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Mechanics of Bubbles in Sludges and Slurries

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Research Objective

Previous studies have established that the waste level of Hanford tanks responds to barometric pressure changes, the compressibility of retained bubbles accounts for the level changes, and the volume of retained gas can be determined from the measured waste level and barometric pressure changes. However, interactions between the gas bubbles and rheologically complex waste cause inaccurate retained gas estimates and are not well understood. Because the retained gas is typically a flammable mixture of hydrogen, ammonia, and nitrous oxide, accurate determination of the retained gas volume is a critical component for establishing the safety hazard of the tanks. Accurate estimates of retained gas from level/pressure data are highly desirable because direct in-situ measurements are very expensive in an individual tank and impossible in many single-shell tanks.

The objective of this research project is to gain a fundamental understanding of the interactions between gas bubbles and tank waste during barometric pressure fluctuations. It is expected that the elucidation of the bubble/waste interaction mechanisms will lead to the development of models for a more accurate determination of: gas content in Hanford tanks, waste properties from level/pressure data, and the effect that barometric pressure fluctuations have on the slow release of bubbles. The results of this research will support critical operations at the Hanford Site associated with the flammable gas safety hazard and future waste operations such as salt-well pumping, waste transfers, and sluicing/retrieval.

Research Progress and Implications

This three-year research program, which began in FY 1998, is divided into four related problems. Progress has been made in each of the areas of modeling bubble behavior in continuum materials (sludges) from both a solid mechanics viewpoint and separately from a fluid mechanics viewpoint, modeling studies of compressible bubbles in particulate materials (slurries), and experimental studies of bubbles in both sludges and slurries.

The modeling of the bubble/waste interactions from a solid mechanics approach was initiated with a theoretical study to understand the effects that smooth external pressure fluctuations have on the deformation history of a single bubble imbedded in a compressible elastic-perfectly plastic isotropic medium of infinite extent. The problem was approached by solving an outer elastic and an inner plastic problem for each compression and decompression sweep of the pressure cycle, then matching the deformations and stresses at the location of the elastic-plastic boundary. Finite deformations were used to determine the displacements in plastic regions. The general case in which yield and yield in reverse zones alternate with each pressure cycle was considered. A consistent solution of these equations showing the dependence that the bubble volume has during pressure fluctuations has been obtained, and the results show the character of bubble/waste interaction that is intuitively expected.

For continuum modeling from the fluid mechanics viewpoint, the interaction and movement of arrays of bubbles involve a number of scientific issues relating to flows of fluids exhibiting a yield stress. Our interest centers on the region surrounding an expanding bubble where the yield stress is exceeded and the fluid flows; when the yielded regions for an array of bubbles intersects, the bubbles can move, coalesce, and rise. Because of the computational difficulty associated with solving for the unknown location of the yield surfaces, we are focusing initially on the relatively simple problem of squeezing flow between approaching disks. Existing results indicate that, in a geometry in which the disk radius R is considered infinite, the fluid cannot yield at any point until it has yielded everywhere; in a geometry of finite radius R, however, an unyielded region exists near the center axis. A scaling analysis suggests that the presence of unyielded regions depends on a dimensionless group which is the product of the Bingham number (which approaches infinity) and the square of the gap to radius ratio (which approaches zero). Numerical studies have been initiated to determine where the transition between the infinite domain case (no unyielded regions) and the finite domain case (unyielded regions along the axis) occurs and the effect of length scale on the development of the unyielded regions. The next step is to examine the expansion and contraction of a single bubble in a yield-stress material, then determine the interaction between yielded regions in an array of bubbles. Rheological characterization is being performed concurrently on slurries that simulate the Hanford wastes. These data will ultimately provide parameters for constitutive modeling of the slurries.

For the modeling studies of bubbles in particulate materials (slurries), the pore structure is modeled as a one-dimensional (1-D) network of identical biconical pores with both converging and diverging sections. From this model and the geometric constraints on interface shapes, one can determine the sequence of bubble shapes and volumes as a bubble responds to changes in barometric pressure at constant mass. The analysis defines when jumps in interface position can occur, especially as interfaces penetrate or retreat into pore throats. These jumps mean that not all possible interface positions are observed as the bubble grows. Modeling of interface movement and effective bubble compressibility in a 1-D porespace is nearly complete. Parameters examined include pore shape, bubble size, contact angle, and ambient pressure. Two additional factors must be addressed in the context of this 1-D model: pore heterogeneity and possible bubble breakup at certain jumps.

For the experimental studies, the initial focus is to quantify the effect of small pressure changes on the volume of a single bubble in a waste simulant. The particular challenges for this problem are to measure accurately the induced volume change of non-spherical bubbles while concurrently visualizing the changes in bubble shape. An apparatus for conducting these experiments has been assembled and tested, and it has been designed to automatically conduct repeated pressure cycles. Initial results have been obtained by manually adjusting the pressure controller for a bubble in a transparent simulant of silica particles in an oil with matching refractive indices. Results for bubble volume and shape during pressure cycles have been obtained and clearly show bubble/waste interactions.

Planned Activities

The first year of this project has been devoted to developing the mathematical and computational frameworks and experimental apparatus and methods. While interesting initial results have been obtained, the more challenging problems will be tackled in the next two years. For the solid mechanics modeling studies, the future focus will be on extensions of the current solution to multiple pressure cycles, and the effects of bubble deformation with other yield criteria will be analyzed. In addition, the contribution of neighboring bubbles (multi-bubble problem) to the plastic and elastic deformations will be investigated. For the fluid mechanics studies, a numerical approach is planned with particular emphasis placed on determining the correct form of the boundary conditions; for yield-stress fluids, the location of the yielded region is unusually dependent on boundary conditions set far from the bubble location. For the modeling studies of compressible bubbles in porous media, the results for simple 1-D porous media will be completed, and then the more challenging problem of multiple bubbles in 3-D pore models will be solved. For the experimental studies, we will continue with the single bubble experiments and will also conduct multiple-bubble experiments. These experimental results will then be compared with the modeling results to reconcile the differences between the observed behavior and the different modeling approaches.