Jet Mixing Analysis for SRS High-Level Waste Recovery

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INTRODUCTION

The process of recovering the waste in storage tanks at the Savannah River Site (SRS) typically requires mixing the contents of the tank to ensure uniformity of the discharge stream. Mixing is accomplished with one to four slurry pumps located within the tank liquid. The slurry pump may be fixed in position or they may rotate depending on the specific mixing requirements.

The high-level waste in Tank 48 contains insoluble solids in the form of potassium tetraphenyl borate compounds (KTPB), monosodium titanate (MST), and sludge. Tank 48 is equipped with 4 slurry pumps, which are intended to suspend the insoluble solids prior to transfer of the waste to the Fluidized Bed Steam Reformer (FBSR) process. The FBSR process is being designed for a normal feed of 3.05 wt% insoluble solids. A chemical characterization study has shown the insoluble solids concentration is approximately 3.05 wt% when well-mixed. The project is requesting a Computational Fluid Dynamics (CFD) mixing study from SRNL to determine the solids behavior with 2, 3, and 4 slurry pumps in operation and an estimate of the insoluble solids concentration at the suction of the transfer pump to the FBSR process. The impact of cooling coils is not considered in the current work.

The work consists of two principal objectives by taking a CFD approach:

- To estimate insoluble solids concentration transferred from Tank 48 to the Waste Feed Tank in the FBSR process and
- To assess the impact of different combinations of four slurry pumps on insoluble solids suspension and mixing in Tank 48.

For this work, several different combinations of a maximum of four pumps are considered to determine the resulting flow patterns and local flow velocities which are thought to be associated with sludge particle mixing. Two different elevations of pump nozzles are used for an assessment of the flow patterns on the tank mixing. Pump design and operating parameters used for the analysis are summarized in Table 1. The baseline pump orientations are chosen by the previous work [Lee et. al, 2008] and the initial engineering judgement for the conservative flow estimate since the modeling results for the other pump orientations are compared with the baseline results. As shown in Table 1, the present study assumes that each slurry pump has 900 gpm flowrate for the tank mixing analysis, although the Standard Operating Procedure for Tank 48 currently limits the actual pump speed and flowrate to a value less than 900 gpm for a 29 inch liquid level. Table 2 shows material properties and weight distributions for the solids to be modeled for the mixing analysis in Tank 48.

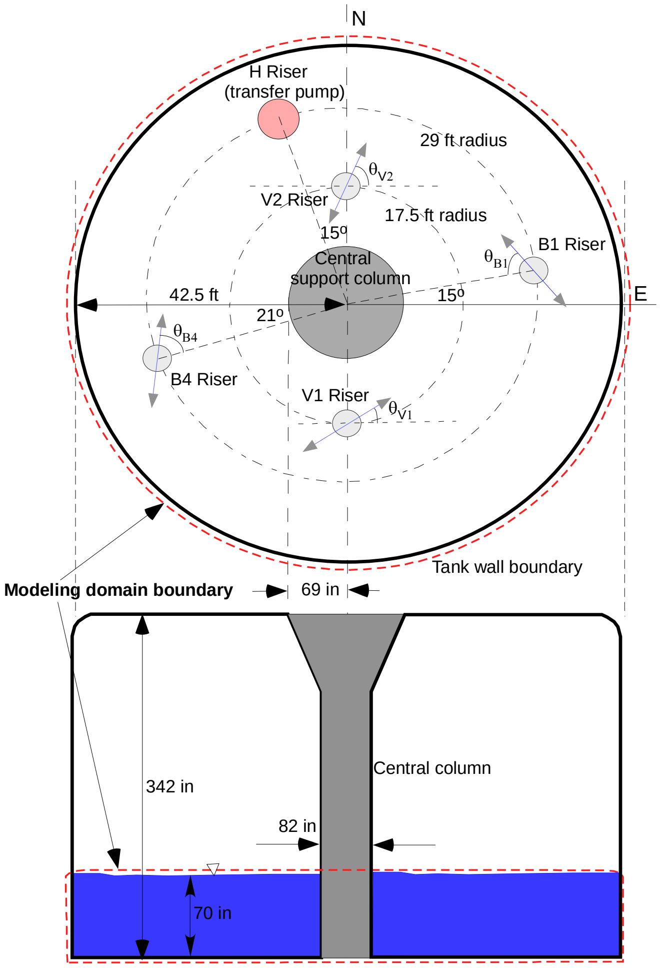

Figure 1. Geometrical configurations and three-dimensional modeling domain containing four slurry pumps and one transfer pump in the analysis of the Tank 48 performance model

Table 1. Pump design parameters for slurry pump used for the baseline analysis

Pumps	Slurry pump
Number of nozzles	2
Flow rate per nozzle, gpm	900 (2 nozzles)
Number of pumps	Up to 4
Nozzle diameter, d_o, inches	1.62
Pump rotation (for the present analysis)	No (Indexed pump)
Pump nozzle elevation above tank bottom (h_o in Fig. 1), inches	16.81" for B1 and B4 pumps, 19.81" for V1 and V2 pumps
Pump nozzle directions (angles in Fig. 1)	$\theta_{B1}=45^o$, $\theta_{B4}=45^o$, $\theta_{V1}=22.5^o$, $\theta_{V2}=67.5^o$
Tank liquid level, inches	70, 29*
Velocity at nozzle exit, U_o, ft/sec (m/sec)	70.04 (21.35)

Note:*Minimum tank liquid level for sensitivity analysis

Table 2. Material properties and weight distributions for the solids contained in Tank 48

Solids material	Solid size (microns)	Density (gm/cm^3)	Liquid level (inches)	Suspension velocity (m/sec)
MST	5	1.8	70	0.036
		2.765	70	0.053
KTPB	40	1.18	70	0.039
Sludge	16	1.2	70	0.028

DESCRIPTION OF THE ACTUAL WORK

A three-dimensional CFD approach is used to calculate flow patterns for the sludge mixing operations of Tank 48 and to evaluate sludge suspension capabilities for the tank. The work used two different solution methods for the modeling analysis. One is a single-phase CFD approach by using the previous method[1,2] since the model predictions were in good agreement with test data and operational observations. The other is a two-phase approach of fluid and solid phases to quantify the solid concentrations near the transfer pump. For the modeling calculations, a prototypic geometry is modeled by hexahedral and tetrahedral meshes over the computational domain. The modeling domain to be used for the present analysis is presented in Fig. 1. Nominal design and operating conditions of the pumps used in the Tank 48 model are presented in Table 1.

Based on the modeling domain and operating conditions, turbulent flow calculations were performed. Typical flow conditions for the slurry pump corresponds to fully-developed turbulent flow since Reynolds numbers are about 1×10^6 in terms of pump discharge conditions. For the turbulence calculations, the standard κ–ε model was used. The three-dimensional model was run in steady state mode for the indexed pump conditions to establish the jet flow patterns. For the single-phase approach, local fluid velocity at any distance from the nozzle is employed as a measure of the slurrying and mixing effectiveness in Tank 48H operations.

The present work focuses on suspending and mixing sludge particles with the turbulent jet generated by a combination of up to four slurry pumps in Tank 48. When liquid flow passes over a settled solids layer containing small solids of 1 to 50 microns, the range of the sludge particles in Tank 48H, it results in hydrodynamic forces being exerted on individual particles in the layer. For a particular stationary solids layer, a condition is eventually reached in which particles in the movable bed are not able to resist the hydrodynamic forces and solids in the top layer start to lift. Average flow velocity, particle size and density, and slurry flow regime are key parameters in determining the transport patterns of particles in a slurry[1]. The critical velocity is defined as the minimum velocity that can initiate the movement of the solids deposited near the bottom of the tank. Following the previous works[1,2], a literature correlation[6] for the critical velocity V_c was used.

$$V_c = \left(\frac{d}{H}\right)^{-0.1}\sqrt{2.5gd\left(\frac{\rho_s}{\rho_f}-1\right)} \qquad (1)$$

In Eq. (1), d and H are the particle diameter and tank liquid level, respectively. ρ_s and ρ_f are solid and fluid densities, respectively. When the flow velocity required for sludge transport and suspension is exceeded, the solid-laden flow can be treated as a suspended fluid-solid mixture. In this case, although solid particles are suspended by the continuous-phase flow, the local amount of solids suspended by the fluid may not be uniform over the entire domain of the tank fluid. However, the present work assumes that when the flow velocity required for sludge transport and suspension is exceeded and transient turbulent kinetic energy is dissipated throughout the tank in a quasi-steady condition, the solid-laden flow can be approximated as a homogeneous fluid. Thus, a flow velocity required for sludge suspension will be used as criteria for particle suspension from different pump combinations and operations in Tank 48. Table 2 shows minimum suspension velocities for particles of different mono-sized particle systems with different particle specific gravities (spg) with a tank level of 70 inches. Thus, local fluid velocity at any distance from the nozzle is employed as a measure of the slurrying and mixing criterion.

For the case of free settling of spherical particles of density ρ_p at a constant velocity and without interaction or hindering effects due to the presence of other particles, the drag force F_D equals the force of gravity F_G, including the buoyancy force of the particle of solid volume V_p submerged in a quiescent fluid.

$$F_G = V_p\left(\rho_p - \rho_f\right)g \;= F_D \tag{2}$$

When the particle has a spherical shape with diameter d_p, the drag force is related to the settling velocity v_f and the ratio of the particle volume to its projected area, $(2/3)d_p$. In the literature correlations[5], the velocity for flow past a single sphere was used in order to obtain an equation relating the settling velocity of a suspension of mono-size spherical particles to the volume concentration of the solid phase. The presence of other particles impedes the motion of a given particle in the same way as if there were an increase in the viscosity of the liquid, so that the effective relative viscosity would reduce the settling rate of the suspended particles.

The Oliver correlation[5] was used to capture the hindering effect of particle settling in a multi-particle system. Relative settling velocity V_r was correlated in terms of solids volume concentration, c.

$$V_r = \frac{v_s}{v_f} = \left(1 - 0.75c^{1/3}\right)\left(1 - 2.15c\right) \tag{3}$$

In Eq. (3), v_s is the settling velocity in a multi-particle system, and v_f is the settling velocity for a single particle in a fluid. The settling velocity of spherical particles was estimated for different solid contents in a slurry. Specific information on the waste characteristics for the present work assumes that the insoluble solids have particle sizes from 5 to 40 microns with a concentration of about 3.1 wt%, a slurry solids density of 1200 to 2800 kg/m^3, and a fluid viscosity of 1 x 10^{-3} Pa-s for a conservative estimate of the sludge settling rate.

Volume fractions of slurry solids (c) can be calculated as about 0.0246 for the present operating conditions when their weight fractions in a slurry flow are 0.0305. The calculations were performed by using Eq. (3) and the literature correlation for the settling rate of mono-sized spherical particles. The results show that it takes a range of about 2 hours to one day for the largest particles, KTPB solid, in a stagnant tank fluid to be settled down to the tank floor. It is noted that when the tank fluid is in motion, the settling time will be longer than the 2 hours' stagnant settling time.

RESULTS

A Tank 48 simulation model with a maximum of four operating slurry pumps has been developed to estimate flow patterns for efficient solid mixing. The modeling calculations were performed by using two approaches. As a primary approach, a single-phase CFD model was developed to evaluate the flow patterns and qualitative mixing behaviors for a range of different operating conditions since the model was previously benchmarked against the test results[1]. As a secondary approach, a two-phase CFD model was developed to estimate solid concentrations in a quantitative way by solving the Eulerian governing equations for the continuous fluid and insoluble solid phases over the entire tank domain. The calculation results for the two approaches were qualitatively compared for the same modeling conditions.

A series of sensitivity calculations for different numbers of operating pumps and operating conditions have been performed to provide operational guidance for solids suspension and mixing in Tank 48. In the analysis, the pumps were assumed to be stationary. Major solid obstructions such as the pump housing, the pump columns, and the 82 inch central support column were included. Steady state analyses coupled with a two-equation turbulence model for the uncoiled tank were performed with the FLUENT$^{\text{TM}}$ and CFX$^{\text{TM}}$ codes. Recommended operational guidance was developed assuming that local fluid velocity can be used as a measure of solids suspension and spatial mixing under a single-phase tank model. For quantitative analysis, a two-phase fluid-solid model was developed for the same modeling conditions as the single-phase model. Figure 2 compares steady state flow velocities of the mixing jet with the literature data along the principal discharge line inside Tank48

The main conclusions drawn from the Tank 48 modeling and calculations are as follows:

- The recent results[1,2] show that it takes about one hour to suspend the tank solids adequately at the transfer pump suction with four slurry pump operations in Tank 48.
- Estimations of minimum suspension velocity and particle settling rate were made for establishment of a flow velocity criterion required for solids suspension and for determination of settling time after stoppage of slurry pump operation.
- The two baseline models of the single-phase and two-phase simulations were developed with four pumps operating to evaluate flow circulation patterns and solid concentrations for the solid mixing operations of Tank 48. The flow pattern results for the single-phase model are qualitatively consistent with those of the two-phase model.
- The calculation results show that the flow patterns driven by four pump operation satisfy the solid suspension requirement, and the average solid concentration at the plane of the transfer pump inlet is about 12% higher than the tank average concentrations for the 70 inch tank level and about the same as the tank average value for the 29 inch liquid level.
- The flow pattern results show that when more than one jet are aiming at the same position of the mixing tank domain, inefficient flow patterns are provided

due to the highly localized momentum dissipation, resulting in inactive suspension zone.

- The modeling results show that when one of the four pumps is not operated, the flow patterns satisfy the minimum suspension velocity criterion. However, the solid concentration near the tank bottom is increased by about 30%, although the average solid concentrations near the transfer pump inlet have about the same value of the four-pump baseline results.
- It is noted that when tank liquid level is reduced from the highest level of 70 inches to the minimum level of 29 inches for a given number of operating pumps, the solid concentrations become more uniform over the tank fluid domain since the ratio of the pump power to the mixing volume becomes larger. These results are consistent with the literature results.

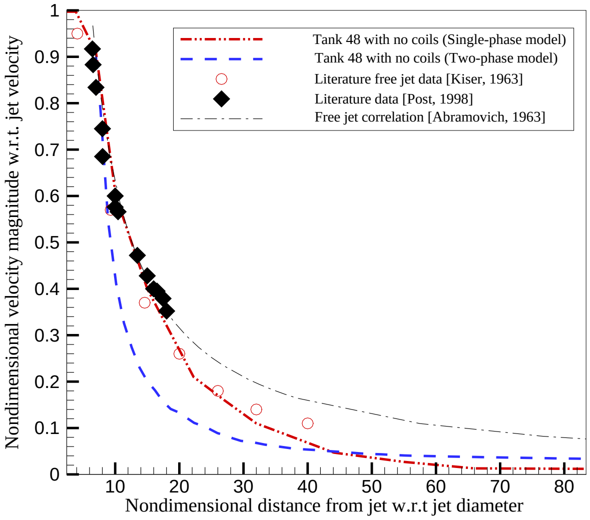

Figure 2. Comparison of steady state flow velocity of the mixing jet with the literature data along the principal discharge line inside Tank48

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