Scaling Laws for Reduced-Scale Tests of Pulse Jet Mixing Systems in Non-Newtonian Slurries: Gas Retention and Release Behavior

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ABSTRACT

The Waste Treatment Plant under construction at the Hanford Site will use pulse jet mixer (PJM) technology for mixing and gas retention control applications in tanks expected to contain waste slurries exhibiting a non-Newtonian rheology. This paper presents the results of theoretical and experimental studies performed to establish the methodology to carry out reduced-scale gas retention and release tests with PJM systems in non-Newtonian fluids with gas generation. The technical basis for scaled testing with unsteady jet mixing systems in gas-generating non-Newtonian fluids is presented in the form of a bubble migration model that accounts for the gas generation rate, the average bubble rise velocity, and the geometry of the vessel. Scaling laws developed from the model were validated by conducting gas holdup and release tests at three scales: large scale, 1/4 scale, and 1/9 scale. Experiments were conducted with two non-Newtonian simulants with in situ gas generation by decomposition of hydrogen peroxide. The data were compared nondimensionally, and the important scale laws were examined. From these results, scaling laws were developed that allow the design of mixing systems at a reduced scale.

INTRODUCTION

Many industrial processes involve gas bubbles generated in fluids, slurries, and sediments. In Newtonian fluids, gas bubbles rise freely and, except for the “holdup” volume of bubbles in transit, do not accumulate. On the other hand, non-Newtonian slurries that exhibit a yield strength behave as fluids only when actively mixed (e.g., by hydraulic jets, mechanical impellers, sparged bubbles, etc.). Small gas bubbles generated in these slurries can rise only in a mixed region and are trapped by the material yield strength when mixing ceases. If the gas in the bubbles is flammable, they represent a potential safety hazard, and it becomes important to be able to predict the maximum gas volumes that can accumulate and release.

From the last century it has become standard practice to design hydrodynamic and aerodynamic systems based on data from tests of smaller-scale prototype systems or models. The foundation of this method is a set of scaling laws that express the system performance characteristics or equations of motion in terms of nondimensional groups of important quantities so that maintaining equality of all or most of the nondimensional groups from small to full scale ensures equality of performance.
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One important system that must handle non-Newtonian slurries with gas generation is the Hanford Waste Treatment Plant (WTP) being built for the U.S. Department of Energy Office of River Protection to pretreat and then vitrify a large portion of the waste in Hanford’s 177 underground radioactive waste storage tanks. Many of the WTP process streams are concentrated waste slurries that are expected to exhibit a non-Newtonian rheology and require a minimum shear to be applied before the material begins to flow. Due to radiolysis and thermolysis, these slurries continuously generate flammable gases, and adequate mixing is required to prevent hazardous gas accumulations.

Pulse jet mixers (PJMs) were initially planned for mixing WTP vessels because they lack moving mechanical parts that would require maintenance. PJMs have been used successfully for mixing Newtonian fluids, but their application to non-Newtonian slurries in the WTP was new. An extensive program of scaled testing was performed to build the technical basis needed to support the plant design. This effort required that new scaling theory be developed to understand and scale up the results to plant scale. Based on the test results and scaling theory, PJMs alone would not provide adequate mixing of the expected non-Newtonian slurries; a hybrid mixing system that is a combination of PJMs and inter-mittently operated air spargers was required. Sparger and PJM construction and operation are briefly described below.

A PJM consists of a vertical pulse tube immersed in the fluid with a jet nozzle on the bottom and a connection to a pressure/vacuum supply on the top. During a PJM drive cycle, pressure is applied to discharge the contents of the pulse tube at high velocity through the nozzle. A vacuum is then applied to refill the pulse tube, after which the pressure is vented to the atmosphere and the fluid level in the pulse tube and tank approach the same level. The full PJM cycle takes several minutes, 15 to 20% of this time is actual drive time. Several PJMs are typically installed in a cluster in the center of the tank such that the combined pulse tubes contain 10 to 15% of the total tank volume.

Sparging provides mixing by introducing large air bubbles near the tank bottom through straight vertical pipes. The bubbles mobilize and entrain an increasing volume of slurry as they rise, producing an expanding upwelling region of bubbles (ROB). The slurry thus brought to the surface spreads out and descends, forming a concentric down-flowing zone of influence (ZOI) that terminates near the base of the sparge tubes. In a hybrid mixing system, sparge tubes are placed between the wall and the PJM cluster such that their ZOIs overlap. The PJM jets create a mixed “cavern” in the bottom portion of the tank, while the sparger ROB and ZOI extend the mixed region to the surface. The hybrid mixing system is illustrated conceptually in Figure 1.

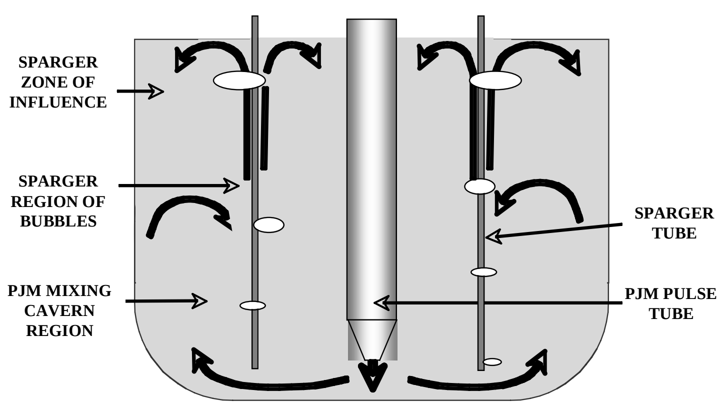

Fig. 1. Mixing in a hybrid PJM-sparger system

The WTP scaled testing program for gas retention and release used seven different vessels ranging in volume from approximately 120 to 40,000 L. Three vessels were designed with identical, PJM-only mixing systems specifically to investigate scaling. Three others used a variety of more prototypic hybrid mixing systems, and one large vessel had only spargers installed. The radioactive waste slurry was represented by kaolin-bentonite clay mixed with water. These slurries were modeled as a Bingham plastic with yield stress adjustable between 7 and 45 Pa and consistencies adjustable between 10 and 30 cP depending on the clay-to-water ratio for a specific test. Gas generation was accomplished by injecting a 30 wt% hydrogen peroxide solution that decomposed to oxygen gas and water. Individual test vessels and operations are described in more detail later.

This paper presents the scaling theory developed for this gas retention and release test program and describes how the test data demonstrate the theory. Despite the transient and nonuniform fluid flows produced by the hybrid systems and the complexities of non-Newtonian rheology, the fundamental bubble rise mechanism so dominates the gas retention and release process that simple one-dimensional, steady conservation laws describe them quite well. Though this work was performed in the context of radioactive waste treatment, the theory and mechanisms apply to any process where non-Newtonian fluids are intermittently mixed with similar systems.

BUBBLE MIGRATION IN A NON-NEWTONIAN FLUID

A simple bubble migration model for a well-mixed slurry explains the basic elements of gas retention and release associated with PJM and sparger operation in non-Newtonian slurries. Though PJM operation is actually intermittent and mixing is nonuniform, the well-mixed model can be applied if the total gas release rate and the total amount of gas in the slurry can be represented by appropriate averages over space and time.

Gas is generated continuously within the waste slurry. Gas molecules form in solution in the liquid phase, but the gas in solution quickly supersaturates, causing bubbles to nucleate and grow. Because most of the gases generated in WTP vessels are not very soluble, we consider only the gas that exists in bubbles, excluding the dissolved gas in the slurry. The large, fast-rising sparger air bubbles do not contribute to the holdup considered in this analysis and are included in this analysis only as a source of mixing.

Consider a population of small gas bubbles distributed uniformly throughout a cylindrical vessel on a mole basis. Gas is generated at a constant, uniform rate, g_m (moles /m^3-s). The gas bubbles rise continually and break at the surface at velocity U_R (m/s). Mass conservation on the total population of bubbles in the vessel is expressed in the following differential equation:

$$\frac{d}{dt}(n_g V_{bs}) = g_m V_s - n_g U_R A \qquad \text{(Eq. 1)}$$

where n_g is the (uniform) number of moles of gas per unit volume of bubbly slurry (mole/m^3), V_{bs} is the total volume of bubbly slurry in the vessel (m^3), V_s is the volume of gas-free slurry (m^3), and A is the area of the slurry surface (m^2)[1]. Dividing through by V_s and noting that $V_{bs} \approx V_s$ for $\alpha < \sim 10$ vol% and that $H = V_s/A$ is approximately the slurry depth for a cylindrical vessel, Eq. (1) becomes:

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1 Air sparging also strips dissolved oxygen from the liquid, but the rate is insignificant compared with oxygen generation in these tests. It is not included in the mass balance.

$$\frac{\mathrm{d}}{\mathrm{dt}} n_g = g_m - n_g U_R \big/ H \qquad \text{(Eq. 2)}$$

We define the gas volume fraction (volume of gas per unit volume of bubbly slurry), $\alpha = n_g RT/p$, using the ideal gas law where T is the average temperature (K) and p is the average pressure (Pa) of the gas and R is the gas constant (R = 8.315 J/mole-K). Applying this definition in Eq. (2) yields

$$\frac{\mathrm{d}}{\mathrm{dt}} \alpha = g_v - \alpha U_R \big/ H \qquad \text{(Eq. 3)}$$

where g_v is the volumetric gas generation rate per unit volume of gas-free slurry at the average system pressure and temperature (s^{-1}). For $\alpha = \alpha_0$ at time $t = 0$, Eq. (3) has the solution:

$$\begin{aligned} \alpha(t) &= \alpha_0 \exp\left(-tU_R / H\right) \\ &\quad + g_v H / U_R \left[1 - \exp\left(-tU_R / H\right)\right] \end{aligned} \qquad \text{(Eq. 4)}$$

Note that for $t \to \infty$, Eq. (4) simplifies to $\alpha_{ss} = g_v H \big/ U_R$, where α_{ss} is the steady state gas "holdup."

While appropriate to model gas retention and release where the gas generation rate is constant, it cannot be applied directly to interpret scaled test data where the gas generation occurs by hydrogen peroxide decomposition. The rate of the reaction $2H_2O_2 \to 2H_2O + O_2$ is first order with respect to hydrogen peroxide and is thus approximately proportional to the concentration of hydrogen peroxide in the slurry. Therefore we express the molar oxygen gas generation rate as $g_m = \varepsilon A_g n_p$, where n_p is the molar concentration of hydrogen peroxide in the interstitial water (moles/m^3), A_g is the rate constant (1/s), and ε is the volume fraction of interstitial fluid in the simulant. The reaction stoichiometry dictates that hydrogen peroxide decomposition rate is twice the oxygen generation rate.

To track the hydrogen peroxide in the system we apply the following mass balance:

$$\frac{\mathrm{d}}{\mathrm{dt}} n_p = \frac{m_p}{V_s M_p} - 2 n_p A_g \qquad \text{(Eq. 5)}$$

where m_p is the mass injection rate of hydrogen peroxide (kg/s) and M_p is its molecular weight (0.034 kg/mole). The effect of solids is incorporated into A_g which serves as a fitting parameter. The solution to Eq. (5) for $n_p = n_{p1}$ at $t = t_1$ is

$$\begin{aligned} n_p(t) &= n_p(t_1) \exp\left(-2A_g t\right) + \\ &\quad + \frac{m_p}{2A_g V_s M_p}\left[1 - \exp\left(-2A_g t\right)\right] \end{aligned} \qquad \text{(Eq. 6)}$$

The solution to Eq. (2) under similar initial conditions after substituting for g_m becomes

$$\begin{aligned} n_g(t) &= n_g(t_1) \exp\left(-tU_R / H\right) + \\ &\quad + \frac{\bar{n}_p A_g H}{U_R}\left[1 - \exp\left(-tU_R / H\right)\right] \end{aligned} \qquad \text{(Eq. 7)}$$

where $\bar{n}_p$ is the result of time averaging Eq. (6) between time *t* and t_1 to obtain

$$\bar{n}_p = \frac{1}{2A_g}\left[\frac{m_p}{V_s M_p} - \frac{n_p(t) - n_p(t_1)}{t - t_1}\right] \quad \text{(Eq. 8)}$$

Eq. (6) through (8), with the ideal gas law to compute the gas volume fraction from the oxygen gas concentration in the slurry, are used to interpret the scaled test data. Fitting this set of equations to test data also determines the bubble rise velocities necessary for scale-up calculations.

SCALING THEORY

Eq. (4) shows that the time dependence of the gas fraction α is completely characterized by the time constant H/U_R, which represents the effective bubble transit time through a slurry column. More generally, the nondimensional group forming the coefficient of the last term in Eq. (4), which represents the ratio of bubble growth rate to transit time, is called the holdup number:

$$\mathrm{N_H} = g_v H / U_R \quad \text{(Eq. 9)}$$

In systems mixed only by PJMs, it is useful to express the time in the exponents of Eq. (4) as the product of the number of PJM cycles and the cycle time. This gives rise to a “gas release number” that relates the bubble transit time to the characteristic mixing time of the system. That is,

$$\mathrm{N_R} = U_R t_C / H \quad \text{(Eq. 10)}$$

The holdup number, however, is the primary scaling law for gas retention and release. It is also equal numerically to the steady-state gas volume fraction or holdup, α_{ss}, which is obtained from Eq. (4) as $t \rightarrow \infty$. This provides the primary means for determining the bubble rise velocity from gas holdup tests where the gas volume fraction is measured at a constant volumetric gas generation rate and slurry depth. Therefore, because the bubble rise velocity should be constant to first order for similar slurry rheology and mixing system configurations, the fundamental scaling principle is that an equal gas holdup at all scales requires the product of the volumetric gas generation rate, g_v, and slurry depth, H, to be constant. The remaining task of scaling is to determine how the bubble rise varies with other system characteristics and properties.

The average bubble rise velocity at the surface, U_R, is the only variable in Eq. (4) that represents the overall effect of the mixing system and should therefore have some dependence on the variables describing the mixing process. The average bubble rise velocity does not, however, depend on the slurry circulation pattern or velocity. Mass conservation requires a zero time- and space-averaged velocity for a constant volume of slurry in a vessel, regardless of temporal and spatial complexities of the flow field involved in mixing. Therefore, the time- and space-averaged bubble rise velocity is the same as that of a stagnant slurry for the same fluid properties and similar bubble size and shape.

Nevertheless, because bubbles can rise only when the slurry is a fluid, the mixing system does affect the average bubble rise velocity through the duration and extent of slurry mobilization it induces. Variables representing these characteristics should include the PJM drive time, total cycle time, the number of PJMs, the PJM nozzle diameter and fluid velocity, the total sparger air flow, the tank diameter, and the depth of the slurry. Nondimensional groups have been described for scaling jet mixing in non-Newtonian slurries.[1] The yield Reynolds number is the ratio of dynamic stress to slurry strength, which directly affects the size of the mixing cavern. It is expressed as

$$\mathrm{Re}_{\tau} = \rho u_0^2 / \tau_s \qquad \text{(Eq. 11)}$$

where ρ is the gas-free slurry density, u_0 is the peak average velocity of the PJM drive cycle, and τ_s is the shear strength of the unmobilized slurry. The jet Reynolds number is the ratio of dynamic stress to viscous stress of the PJM jet and influences the degree of turbulence in the mixed region and transitional flow regimes associated with non-steady mixing as well as the cavern height. The jet Reynolds number is defined by

$$\mathrm{Re}_0 = \rho u_0 d_0 / \kappa \qquad \text{(Eq. 12)}$$

where d_0 is the PJM nozzle diameter. The jet Reynolds number at small scale is reduced by the geometric scale factor. A Strouhal number can be defined as the ratio of pulse time to jet flow time scale:

$$\mathrm{S}_0 = t_D u_0 / d_0 \qquad \text{(Eq. 13)}$$

where t_D is the PJM drive time. It theoretically affects the degree to which the jet approaches steady behavior.

These nondimensional groups determine volume and duration of the mobilized region in which the slurry behaves as a liquid. Within this mobilized region, the bubble rise velocity should be a function of the bubble diameter and the non-Newtonian slurry density and rheology (expressed by the Bingham plastic model in terms of the yield stress, τ_y, and consistency, κ). The bubble diameter, in turn, depends on product of the gas generation rate and bubble transit time, which is proportional to the slurry depth. The functional dependencies of the bubble rise velocity on these variables are not yet known precisely, though tests with hybrid mixing systems shows some obvious trends, as is discussed below.

Slurry mixing or mobilization by air sparging exhibits a complex, nonlinear scaling due to gravity. Nevertheless, single-tube sparging performance data can be used to design multiple sparger arrays for PJM hybrid mixing systems. These data [2] show that diameter at the surface of the upwelling ROB and of the downward flowing ZOI induced by the rising column of air bubbles both vary with the volumetric air flow rate raised to approximately the 1/3 power. The diameter of the ZOI is three times that of the ROB. Therefore, the tube spacing required for the ZOIs to overlap such that they meet the ROB of adjacent tubes is equal to 2/3 of the ZOI diameter. This spacing also results in approximately equal superficial air velocities calculated as the actual volumetric flow rates at the sparge tube exit divided by the tank cross-sectional area available to sparger air flow (not including the area within PJMs).

OBSERVATIONS FROM DATA

Scaled PJM Systems

Tests were performed in geometrically similar vessels at three different scales to validate these scaling laws.[1] The largest vessel was 3.89 m in diameter with a slurry volume of 38,000 L and four 61-cm diameter PJMs spaced evenly on a pitch diameter of 2.45 m, placing each PJM at approximately the centroid of a quadrant. The PJM drive cycle time was one minute and the actual drive time 0.15 minute, producing a nozzle velocity of 8.5 m/s. The two smaller vessels were built at linear scales of 1:4.5 and 1:9, respectively. The PJM drive cycle times were also reduced by the geometric scale factor, while peak

PJM nozzle velocity was approximately constant with scale. Gas retention or holdup tests were conducted with kaolin/bentonite clay simulant with yield stress ranging from 7 to 44 Pa and consistency factors from 9 to 23 cP (based on the Bingham plastic model). Holdup tests were performed by injecting hydrogen peroxide continuously into the PJM mixing cavern at rates to produce relative gas generation rates from 0.1 to 0.7 vol%/min. In some tests a second, higher hydrogen peroxide injection rate was applied after the initial steady state occurred. The retained gas volume or holdup was calculated from differences in slurry surface level measured during the quiescent portion of the PJM drive cycle.

In vessels mixed only by PJMs, the scaling theory outlined above dictates that the holdup number should be a function of the yield Reynolds number, the jet Reynolds number, and the Strouhal number. A linear least squares fit to gas holdup test data from the three scaled four-PJM vessels [3] gives the relationship

$$N_H = 8.42\,\mathrm{Re}_\tau^{-0.76}\,\mathrm{Re}_0^{0.16}\,S_0^{0.52} \qquad \text{(Eq. 14)}$$

The R^2 value of the fit, illustrated in Figure 2, is 0.90.

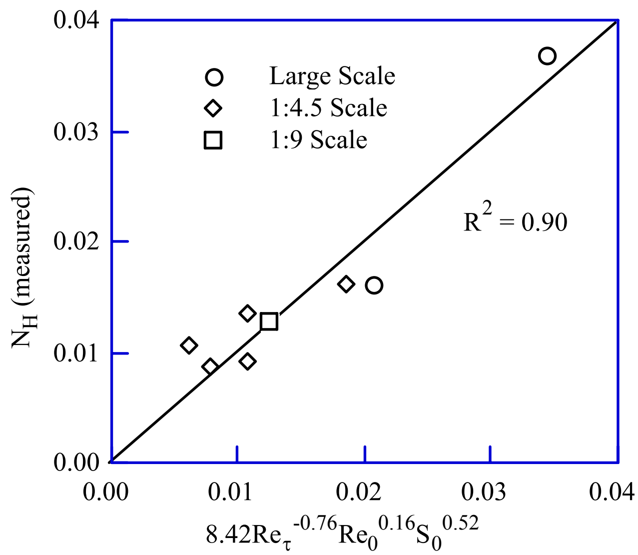

Fig. 2. Gas holdup scaling relationship for vessels mixed by identical four-PJM systems

Gas release tests were also conducted in the three scaled vessels by starting the PJMs after a stagnant period during which decomposition of previously injected hydrogen peroxide caused gas accumulations up to 10 vol%. Data from these tests did not scale. Apparently, the gas released near the bottom of the tanks in the first few PJM cycles created a sparging effect that quickly released gas probably from the central region inside the PJM pitch diameter. After this initial rapid release, however, the resulting density stratification may have resisted further mixing and greatly slowed long-term gas release. In other words, the additional density-driven processes involved in these tests overwhelmed the dynamics of PJM mixing represented by the nondimensional groups introduced above. These effects are still present but somewhat less powerful in hybrid systems where sparging helps defeat density stratification.

Scaled Prototype Hybrid Systems

Gas retention and release tests were also conducted in two approximately 1/4 scale prototype vessels using hybrid mixing systems. These systems included both air spargers and recirculation pumps, though one or the other was used in addition to PJMs during tests. The purpose of these tests was to confirm the adequacy of the hybrid mixing system configurations rather than to investigate the effects of specific features or operating parameters. Several conditions varied between tests so it was not possible to extract the influence of any one of them. At the same time, the hybrid mixing systems were operated at much less than full capacity so the simulant may not have been very well mixed. Nevertheless, it will be shown that the results of these tests confirm the basic scaling principles expressed by Eq. (9) and the simple gas inventory model of Eq. (6–8). Tables and a detailed explanation of the test configuration and operating conditions are given in.[3]

Prototype test vessel A (generic identifiers are used because the precise nomenclature and function of the vessels in the plant process stream are not important to this discussion) was built at 1:4.9 scale with a diameter of 0.86 m. Two slurry levels, 1.2 m and 1.55 m, were used for aspect ratios (H/D) of 1.4 and 1.8, respectively. Four 15-cm-diameter PJMs were installed in a central cluster (three around one) with four spargers, three placed between the three outer PJMs and one next to the central PJM (only the central sparger was used in tests, air flow 85 L/min). A single recirculation nozzle discharged downward next to the central PJM (flow rate 340 L/min).

Test vessel B had a diameter of 1.8 m and a simulant depth of 1.3 m to model a different plant vessel at 1:4.3 scale. Eight 30-cm-diameter PJMs were placed in a central cluster (7 around one). In one test, three of the seven perimeter PJM nozzles were angled upward at 135 degrees while the other four pointed downward at 45 degrees. In the second test, all seven outer nozzles were angled at 45 degrees. Eight spargers were equally spaced near the tank wall (only four spargers were used in the tests, each at an air flow rate of 85 L/min). Four recirculation nozzles discharged a total flow of 454 L/min at 30 degrees upward tangential to the tank wall, fed by a single suction line next to the central PJM.

The progress of gas holdup tests for these two scaled prototype vessels is shown in Figure 3. Vessel A, with at least twice the slurry depth of Vessel B, showed a much higher gas holdup. However, the aspect ratio is probably not the dominant effect because the second test in Vessel A used a 30% deeper simulant with only a small increase in holdup. More likely, the single central sparger or single central downward-discharging recirculation nozzle did not mix the slurry as effectively as the four peripheral spargers or four upward-discharging recirculation nozzles used in Vessel B. The central PJM in Vessel A may have limited the ZOI of the sparger or recirculation nozzle to one side of the tank, effectively creating a much larger volume-to-area ratio for gas release. The simulant rheologies were similar; Vessel A had a yield stress of 36 Pa with a consistency of 20 cP, while Vessel B used the same yield stress but a higher consistency of 27 cP.

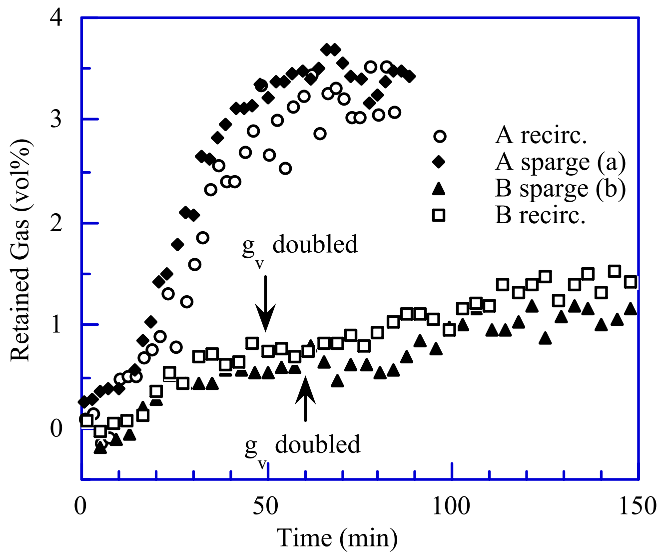

Fig. 3. Gas retention test results in scaled prototype vessels: (a) H/D = 1.8, (b) three PJM nozzles angled up at 135 degrees.

Based on experience with the ~1:4 scale prototype vessels, a third half-scale prototype test vessel was constructed to confirm gas retention and release performance under the intermittent mixing schedule planned for the WTP. The half-scale prototype was very similar to but about twice the scale of Vessel B, hence it is called Vessel 2xB. This vessel has a diameter of 3.89 m and a slurry depth of 3.62 m, and a cluster of eight 60-cm-diameter PJMs, similar to Vessel B except that the cluster was enclosed in a shroud congruent with the pitch circle of the peripheral PJMs to keep slurry out of the dead zone among the PJM tubes. Seven sparge tubes were spaced uniformly on a 2.8-m pitch diameter aligned in the gaps between PJMs. All seven spargers operated at a total air superficial velocity about twice that of the four spargers in Vessel B. No recirculation pump was provided. Though most of the tests, which are discussed later, used intermittent mixing, measurements of steady-state holdup with both spargers and PJMs operating were obtained at three gas generation rates.

Because mixing is not dominated by the action of PJMs in these hybrid systems, the correlation expressed by Eq. (14) does not apply. In fact, the three nondimensional groups related to PJM mixing do not correlate with the holdup number. However, the fundamental influence of the gas generation rate and slurry depth (actually volume-to-area ratio) is clear, even with widely different mixing systems.[4] Figure 4 plots the measured holdup (volume fraction of gas retained) against the product, g_vH, for both the scaled prototypes and the four-PJM tests described above. This is equivalent to plotting gas retention against the holdup number with a constant bubble rise velocity.

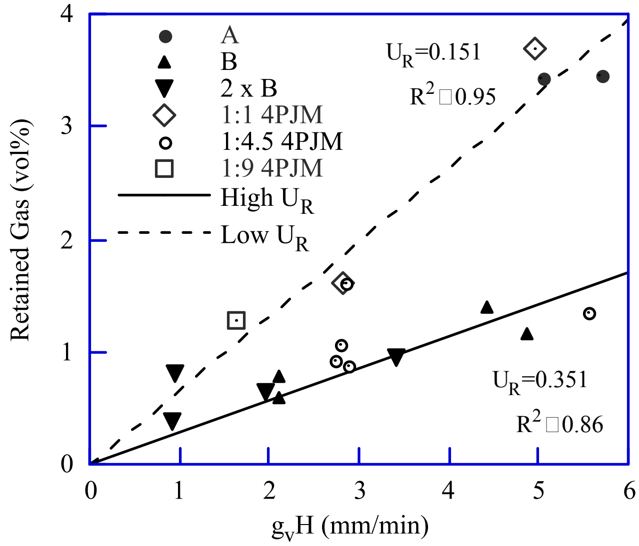

Fig. 4. Basic scaling of gas retention with gas retention and slurry depth at constant bubble rise velocity

The plot separates the data into two distinct groups, each well correlated by a linear curve fit through the origin. Equating the holdup number (Eq. 9) to the measured steady-state retained gas volume fraction, the slopes of the two lines are consistent with bubble rise velocities of 0.15 and 0.35 m/min. While both hybrid and four-PJM systems occupy both the high and low U_R lines, they appear to be differentiated generally by the degree or intensity of mixing. The tests fit by the low U_R line appear to have incomplete or less intense mixing compared with those on the high U_R line. The two high holdup data points from Vessel A on the low U_R line have already been discussed. The full-scale four-PJM test on the upper right used a very stiff simulant of 44 Pa yield stress, and both tests in this vessel had a relatively low peak PJM nozzle velocity, ~80% of the 1:4.5-scale four-PJM tests. The one result from the 1:4.5-scale four-PJM series that overlays the full scale four-PJM data point also used clay with a high yield stress (40 Pa). The other 1:4.5-scale tests that lie on the high U_R line used relatively weak clay with yield stress from 7 to 18 Pa. The single test in the 1:9 scale four-PJM vessel likely suffers from the fact that the jet Reynolds number is not preserved at small scale with a uniform rheology, making the slurry in the PJM mixing cavern effectively more viscous at small scale. In the 1:9-scale system, this effect and a lower PJM jet velocity may have become sufficiently powerful to prevent complete mixing. Given that the four tests in Vessel B on the high U_R line had either four peripheral spargers or four up-angled recirculation nozzles operating along with eight PJMs at double the peak nozzle velocity of the four-PJM systems, we may assume the simulant is well-mixed. With an even greater sparge air flow, the three data points from half-scale Vessel 2xB should be at least as well-mixed. However, the one test in Vessel 2xB on the low U_R line used spargers only, no PJMs. Independent tests and calculations showed that this mode mixed only about 60% of the slurry volume.[4]

Thus, tests on the high U_R line using systems with or without spargers and recirculation systems, and with a wide range of slurry rheology and physical scales, all have the same bubble rise velocity. The same can be said for tests on the low U_R line. However, the low U_R group is characterized by generally higher simulant yield stress and consistency, lower PJM jet velocity, or fewer components of the mixing system operating. The high U_R group has a lower stimulant yield stress and consistency or high PJM nozzle velocity and better distributed larger sparger and recirculation flows. Though the differences can be explained qualitatively in terms of mixing systems and slurry properties, it is unclear why the differences bin the tests so conspicuously into two distinct bubble rise velocities about a factor of two apart.

The observation that a wide variety of configurations and conditions can be described by the same bubble rise velocity implies that the gas inventory model defined by Eq. (6) and (7) should also represent the test data well. Figure 5 presents a fit of the model to retained gas volume data from a combined gas holdup and release test in Vessel B.[3] The predicted hydrogen peroxide mass is also plotted. The two-stage holdup test started from a zero-gas state in which hydrogen peroxide solution was injected at two different rates with the mixing system (8 PJMs and four spargers) operating continuously. After the gas holdup reached a constant value with the higher gas generation rate (~190 minutes in Figure 5), hydrogen peroxide injection stopped and the mixing system was shut down for 30 minutes to allow gas to accumulate. At this point the mixing system was restarted to release the accumulated gas. The hydrogen peroxide decomposition rate constant, A_g, and the bubble rise velocity, U_R, in the model were adjusted to minimize the error in the two test stages. These same constants were then applied to the accumulation and release stages, except that U_R was set to zero for the accumulation phase. Qualitatively similar results were obtained for the other test in Vessel B and the two tests in Vessel A, except for persistent gas retention in the latter stages of the gas release tests, possibly the result of density stratification.[3] That a single value for the bubble rise velocity in a simple gas inventory model provides a good match for data from both gas retention and release processes shows that bubble migration is the dominant mechanism.

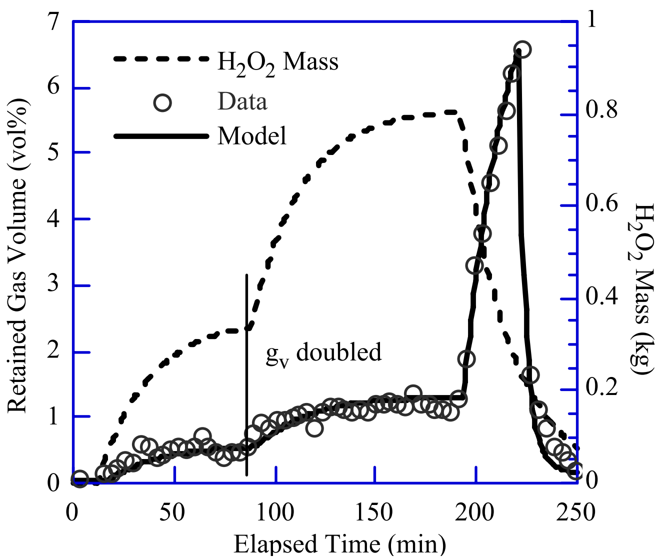

Fig. 5. Predictions of gas inventory model compared with data from Vessel B, test 1

Intermittent Mixing

While the mixing action in a PJM mixing system is inherently cyclic, the overall system performance over long periods represents essentially a steady state, more so in hybrid systems where steady sparger air flows cancels some of the cyclic effects from the PJMs. However, the Hanford WTP is designed to operate intermittently on a time scale of several hours, an order of magnitude greater than the PJM cycle time. The normal plant operating cycle is to run PJMs continuously with spargers at full flow for one hour and at idle flow (about 5% of full flow to prevent slurry ingress and potential plugging) for two hours. Two additional off-normal cycles were defined depending on the availability of compressed air: run spargers at full flow and PJMs for two hours with idle-flow sparging only for 12 hours (Cycle A), and run spargers at full flow for two hours and at idle flow for 12 hours (Cycle B).

Confirmatory tests of these three intermittent operating cycles were performed with the half-scale system of Vessel 2xB. To maintain correct scaling, the PJM cycle time and durations of the various operating modes in each cycle were reduced by the geometric scale factor of two. For example, the half-scale off-normal Cycle A test ran spargers at full flow with PJMs for one hour and idle-flow sparging for six hours. It was difficult to simulate the constant, uniform gas generation expected in the plant with hydrogen peroxide decomposition. The hydrogen peroxide solution could only be injected while the simulant was being mixed; it could not be injected in near-stagnant conditions during idle sparging. Thus a large volume of additional solution was injected during the mixing period to provide gas generation during the longer idle period. However, the relatively rapid decomposition rate also required the idle period to be shortened from six to two hours to avoid long periods of essentially zero gas generation. The details of these half-scale tests are given in.[4]

The three operating cycles consisted of various combinations of four operating modes: PJMs plus full-flow sparging, PJMs plus idle-flow sparging, full-flow sparging only, and idle-flow sparging only. Based on the experience with steady-state data described above, we believed that all three tests could be represented by applying a single value of bubble rise velocity for each mode. These values were extracted by fitting the gas inventory model to the entire set of test data. Uncertainties in the measurements and properties were included by assigning a probability distribution to each parameter and performing the error minimization procedure within a Monte Carlo simulation.[4] An example of the model fit to off-normal Cycle A is shown in Figure 6.

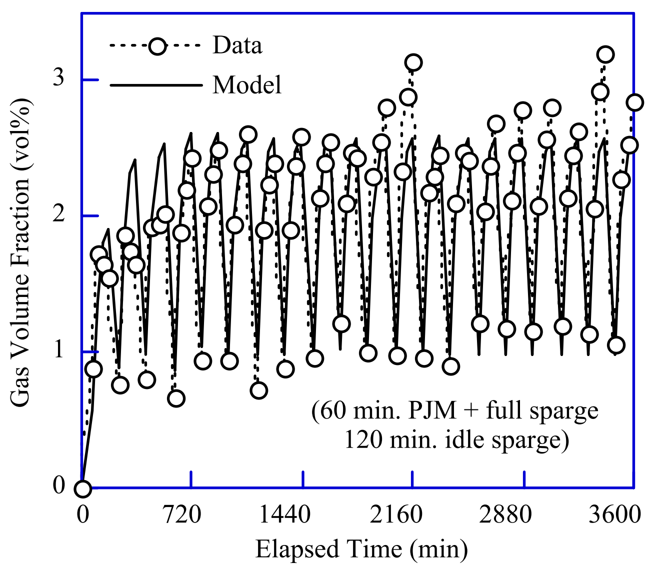

Fig. 6. Comparison of the gas inventory model and data for intermittent mixing

The resulting probability distributions of the bubble rise velocity for each operating mode are shown as a histogram in Figure 7. It is noteworthy that intermittent operation reduced the bubble rise velocity for PJM plus full-flow sparging from its place on the high U_R line in Figure 5 to a value consistent with the low U_R line. But the full-flow sparging-only mode remained close to its original value. This change may be because the PJM plus full-flow sparging mode typically operated for only half an hour at a time, probably not long enough to reach steady state. On the other hand, the full-flow sparging mode ran for one or two hours at a time. The bubble rise velocity for PJMs with idle sparging was about double that of idle sparging alone and about 1/3 of the highest two modes. Until additional data become available, it is not known whether these lower bubble rise velocities represent other sharply defined "quantum states" like the two shown in Figure 5. Assuming this is at least approximately true, these same bubble rise velocities can be applied in the gas inventory model to predict full-scale plant behavior during these same intermittent operations (with the durations at their full-scale values).

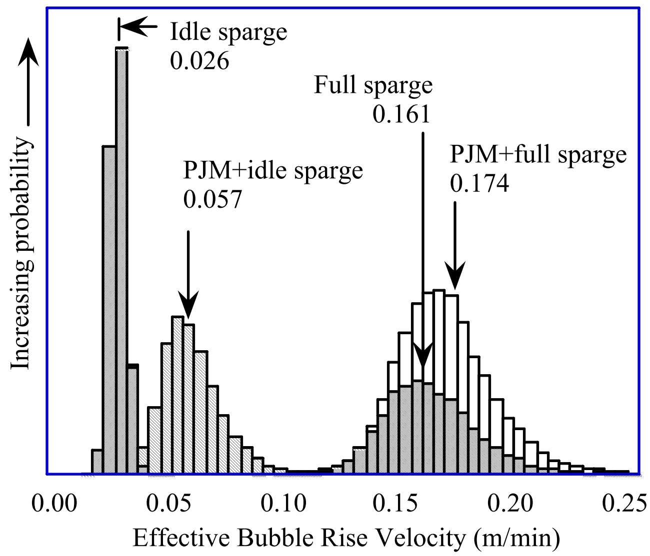

Fig. 7. Distribution of bubble rise velocities for four operating modes

CONCLUSIONS

The test results and the simple gas inventory model confirm that the theory of bubble migration in a well-mixed slurry describes gas retention and release in non-Newtonian slurries in PJM mixing systems and hybrid systems including air sparging and recirculation with PJMs. The model and theory apply to continuous cyclic operations (e.g., continuous PJM operation with drive cycles on the order of one minute) as well as intermittent operation over periods on the order of hours.

With PJM-only systems, gas retention correlates well with the three nondimensional groups defined for jet mixing in non-Newtonian slurries: the yield Reynolds number, the jet Reynolds number, and the Strouhal number. However, gas retention in hybrid mixing systems is correlated only with the product of volumetric gas generation and slurry depth. The test data, including PJM-only systems, seem to indicate that gas retention behavior falls into one of two distinct groups with different uniform bubble rise velocities: 0.35 m/min in well-mixed systems and 0.15 m/min in less well-mixed systems. However, what constitutes membership in either group can only be defined qualitatively at this time. A quantitative, parametric description of mixing as it directly affects gas retention is needed.

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