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CONCENTRATION DISTRIBUTION DURING PULSE JET MIXING

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ABSTRACT

Obtaining real-time, in situ slurry concentration measurements during unsteady mixing can provide increased understanding into mixer performance. During recent tests an ultrasonic attenuation sensor was inserted into a mixing vessel to measure the slurry concentration during unsteady mixing in real time during pulse jet mixer operation. These pulse jet mixing tests to suspend noncohesive solids in Newtonian liquid were conducted at three geometric scales. To understand the solids suspension process and resulting solids distribution, the concentration of solids in the cloud was measured at various elevations and radial positions during the pulse jet mixer cycle. In the largest scale vessel, concentration profiles were measured at three radial locations: r = 0, 0.5 and 0.9 R where R is the vessel radius. These radial concentration data are being analyzed to provide a model for predicting concentration as a function of elevation.

This paper describes pulse jet mixer operation, provides a description of the concentration probe, and presents transient concentration data obtained at three radial positions: in the vessel center (O R), midway between the center and the wall (0.5 R) and near the vessel wall (0.9 R) through out the pulse to provide insight into pulse jet mixer performance.

INTRODUCTION

The Hanford Waste Treatment Plant (WTP) is applying pulse jet mixer (PJM) technology for slurry mixing applications requiring solids mixing, solids suspension, fluid blending, and release of gases generated by radiolysis and thermal processes.[1-6] During normal mixing operations the process areas of concern are solids re-suspension and overcoming increased rheological properties associated with solids settling. Scaled tests with noncohesive solids in Newtonian liquids[7-9] were conducted to evaluate issues related to mixing system designs that could result in insufficient mixing and/or extended mixing times.

This paper describes pulse jet mixer operation, provides a description of the concentration probe, and presents transient concentration data obtained at three radial positions: in the vessel center (0 R), midway between the center and the wall (0.5 R) and near the vessel wall (0.9 R) through out the pulse to provide insight into pulse jet mixer performance.

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NOMENCLATURE

C(r, z, t)	solids vertical concentration distribution
D	diameter
d	nozzle diameter
DC	duty cycle
D_{PT}	pulse tube diameter
d_S	solids diameter
Fr	Froude number
g	gravitational constant
H	fluid fill or operating level
H_C	solids cloud height
N	number of pulse jets in the vessel
N_J	number of operating pulse jets
N_o	number of pulse jets in outer ring
R	vessel radius
R_o	radius of outer ring of pulse jets
Re	jet Reynolds number
r	radial location
s	density ratio
t_C	cycle time
t_D	discharge time at end of pressurization
t_{DA}	actual drive time
U	nozzle exit velocity
U_{CS}	complete suspension velocity
U_{peak}	peak velocity
V_P	volume of fluid dispelled during a pulse
V_{PT}	pulse tube volume
V_{REF}	reference volume = $\pi D^3/4$
V_S	volume of solids
V_T	volume of tank
ΔH	level increase during PJM discharge
ΔL	level change in the tube during discharge
ϕ_J	jet density
ϕ_P	pulse volume fraction
ϕ_{PT}	ratio of pulse tube to vessel cross-sectional area
ϕ_S	solids volume fraction
ν	kinematic viscosity
μ	viscosity
ρ_l	liquid density
ρ_s	solids density

PULSE JET MIXER OPERATION

Pulse jet mixers differ from steady jet mixers and mechanical agitators. The components of a PJM system are shown in Figure 1. The vessel has diameter (D), volume (V_T), and fill level (H). There are N pulse jets in the vessel, each with pulse tube diameter (D_{PT}) and volume (V_{PT}). Each PJM has a conical nozzle with diameter (d). The volume of fluid dispelled during a pulse (V_P) is about 80% of the pulse tube volume to avoid the potential for a pressurized air overblow (when air is expelled through the PJM nozzle). Typically, the total pulse volume (NV_P) is approximately 5 to 10% of the operating volume of the vessel. The level change in the tube during discharge is ΔL with a corresponding increase in fill level (ΔH) which is also about 5 to 10% of the operating level (H). The jet velocity associated with this cyclic process is shown in Figure 2.

During pulse jet mixing, pressurized air is used to expel the fluid contained in the pulse tubes through the nozzles into the vessel. During the drive phase the jet mixes with the fluid in the vessel and mobilizes and entrains solids. This mobilization and increase in cleared radius is shown through a window viewed from beneath the vessel in the sequence shown in Figure 3. After the completion of the drive phase, the high pressure air is vented, and vacuum is applied to the pulse tube to hasten the pulse tube refill. During the refill phase, solids suspended in the vessel may start to settle.

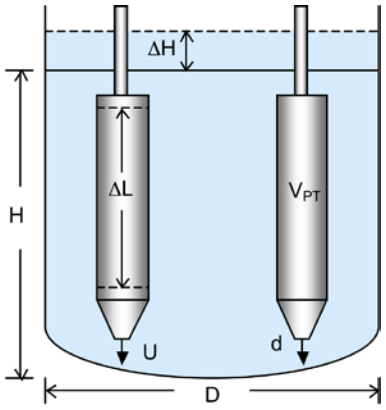


Figure 1. Pulse Jet Mixer System Components

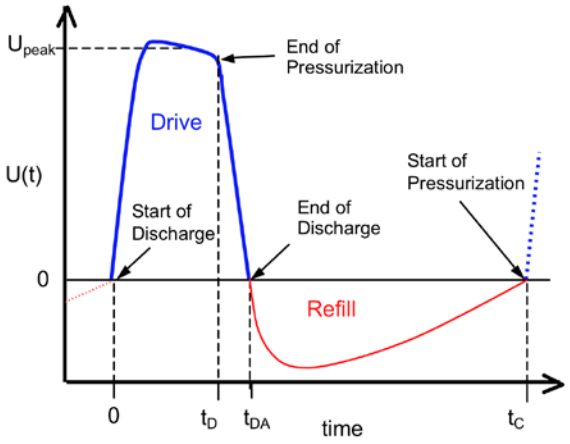


Figure 2. Jet Velocity during the Pulse Jet Mixer Cycle

The primary mixing system parameters: slurry properties, mixing system geometric parameters, and operational parameters are shown in Table 1. Mixing performance in general depends on the values of these parameters, which can be formed into an equivalent set of dimensionless groups.

Dimensional analysis applied to the physical parameters in Table 1 results in 11 (13 parameters constrained by consistency in three units, mass, length, and time) nondimensional variables when considering single-ring PJM configurations.[3] Double-ring PJM configurations introduce up to two more variables (N_o and R_o/D). The primary nondimensional variables are shown in Table 2. These nondimensional variables are not unique; others can be selected that favor physical insight or specific processes or provide better models of test data. However, they all can be expressed in terms of the physical parameters listed in Table 1.

Three metrics were selected for assessing mixing system performance.

U_{CS} – Complete Suspension Velocity: The velocity at which all solids on the vessel bottom are set into motion.

H_C – Solids Cloud Height: The maximum height the solids cloud achieves during a pulse.

C(r, z, t) – Solids Vertical Distribution: The solids concentration profile as a function of time and position.

[3] This is true because all single-ring PJM configurations have the same relative radial positioning (r/D). Hence, r/D is not a variable with respect to the plant mixing system designs.

The solids vertical distribution data for a PJM test in the large diameter vessel (1.78 m, 70 in.) with flanged and dished bottom at the velocity for complete suspension was obtained using an in situ attenuation probe to measure slurry concentration in real time.

Table 1. Primary Mixing System Physical Parameters

Slurry Properties/Variables	Symbol	Units
Solids diameter	d_S	μm
Solids volume fraction	ϕ_S	(a)
Solids density	ρ_s	g/cm^3
Liquid density	ρ_l	g/cm^3
Liquid kinematic viscosity	$\nu = \mu/\rho_l$	m^2/s
Geometric Configuration	**Symbol**	**Units**
Vessel diameter	D	m (in.)
Nozzle (jet) diameter	d	m (in.)
Number PJMs[(b)]	N	each
Radial location of PJMs[(b)]	r	m (ft)
Operational Parameters	**Symbol**	**Units**
Fill level	H	m (in.)
Pulse volume	V_P	m^3
Drive time	t_D	s
Cycle time	t_C	s
Jet velocity	U	m/s

(a) Indicates the parameter is nondimensional.
(b) Includes single and double rings.

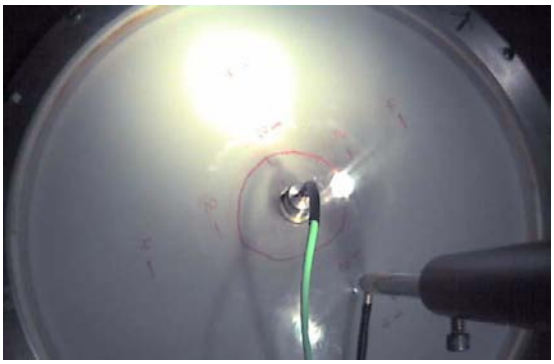
Table 2. Mixing System Nondimensional Variables

Slurry Property	Nondimensional Variable
Density ratio	$s = \rho_s/\rho_l$
Solids volume fraction	$\phi_S = V_S/ V_{REF}$
Particle diameter ratio	d_S/D
Geometric Properties	
Nozzle diameter ratio	d/D
Number of pulse tubes	N
Jet density	$\phi_J = N_J(d/D)^2$
PJM location	r/D
Ratio of pulse tube to vessel cross-sectional area	$\phi_{PT} = N(D_{PT}/D)^2$
Operational Parameters	
Fill level	H/D
Pulse volume fraction	$\phi_b = N V_P/ V_{REF}$
Duty cycle	$DC = t_D / t_C$
Jet Reynolds number	$Re = U d / \nu$
Froude number	$Fr = U^2 /[gd(s-1)]$

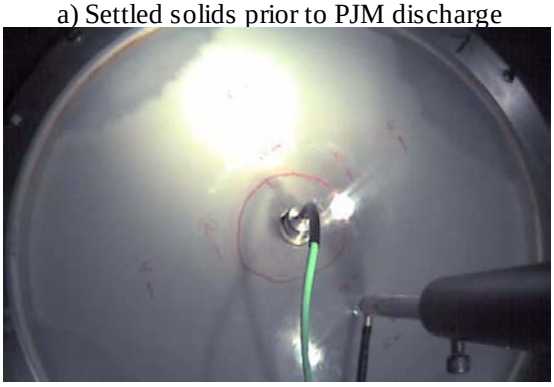
REAL TIME IN SITU MEASURMENT OF SLURRY CONCENTRATION

When ultrasound passes through slurry, the signal strength is reduced by the interaction of the ultrasound with the particles within the slurry.[10-11] This ultrasonic signal attenuation can be analyzed to provide real-time in-situ measurement of slurry concentration and particle size distribution.[12-15] This technique using a single transmitter-receiver pair was demonstrated to track concentration in a vessel during mixing.[16-20] Prior to sensor deployment, the sensor attenuation versus volume fraction response was calibrated using known slurry concentrations to permit interpretation of the on-line attenuation measurements.[21]

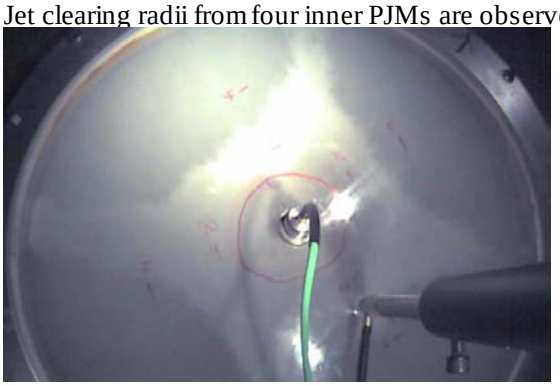
The sensor, shown in Figure 4, consists of two ultrasonic transducers a transmitter and receiver separated by 5 cm. The sensor is used to characterize the concentration as a function of elevation and radial location during cyclic, steady state operation of the pulse jet mixer. The sensor was placed in the vessel so that during the pulse jet operation the slurry passing between the transducers would be characterized in real time.



a) Settled solids prior to PJM discharge



b) Jet clearing radii from four inner PJMs are observed



c) Increased jet clearing radii

d) Approaching the U_{CS} condition

Figure 3. Solids Mobilization during Drive Phase Viewed through Window beneath Tank

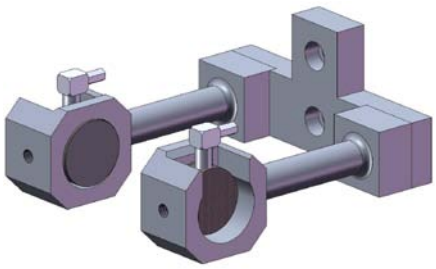


Figure 4. **Ultrasonic Probe Configuration**

An example of the repeatability of the measurements obtained at one location is shown in Figure 5. The measurements were taken over four sequential pulse cycles. These measurements were then averaged to provide data for a representative concentration at that location. Radial Concentration Measurements

Examples of concentration profiles obtained during PJM operation are shown in Figures 6, 7, and 8. The profiles in the left column were taken at the vessel center. The profiles in the middle column were taken midway between the vessel center and the wall. The profiles in the right column were taken near the vessel wall. In each of the plots the number in parenthesis in the title shows the number of cycles averaged to obtain the plot. The test conditions are listed in Table 3.

Table 3. Test Conditions

Property (Case ID)	Symbol	Value
Solids diameter (d2)	d_S	69.3 μm
Solids volume fraction (V)	ϕ_S	0.0143
Solids density (s1)	ρ_s	2.48 g/cm^3
Liquid		water
Vessel diameter (70)	D	1.788 m (70 in.)
Vessel head shape (F)		Flange and dish
Nozzle (jet) diameter (4)	d	1.557 m (0.613 in.)
Number of PJMs	N	12
Pulse volume fraction (_1)	ϕ_P	0.050
Duty cycle (c)	DC	33.6 %
Cycle time	t_C	44.2 s
Jet velocity	$U = U_{CS}$	7.1 m/s

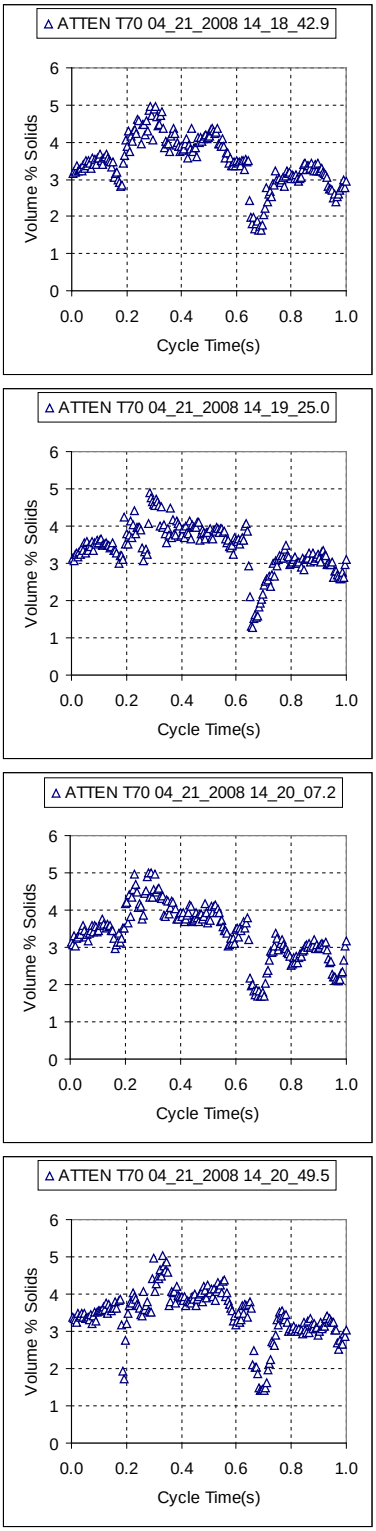


Figure 5. Slurry Concentration Variation during Four Consecutive Cycles at H/D = 0.3 and r/R = 0

During these measurements, the jet velocity was at the U_{CS} condition which means that all solids were in motion at the end of the discharge portion of the cycle. The solids were monodisperse glass beads manufactured by XLSciTech suspended in water. The concentration was measured continuously throughout the PJM cycle. Measurements shown in Figure 7 were obtained with the probe at the upper three vertical positions within the cloud (H/D = 0.35, 0.4, and 0.45).

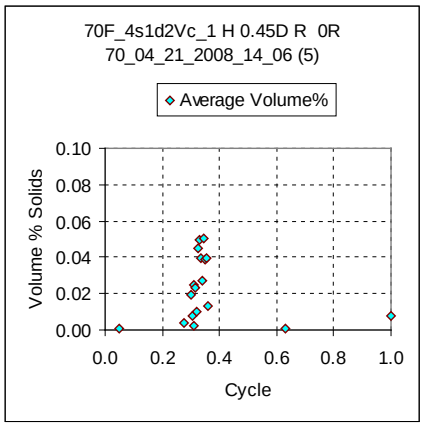
During the PJM cycle solids rose to an elevation of H/D = 0.45 at the center of the tank. No solids were measured at this elevation at the other two radii. The solids appeared at $0.3t_C$. The maximum solid concentration was ~0.05 Vol%.

At an elevation of H/D = 0.4 the maximum solids concentration occurred at a similar time but rose to nearly 4 Vol% solids.

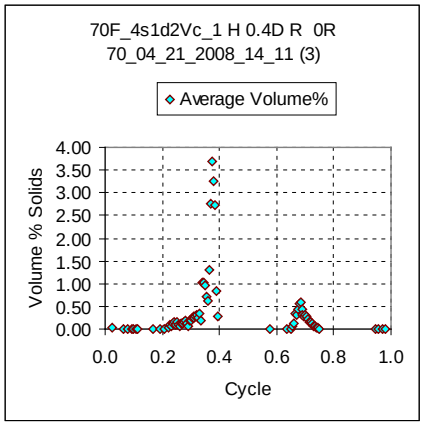
At an elevation of H/D = 0.35 solids were measured at all three radial locations. In each location the concentration peaked near 0.4 t_C. Also at the center and at 0.5 = r/R solids were present between 0.2 and 0.8 t_C. Near the wall solids were observed to 1 t_C. The solid concentration reached 4 Vol% at the center and half that 2 Vol% at the other two locations.

In Figure 7 the solids were measured throughout the cycle at all three elevations; H/D = 0.2, 0.25, and 0.3. In the vessel center at H/D = 0.2 the concentration shows a peak of 7 Vol% at 0.1 t_C. Higher in the vessel at H/D = 0.25 this peak drops to 6 Vol% and shifts to 0.15 t_C. Higher in the vessel at H/D = 0.3 this peak drops to slightly below 5 Vol% and shifts further in time to near 0.3 t_C. At the other two radial measurement locations the concentration remains relatively constant throughout the pulse with slightly more variation at the highest location.

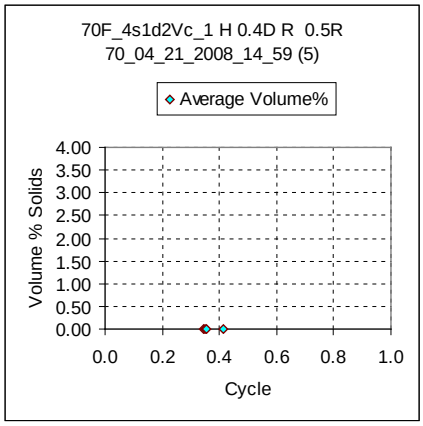
In Figure 8 the same trends are observed as in Figure 7. In the vessel center at H/D = 0.05 the concentration shows a peak of 8 Vol% before 0.1 t_C. Higher in the vessel at H/D = 0.1 this peak drops to slightly below 8 Vol% and shifts to 0.1 t_C. higher in the vessel at H/D = 0.15 this peak drops to near 7 Vol% and occurs at 0.1 t_C.



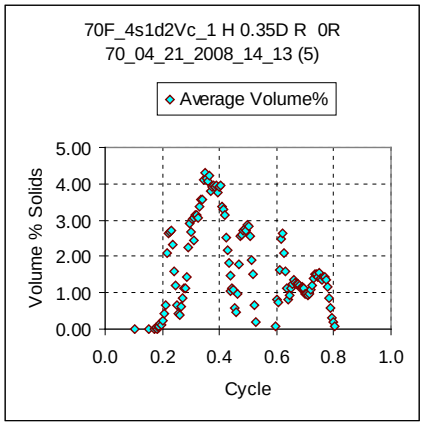
r/R = 0 and H/D = 0.45



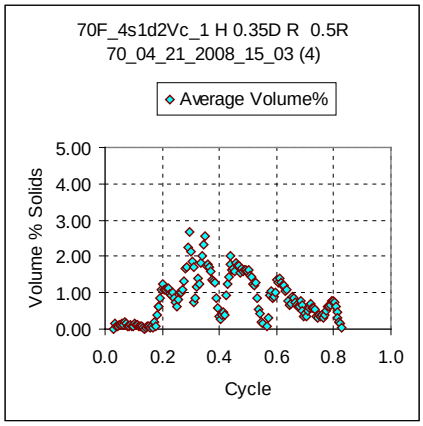
r/R = 0 and H/D = 0.4



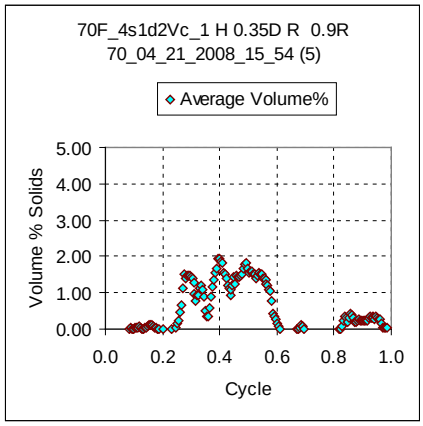
r/R = 0.5 and H/D = 0.4



r/R = 0 and H/D = 0.35



r/R = 0.5 and H/D = 0.35



r/R = 0.5 and H/D = 0.35

Figure 6. Concentration during the pulse at the three highest measurement elevations in the cloud

At H/D = 0.1 and 0.15 away from the center the concentration remains relatively constant throughout the pulse near 4 Vol%. However, at r/R = 0.5 and H/D = 0.5 the concentration peaks at 13 Vol% at near 0.1 t_C. This is the highest concentration observed during measurements made for these test conditions. The curvature of the flange and dish head prevented measurement of concentration at r/R = 0.9 at H/D = 0.05 and 0.1.

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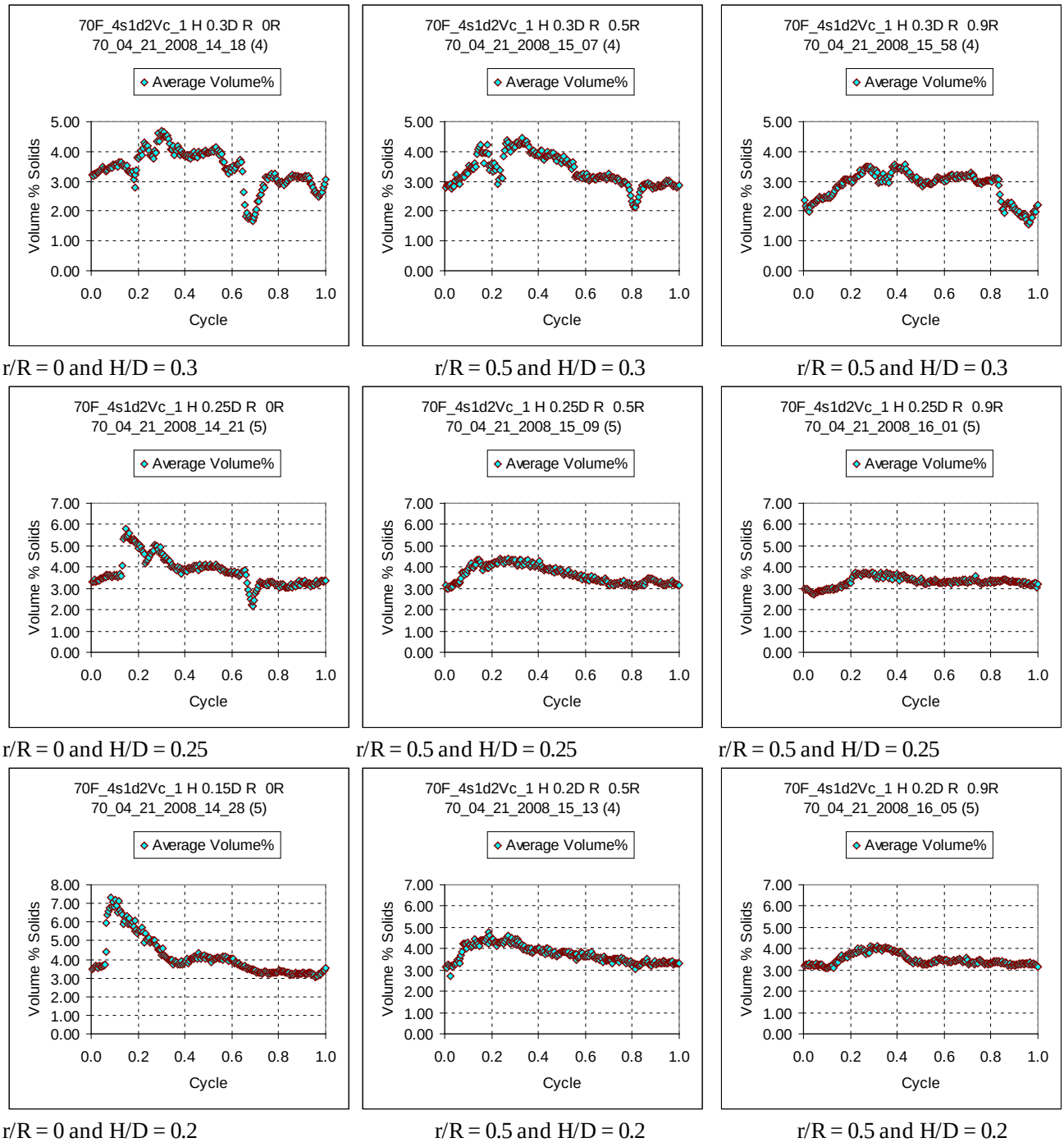
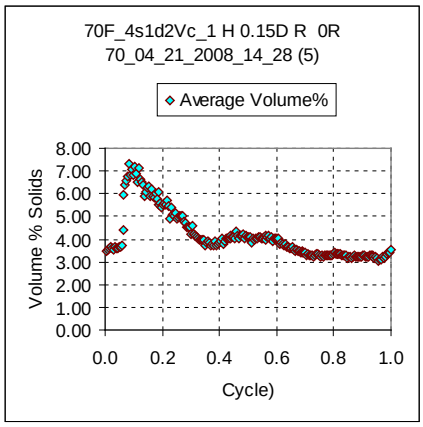
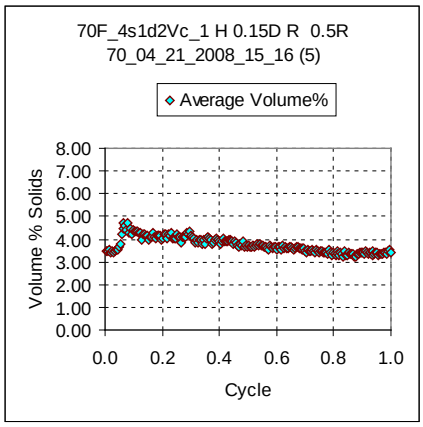


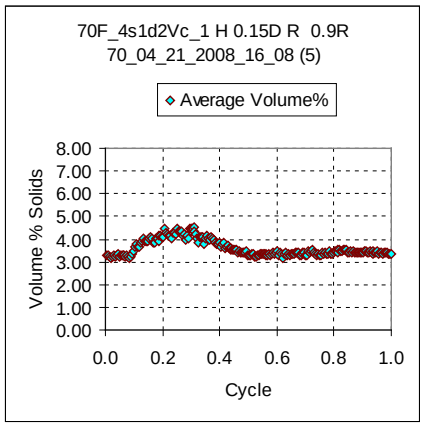
Figure 7 Concentration during the pulse at the three middle measurement elevations in the cloud



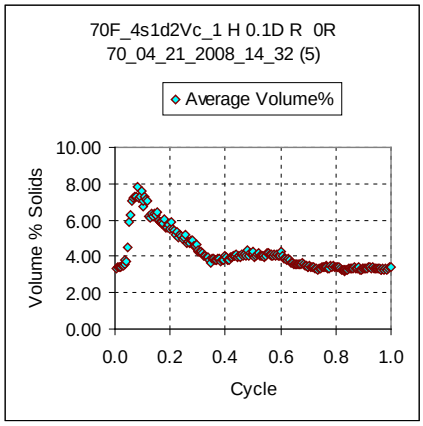
r/R = 0 and H/D = 0.15



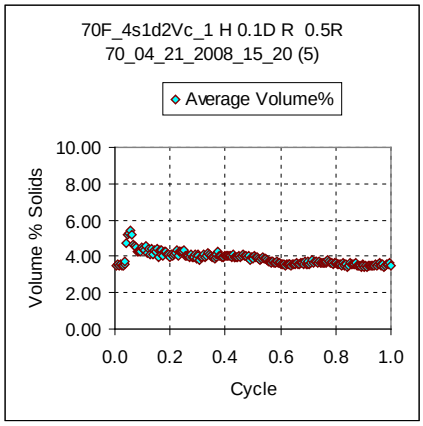
r/R = 0.5 and H/D = 0.15



r/R = 0.5 and H/D = 0.15



r/R = 0 and H/D = 0.1



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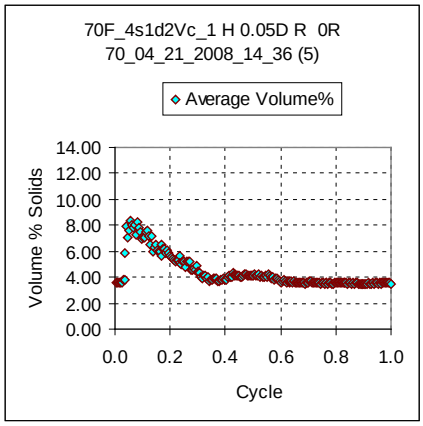
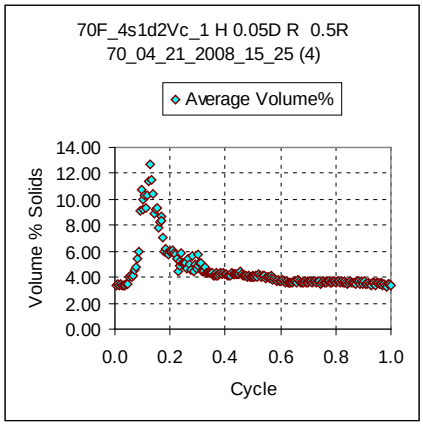


r/R = 0 and H/D = 0.05



r/R = 0.5 and H/D = 0.05

Figure 8. Concentration during the pulse at the three lowest measurement elevations in the cloud

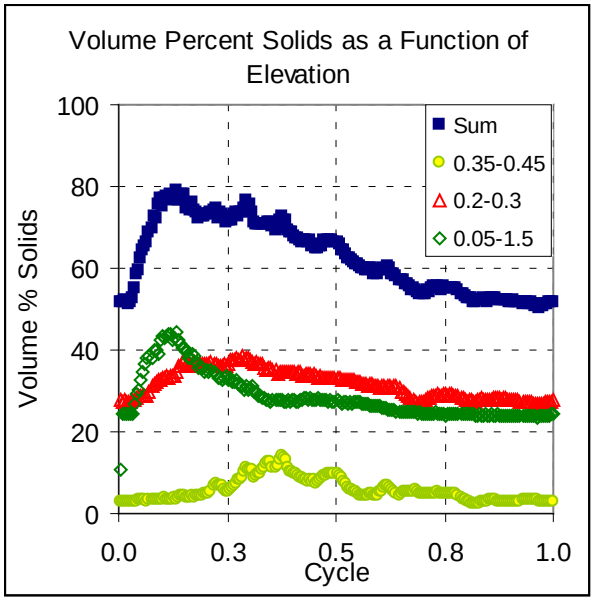


Figure 9. Volume Percent Solids Measured at Specified Elevations

The solids suspended during the cycle in the elevation range from H/D = 0.05 to 0.45 are plotted in Figure 9. This plot shows that the solids measured by the ultrasonic sensor account for about 80% near 1.5 t_C, The quantity of solids suspended in the lower and middle thirds of the cloud are similar with much less solids suspended in the upper third of the cloud.

Photographs of the cloud were taken during this test. They are shown in Figure 10. The first photo shows the maximum cloud height observed during the pulse. As shown in Figures 6 through 8 this would have occurred during the beginning of the drive cycle. The other photographs show what was observed at the start of the drive cycle, during the middle of the drive cycle, and the end of the drive cycle, and during the middle of the non drive portion of the cycle. The most distinct cloud photo occurs at the maximum cloud height early in the drive portion of the cycle.

CONCLUSIONS

Pulse jet mixing (PJM) tests with noncohesive solids in Newtonian liquid were conducted at three geometric scales to support the design of mixing systems for the Hanford Waste Treatment and Immobilization Plant. Measurements of the solids concentration at three radial locations within the mixed region were made to understand the solids distribution during the unsteady mixing process of the pulse jet mixers. Data at three radial locations were obtained and analyzed to provide insight into the solids distribution at the just suspended condition. This data complemented the visual measurement of cloud height.

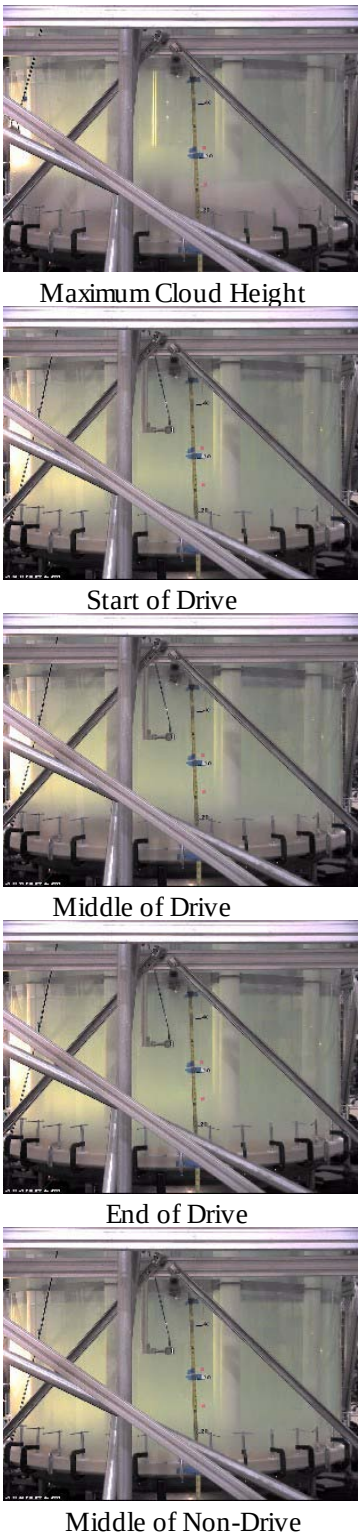


Figure 10. Observations of the Cloud during the Cycle

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