diffusion. Normal stresses created by the irreversible collisions of particles during shearing are added to the pressure tensor [8].

The sediment is modeled using a phase-field representation where the phase interface is represented by a continuous order parameter profile that moves smoothly through the computational grid [9].

$$\frac{\partial \psi}{\partial t} + u \cdot \nabla \psi = \nabla \cdot \left[\gamma \nabla \left(\frac{\partial F}{\partial \psi} \right) \right] + S \qquad \text{(Eq. 4)}$$

Where:

- ψ is the phase field order parameter
- u is the sediment velocity field
- γ is the mobility
- F is the free energy
- S is a source term

The sediment bed changes through deposition by hindered settling and erosion when the surface shear stress exceeds a specified yield stress. The rate of erosion is given by the expression

$$S = E\left(\max(0, \tau_s - \tau_{cr})\right)^n \qquad \text{(Eq. 5)}$$

where S is the solids eroded per unit surface area per unit time

- E is the erodability coefficient
- τ_s is the surface turbulent shear stress
- τ_{cr} is the critical shear stress
- n is typically in the range of 1.0-1.5.

The erodability coefficient is a function of fluid viscosity, particle size distribution in the sediment and interparticle cohesive forces. The critical shear stress may be determined either empirically or using a correlation that matches the Shields parameter

$$\tau_* = \frac{\tau_{cr}}{(\gamma_s - \gamma_m)d} = \frac{\rho_m u_*^2}{(\gamma_s - \gamma_m)d} \qquad \text{(Eq. 6)}$$

where s is for solids

- m is the mixed value

with the grain shear Reynolds number

$$\mathrm{Re}_* = \frac{u_* d}{\nu} \qquad \text{(Eq. 7)}$$

where γ is the specific gravity

- d is the particle size

u_* is the turbulent shear velocity.

A dynamic lithostatic model was included where the internal stresses in the sediment bed are calculated and the sediment can flow when a yield stress is exceeded. This capability has been demonstrated by simulating a slump test, where a cylindrical sample of Bingham plastic material is deposited on a flat surface and the degree of spread corresponds to the yield-stress of the material.

Future plans for capability development include the extension of this work to tank mixing and the incorporation of a thermodynamically based chemical reaction model.

SLURRY PIPE TRANSFER EXPERIMENTS

The method is compared with data from pipeline experiments conducted at PNNL.[1] The experimental flow loop consists of 3-inch schedule 40 piping with instrumentation for determining flow rate and pressure gradient. The simulant test particles ranged in density from 2.5 to 8 g/cc while the nominal particle size ranged from 10 to 100 μm.

At the beginning of each test, the slurry flow velocity was nominally set to 8 ft/sec. The flow was incrementally ramped down, and a steady-state pressure gradient was obtained at each flow condition. A rise in pressure gradient as the flow rate drops indicates that the pipe cross-sectional area is beginning to fill with sediment. This point is referred to as the “critical velocity”. The distribution of solids in the pipe was visualized using Electrical Resistance Tomography (ERT).

SIMULATION RESULTS

A series of simulations were performed to determine the critical velocity for each suspension type. At high flow rates, a pressure drop was specified using inlet and exit pressure boundaries, and the resulting flow rate was plotted. As the flow approaches the critical velocity, it is more practical to specify a set flow rate. For these cases, the specified total flow was achieved by continuously adjusting the pressure boundaries.

A typical simulation begins by establishing a steady-state condition with a high flow rate. The flow is then reduced and, if the flow is sufficiently low, a sediment bed forms and grows until equilibrium is reached. At that point, the rate of deposition by sedimentation is balanced by the rate of erosion.

A snapshot from a simulation of a half-pipe during a fill transient is shown in Figure 1. The dark region represents the sediment bed. The colored planes along the pipe symmetry plane and at the exit are the solids concentrations in the suspension. The axial length aspect has been reduced by a factor of ten. Note that the suspension solids concentration decreases in the direction of flow as solids are deposited onto the sediment bed.

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[1] Poloski, A., et al. (2008). *Critical Velocity of Newtonian and Non-Newtonian Slurries in Straight Horizontal Piping*. WTP-RPT-175, Pacific Northwest National Laboratory, Richland, WA.

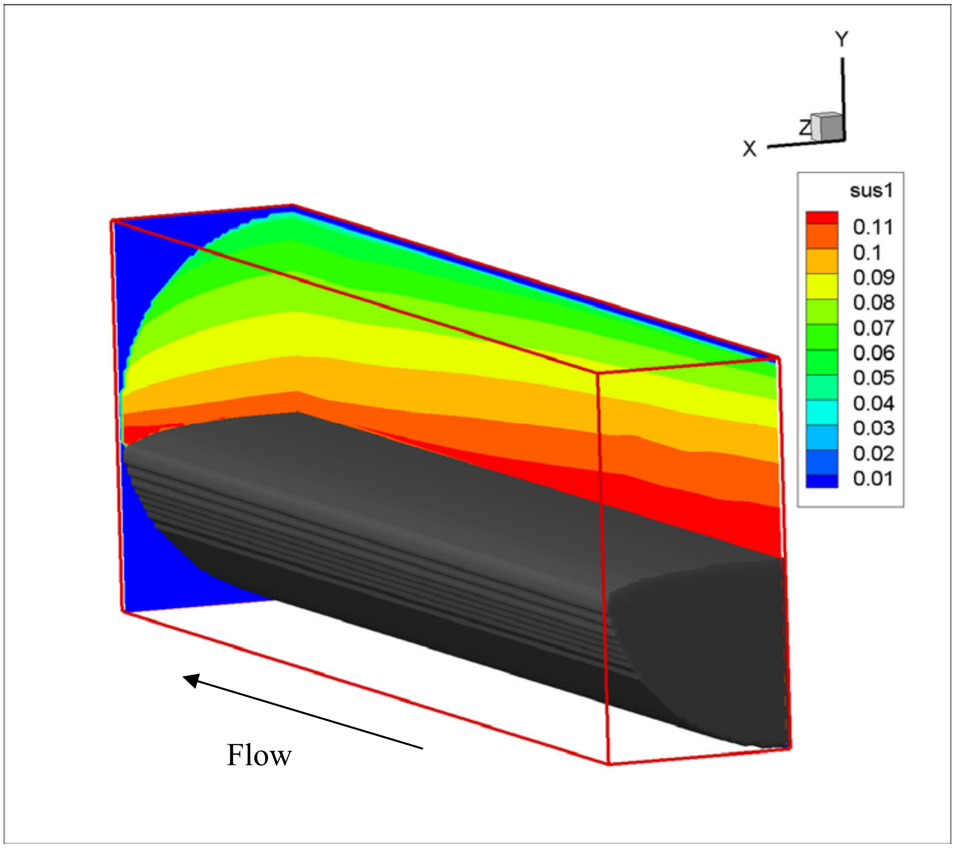

Fig. 1. Simulation of a sediment bed and solids concentrations (vol%) in a slurry pipe. Black represents the sediment bed.

After a series of simulations are performed at different flow conditions, the critical velocity is determined by identifying the inflection point in the pressure drop vs. flow rate curve. An example is shown in Figure 2 for 100-μm glass beads in water. The dotted line represents the turbulent pressure drop for a pure fluid with the equivalent density and viscosity as calculated using the Darcy equation with a standard turbulence friction factor.

The colored circles are the electrical resistance tomograms at different flow rates. The dark blue region represent the sediment bed cross-section. The color in the upper region indicates the suspended solids concentration.

For high flow rates, turbulent mixing produces a suspension that is nearly homogeneous and behaves like a pure fluid. As the flow rate decreases, the solids concentration increases near the bottom of the pipe and decreases near the top. This trend continues as the flow rate decreases until a moving bed is formed on the bottom of the pipe. At a flow rate just above the critical velocity, a stationary bed begins to form on the bottom of the pipe. This can be seen in the electrical resistance tomography images provided. As the flow rate decreases, the sediment bed grows and reduces the flow area.

The lattice kinetics (LK) simulation results are represented by the squares. Note the very good agreement with experimental data throughout the range of flow rates. For flow rates above the critical velocity, the agreement indicates that the turbulence model and suspension behavior is correctly captured.

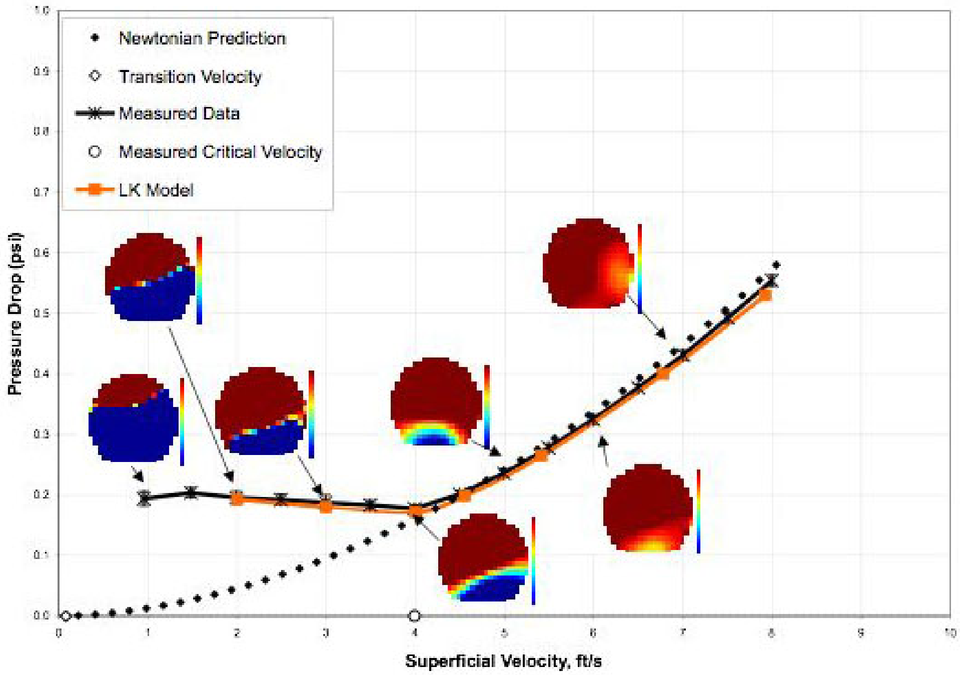

Fig. 2. Pressure drop vs. superficial velocity and electrical resistivity tomograms for 100-□m glass beads in water.

The predicted critical velocity value and the shape of the pressure curve below that value are strongly affected by the critical shear stress selected for the erosion expression (Eq. 5) and less strongly by the erodability coefficient. The critical shear stress was determined using the Shields parameter correlation. The erodability coefficient was adjusted to yield the best fit to the data. Although some literature exists on determining this coefficient for coarse particle systems, additional work is needed for particle mixtures.

CONCLUSIONS

A new simulation tool has been developed for modeling the flow and thermal performance of chemical processes that involve multiphase, chemically complex flows This capability was demonstrated by modeling the transport of solid-liquid suspensions in a horizontal pipeline. The sediment bed was modeled using a phase-field representation. Preliminary simulation results compared extremely well with data from experiments and demonstrated the ability to determine the critical velocity for a suspension. Accurate predictions depend on knowing the parameters for the sediment erosion rate. Future plans for capability development include the extension of this work to tank mixing and the incorporation of a thermodynamically-based chemical reaction model.

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