Mechanics of Bubbles in Sludges and Slurries

Project ID: 60451

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Research Objectives

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 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 report summarizes work done in 2.5 yr of a 3-yr project.

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.

Experiments have quantified the effects of small pressure changes on bubble volumes in simulated waste. In single- and multiple-bubble experiments, a fluid of known rheological properties fills an apparatus attached to a pressure regulation system. As step changes or cycles of pressure are made, level changes are tracked. For single bubbles, cameras capture bubble shape and changes as well as level changes in a capillary tube standing over the vessel. For multiple-bubble experiments, the level is measured by the same gauge used in the Hanford tanks. Experiments have been performed on both water- and oil-based simulants, but each has limitations. The data shows “hysteresis,” where the level depends on the pressure history in addition to the current pressure, indicating that some stresses must be overcome before bubble volume responds.

A general procedure was developed to find the stress and strain fields produced by periodic pressure variations for a spherical bubble in an elastic-plastic medium where the gas inside the bubble is considered soluble in the medium. For a given set of parameters, the bubble volume was computed

as a function of applied pressure and solubility coefficient. Residual stresses are originated by plastic deformations that occur during the expansion or the compression of the bubble.

The current model is significantly more rigorous than those of previous studies at PNNL and has yielded significant new results. New estimates of material strength based on the model are an order of magnitude smaller than previous calculations that accounted poorly for elastic and plastic regions and residual stresses. Results show that increasing the waste strength causes an increasing hysteresis in the relationship between bubble radius and pressure. This occurs because the waste, which is a soft solid, resists the expansion and compression of the bubble. In addition, the hysteresis depends on Young's Modulus as well. It was also found that the pressure cycles are not symmetric and the whole loop may be markedly curved.

This model enables the engineer to estimate the rate at which bubbles rise through the sludge as a function of the specific barometric pressure history. Within the model assumptions, bubble rise takes place as long as the magnitude of the pressure fluctuations (regardless of whether the medium is compressed or decompressed) exceeds the yield condition for the material. Work to gain a better understanding of the interplay among the various parameters and the feasibility of estimating mechanical properties continues.

From the fluid mechanics point of view, as a bubble expands under the influence of gravity and changing barometric pressure, the yield stress of the surrounding fluid is eventually overcome its structure collapses, and the bubble rises within the yielded region. As the bubble grows, the yielded region grows and interacts with the yielded regions of nearby bubbles. In a fully connected, yielded region, bubbles move about, coalesce, and rise. How this interaction occurs and what happens when the yielded regions intersect is the heart of the problem. The project team is most interested in determining which regions are yielded (act like viscous liquids) and which are unyielded (act like solid).

The mechanics of bubble movement in slurries representative of Hanford tank wastes are more appropriately modeled as porous media. A one-dimensional biconical-pore network model is being applied to determine the effective compressibility of the gas in the slurry. This information is important for calculating the volume of gas in the slurry from changes in waste level produced by fluctuations in barometric pressure.

The compressibility of the gas is a function of its pressure, which is the sum of barometric pressure, the known hydrostatic pressure from the liquid in the tank, and capillary pressure in the porous medium formed by the slurry. Three time scales are involved. Over a period of months or years, chemical reactions in stored liquid waste create volatile components that diffuse to and accumulate in bubbles. Bubble mass and volume increase slowly at fixed liquid pressure, determining the initial states of bubbles when barometric pressure changes. On a time scale of hours, bubble volume responds to changes in barometric pressure. On this time scale, effective compressibility is observed.

On a still shorter time scale, seconds or less, interfaces between the viscous liquid and bubble advance or retreat impulsively, driven by capillary forces. For expanding bubbles, whether due to accumulation of mass over a period of months or to a short-term decrease in barometric pressure, impulsive jumps occur from the throat of one pore to near the throat of the next. During pressure *increases*, however, interfaces jump from pore *body* to pore body. Because most jumps in tank waste have occurred during the slow growth of bubbles over months, most bubbles are lodged at pore throats, ready to jump again if pressure decreases. However, these same bubbles do *not* jump backward if pressure increases, until their interfaces first retreat to pore bodies. Thus, a population of bubbles has a significantly higher effective compressibility during decreasing than during increasing pressure.

The project's constricted-tube model can fit tank data with level-pressure hysteresis, but ambiguity remains on the relationship between bubble geometry and capillary pressure. The PNNL experiments or other threads of the project may provide the information needed to solve that problem.

Planned Activities

For the remaining seven months of this project the parametric study on the multiple pressure cycles will be extended. In addition, the effect of neighboring bubbles (multi-bubble problem) to the plastic and elastic deformations will be assessed. The numerical simulations of a bubble moving in a

viscoplastic fluid will focus on the calculation of the topology of the yielded regions. Further multiple-bubble experiments will be performed and compared to the modeling results to reconcile the differences between the observed behavior and the different modeling approaches.

Information Access

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