PROCEEDINGS OF ATH '12
SAN DIEGO, CA, NOVEMBER 11-15, 2012
PAPER# 6089

Blending Analysis for Radioactive Salt Waste Processing Facility

Si Y. Lee
Savannah River National Laboratory
Savannah River Site
Aiken, SC 29808
Phone: (803) 725-8462
si.lee@srnl.doe.gov

Abstract - Savannah River National Laboratory (SRNL) evaluated methods to mix and blend the contents of the blend tanks to ensure the contents are properly blended before they are transferred from the blend tank such as Tank 21 and Tank 24 to the Salt Waste Processing Facility (SWPF) feed tank. The tank contents consist of three forms: dissolved salt solution, other waste salt solutions, and sludge containing settled solids. This paper focuses on developing the computational model and estimating the operation time of submersible slurry pump when the tank contents are adequately blended prior to their transfer to the SWPF facility.

A three-dimensional computational fluid dynamics approach was taken by using the full scale configuration of SRS Type-IV tank, Tank 21H. Major solid obstructions such as the tank wall boundary, the transfer pump column, and three slurry pump housings including one active and two inactive pumps were included in the mixing performance model. Basic flow pattern results predicted by the computational model were benchmarked against the SRNL test results and literature data. Tank 21 is a waste tank that is used to prepare batches of salt feed for SWPF. The salt feed must be a homogeneous solution satisfying the acceptance criterion of the solids entrainment during transfer operation. The work scope described here consists of two modeling areas. They are the steady state flow pattern calculations before the addition of acid solution for tank blending operation and the transient mixing analysis during miscible liquid blending operation. The transient blending calculations were performed by using the 95% homogeneity criterion for the entire liquid domain of the tank. The initial conditions for the entire modeling domain were based on the steady-state flow pattern results with zero second phase concentration. The performance model was also benchmarked against the SRNL test results and literature data.

I. INTRODUCTION

Nuclear waste is stored at Savannah River Site (SRS) in 49 underground storage tanks that vary in capacity from 850,000 to 1.3 million gallons. Waste in the tanks exists in different forms: saltcake, supernate, and sludge. Precipitated radioactive salts, or saltcakes, nearly fill some tanks. In other tanks, combinations of saltcake, supernate, and sludge are present in different ratios. The sludge is a dense, viscous liquid comprised of water and solids settled to the tank bottom, where the sludge solids consist of soluble solids predominated by $NaNO_3$, $NaNO_2$, $NaAlO_2$, Na_2CO_3, and Na_2SO_4. The insoluble solids contain small quantities (< 1% each) of radioactive and stable fission products, but the principle insoluble components are $Fe(OH)_3$, $Al(OH)_3$, MnO_2, $CaCO_3$, zeolite, and SiO_2. Iron and aluminum are the predominant solids in the sludge. Supernate is the term for the salt solution above the sludge layers settled at the bottom floors of the tanks, and in addition to soluble salts the supernate contains radioactive Cesium.

Although there are numerous nuclear waste processes at SRS, each waste form has a primary process associated with long term disposition of that specific waste. Sludges are vitrified into a radioactive glass form at the Defense Waste Processing Facility for future storage. Saltcakes are rewetted into solution and blended with grout for permanent storage at the Saltstone Facility. Of specific interest to this work, supernates, or salt solutions, are planned to be decontaminated and processed at the Salt Waste Processing Facility (SWPF).

Prior to transferring the salt solutions to the SWPF Facility, 300,000 to 800,000 batches of salt solutions will be blended in storage tanks in the tank farms, which will be specified to be blend tanks. These blend tanks are part of a salt solution disposition strategy, referred to as the Salt Disposition Integration (SDI) Projects. The specific task considered here is the blending of salt solutions to ensure that the blended salt solutions are homogeneously blended.

The objective of the present work is to develop the computational fluid dynamics (CFD) models to predict blending time in tank to mix and blend the tank contents. Disturbance of the settled sludge on the tank bottom is permitted during the blending operation, and estimates for the time required for different size sludge particles to settle was estimated by calculations, using the Phase 1 and Phase 2 SDI data [1,2] and other SRS sludge data. The exact settling times will be indeterminate, since sludge properties and volumes in Tanks 21 and 24 are unknown.

II. MODELING APPROACH AND SOLUTION METHOD

The salt feed must be a reasonably homogeneous solution prior to transfer operations to SWPF when disturbance of the settled sludge on the tank bottom is permitted. To consider this blending process, the primary objective of the work was to estimate the blending time of the miscible tank solutions using the existing Standard Slurry Pump in Tank 21, before transferring the solutions to the SWPF feed tank. During transfer operations of the blended tank contents to the SWPF, solids entrainment of the sludge particles must be controlled to less than 1200 mg/liter by allowing the solids disturbed by the blending operation to be settled on the tank floor.

A two-stage operation strategy for the waste processing in Tank 21 was taken for satisfaction of two operation requirements such as solution homogeneity and solids entrainment criterion. For the first stage, the homogeneous blending of tank contents needs to be established during the mixing period. The second one is to allow the settling time for insoluble solid sludge to be settled down, prior to transfer operation of the tank contents blended by the first stage. In this case, the particle size ranges from 1 micron up to about 60 microns. The time required for different size sludge particles to settle was conservatively estimated by calculations [1,2]. This work is focused on the evaluation and analysis of the Tank 21 blending to satisfy the homogeneous mixing requirement.

A three-dimensional CFD approach was taken to achieve the objectives. The commercial finite volume code, FLUENT, was used to create a full scale geometry file in a non-orthogonal mesh environment. The model geometry was created using the body-fitted coordinate system and structured multi-block grids. For the blending calculations and analysis, the reference modeling conditions were considered as shown in Figure 1 and Table 1. The blending pump is submerged inside a cylindrical tank that is 345 inches high in solution level and 85 feet in diameter. The nozzle diameters equaled 1.5 inches, and the dual opposing nozzles were directed parallel to the tank wall as shown Figure 1.

For the modeling calculations, the governing equations consisted of one mass balance, three momentum equations, two turbulence transport equations for kinetic energy (k) and dissipation rate (ε), and one species transport equation. These equations were solved by an iterative technique until the species concentrations of tank fluid were reached at equilibrium concentration within 5% relative error, which represented the 95% blending criterion. The relative error ε_m was estimated by Eq. (1). The steady-state flow solutions for the entire tank fluid were used for the initial conditions.

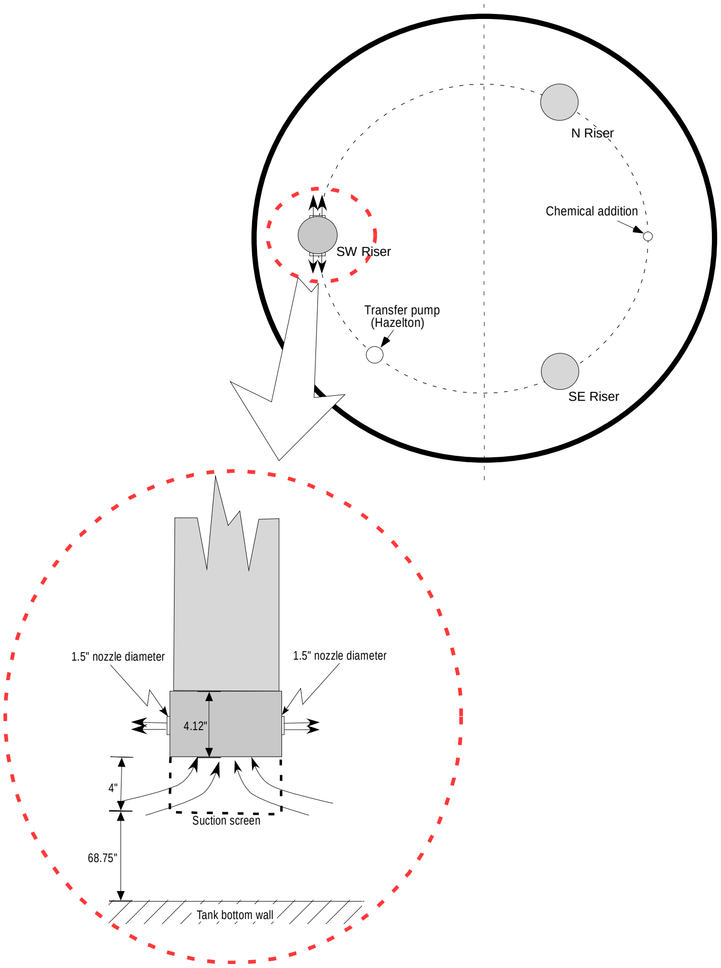


Figure 1. Modeling geometry used for the Tank 21 blending time calculations of the standard slurry pump with dual jets

$$\varepsilon_m = \left| \frac{C - C_{eq}}{C} \right| < 0.05 \qquad (1)$$

The parameters in Eq. (1), C_{eq} and C, are equilibrium and transient concentrations at a monitoring point, respectively.

In the analysis, the upper liquid surface in the tank was assumed to be frictionless for computational efficiency, neglecting the detailed wave motion of the free surface. That behavior does not have a significant impact on the flow patterns inside the blending region, since there is a large separation distance of about 276 inches between the top liquid surface and the discharge nozzle in this 345 inch deep tank.

Table 1. Pump design and modeling parameters for slurry pump used for the blending operations at SRS

Pumps		Standard slurry pump
Tank diameter, ft		85 (= 25.908 m)
Tank liquid level, inches		345 (= 8.763 m)
Power, hp		300
Number of nozzles		2
Flow rate per nozzle, gpm		600 (= 0.038 m^3/sec)
Number of pumps		1
Nozzle diameter of standard slurry pump, inches		1.5 (= 0.0381 m)
Pump rotation		No (Indexed pump)
Tank fluid properties (Nitrate)	Density, gm/ml	1.32
	Viscosity, cp	2.26
Pump nozzle elevation above tank bottom, inches		68.75 (= 1.7463 m)
Velocity at nozzle exit ft/sec (m/sec)		108.9 (33.2)
$U_o d_o$, $m^2 sec^{-1}$ ($ft^2 sec^{-1}$)		1.265 (13.6)

The fluid properties of salt solution were applied at constant temperature (20°C), as listed in Table 1. The flow conditions for the pump operations were assumed to be fully turbulent since Reynolds numbers for typical operating conditions are in the range of 7 $x10^5$ to 1.0 $x10^6$, in terms of the pump nozzle inlet conditions. A standard two-equation turbulence model, the κ–ε model [7] was used to capture the turbulent flow evolution driven by the dual jets of the blending pumps. To further demonstrate the applicability of the turbulence model, previous work [7,9] showed that the two-equation model predicted the flow evolution of turbulent jets in a large stagnant fluid domain with reasonable accuracy. This model specifies the turbulent or "eddy" viscosity ν_t by the empirical equation.

$$\upsilon_t = \frac{\mu_t}{\rho_f} = \left(\frac{C_\mu k^2}{\varepsilon} \right) \qquad (2)$$

In Eq. (2), C_μ is an empirical constant. In the present calculations, C_μ equals 0.09. Thus, the turbulent energy dissipated by the blending operation is computed by solving two transport equations for k (turbulent kinetic energy), and ε (rate of dissipation of turbulent energy).

From these two key parameters of k and ε, a length scale ($k^{1.5}/\varepsilon$), a time scale (k/ε), and a quantity of turbulent eddy diffusivity (k^2/ε), can be formed without specification of a flow-dependent mixing length scale λ [11]. Turbulence kinetic energy (k) is the mean kinetic energy per unit mass associated with eddies in turbulent flow. Physically, the turbulence kinetic energy is characterized by measured root-mean-square (rms) velocity fluctuations. In the Reynolds-averaged Navier Stokes equations, the turbulence kinetic energy can be calculated based on the closure method, i.e. a turbulence model. Generally, the turbulent kinetic energy can be quantified by the mean of the turbulence normal stresses:

$$k = \frac{1}{2} \left\{ \overline{(u_x)^2} + \overline{(u_y)^2} + \overline{(u_z)^2} \right\} \qquad (3)$$

k can be produced by fluid shear, friction or buoyancy, or through external forcing at low-frequency eddie scales (integral scale). Turbulence kinetic energy is then transferred down the turbulence energy cascade, and is dissipated by viscous forces at the Kolmogorov scale. This process of production, convective transport, and dissipation as modeled for a k transport balance in the two-equation turbulence model can be expressed as:

$$\frac{Dk}{Dt} = \nabla \bullet \left(\frac{\upsilon_T}{\sigma_k} \nabla k \right) + P - \varepsilon \qquad (4)$$

The three other terms, $-Dk/Dt$, P, and ε, are in closed form, given the turbulent-viscosity hypothesis.

Turbulence consists of high levels of fluctuating vorticity. At any instant, vortical motion called eddies are present in the flow. These eddies range in size from the largest geometrical scales of the flow; such as tank diameter, down to small eddies where molecular diffusion dominates. Eddies are continuously evolving, and the superposition of their induced motions leads to fluctuating waves. In this situation, turbulent kinetic energy is dissipated from the largest eddies down to the smallest through a process called energy cascade. In order to maintain turbulence, a constant supply of energy must be fed to the turbulent fluctuations at the largest scales from the mean motions, where motions are driven by a jet pump or mechanical agitator. Thus, the turbulent energy dissipation rate ε is viewed as the energy-flow rate in the cascade, and the rate is determined by large-scale motions, which are independent of the viscosity at high Reynolds number. Consequently, the transport equation for ε may be considered as being entirely empirical. That is,

$$\frac{D\varepsilon}{Dt} = \nabla \bullet \left(\frac{\upsilon_t}{\sigma_\varepsilon} \nabla \varepsilon \right) + C_1 \left(\frac{\varepsilon}{k} \right) P - C_2 \frac{\varepsilon^2}{k} \qquad (5)$$

Consequently, the governing equations to be solved for the flow pattern calculations are composed of one continuity equation and three momentum equations for the three component directions (x, y, and z directions), and two constitutive equations for the turbulence descriptions.

When a tracer species such as acid material is added to the tank during blending operations before transferring the tank contents, the added species are transported over the tank domain by the continuous fluid motion driven by the pump. The transient modeling calculations for the blending time require a balance equation for tracer species. The species balance equation is given by

$$\frac{\partial \rho Y_v}{\partial t} + \nabla \cdot \left(\rho \vec{v} Y_v \right) = -\nabla \cdot \vec{J}_v + S_v \tag{6}$$

Y_v is local mass fraction of tracer species in the continuous fluid. $\vec{J}_v$ is a diffusion flux of the tracer species. S_v in the equation is a source term of tracer species added to the tank fluid due to the injection of the acid from the top of tank. The diffusion flux of the tracer under turbulent fluid flow is computed by

$$\vec{J}_v = -\left(\rho D_v + \frac{\mu_t}{Sc_t} \right) \nabla Y_v \tag{7}$$

D_v is a molecular diffusion coefficient of a tracer in the continuous fluid medium. Typical molecular diffusion coefficients of liquid species in the liquid domain are about 1 x 10^{-9}, which is much smaller than gas species.

The governing equations described above are solved over the entire tank domain of an SRS Type-IV tank without central support column and with no cooling coils, as shown in Figure 1. As shown in the figure, one inactive transfer pump and two slurry pumps were included in the modeling domain to consider the impact of the flow obstructions on the blending flow patterns. For the calculations, the domain was meshed by a hybrid meshing technique combined with hexahedral and tetrahedral meshes. Number of meshes for the domain with no cooling coils was established as about 4.2 x 10^6 nodes as partially shown in Figure 2.

A blending model of the Tank 21 configuration was set up with the horizontal discharges through the dual jets and flow return via pump suction, reflecting the full scale pump configuration shown in Fig. 1. Based on the two-step approach for the pump configuration, the modeling calculations were made for the numerical simulation similar to those performed for the Phase 1 and 2 blending tests conducted at Savannah River National Laboratory (SRNL) [1,2]. The first step was to establish the steady-state flow patterns of submersible jet flows as performed for the experiment. The second step was to perform the transient modeling calculations starting with another set of species balance equation in addition to the continuity, momentum, and two turbulence equations.

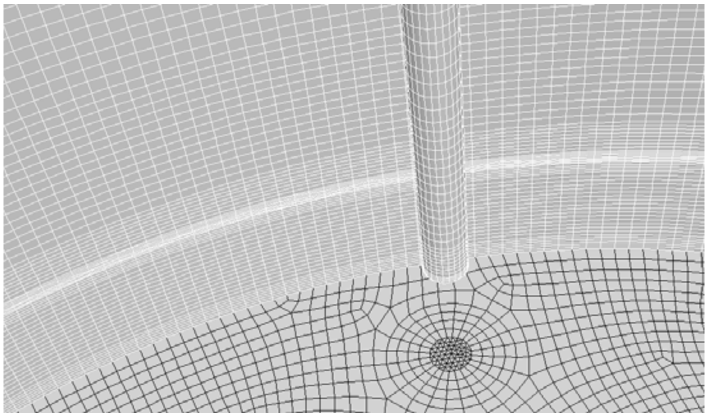


Figure 2. Computational mesh nodes near the blending pump domain (total number of meshes = 4.2 x 10^6 meshes)

III. RESULTS AND DISCUSSIONS

The model was benchmarked against the SRNL test results and literature data. The benchmarked model was applied to the performance calculations.

III.A Benchmarking Results

The benchmarking studies of the computational models against local velocity data and blending time measurements done for the SRNL-scale tests were performed for the initial design requirements for a full scale blending pump. When a jet stream of liquid is discharged into a stationary bulk liquid, the relative velocity between the jet region and the stagnant bulk liquid creates a turbulent mixing layer via the formation of turbulent eddies at the jet boundary. Thus, the momentum dissipation rate is closely related to the blending time of miscible fluids. When the blending pump is used inside the SRNL 1/10th scale tank with no coils, the steady-state flow evolutions of the blending jet along the principal discharge line are benchmarked against the literature results as shown in Table 2. The benchmarking results against the literature data [5,6] for local velocities along the jet discharge direction are shown in Figure 3. The modeling predictions of local velocities for the wall boundary and remote regions away from the principal jet direction were compared with the SRNL 1/10th scale and prototypic test data [2,7]. As shown in Fig. 4, the results demonstrated that the CFD model predicts the test results for a range of the jet operating conditions of $U_o d_o$ within about 20%.

For the benchmarking test of the blending performance model, a two-step modeling approach was taken as done experimentally. A transient run was started with acid species injected into the fully-developed steady-state flow pattern established by the first step, and it continues to run until the acid species was mixed with continuous phase in a homogeneous way within 95%. The calculated blending time was benchmarked against both SRNL test results and literature data. Quantitative comparisons to Grenville and Tilton's research from the literature [8], as well as the SRNL Phase 1 and 2 research results, were made as shown in Fig. 5.

Table 2. Data conditions of turbulent jets used in Fig. 12

Authors	$U_o d_o$ (ft^2/sec)*	Jet diameter (mm)	Fluid	Reynolds number, Re_{jet}
EDL/SRNL (2010)	0.81	5.31	Water	75,000*
Kiser (1963)	0.38	9.525	Water	35,000
Post (1998)	1.62	10	Air	10,000

Note:*1 ft = 0.3048 m

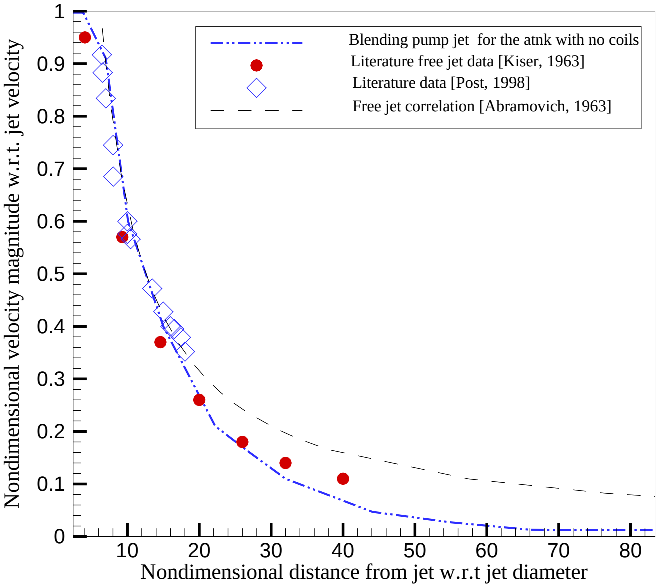


Figure 3. Comparison of steady state flow evolutions of the blending jet with the literature data along the principal discharge line inside the EDL scale tank with no coils

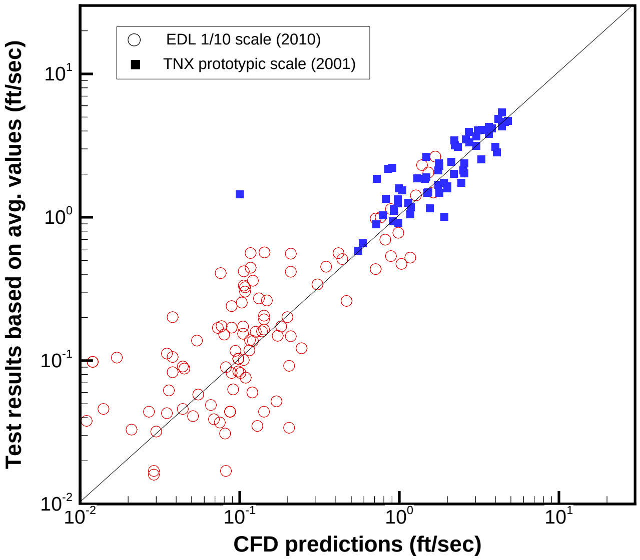


Figure 4. Benchmarking results of local fluid velocities compared to experimental test results [Ref. 9]

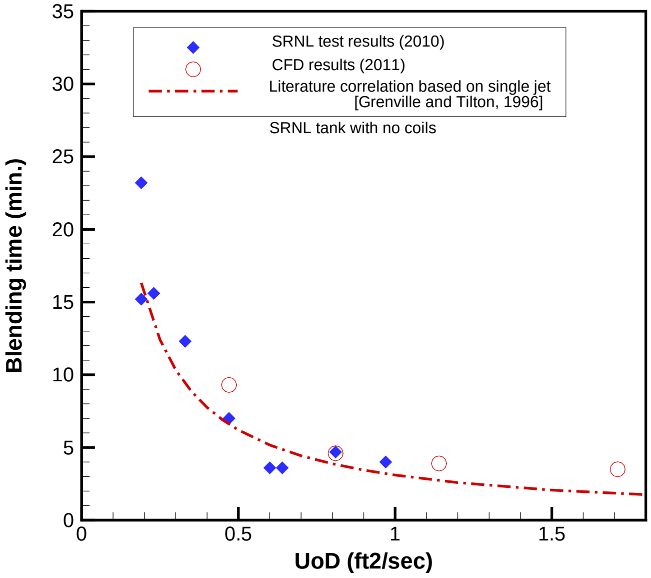


Figure 5. Benchmarking results of theoretical tank blending time compared to experimental test results [Ref. 9]

III.B Performance Model Results

As discussed previously, the current work consisted of two main goals. One goal was to develop the computational model for the numerical blending simulations of tank contents. The other goal was to benchmark the modeling predictions and to compute the blending time that adequately blends two miscible liquids under a full-scale SRS tank.

A blending model of the Tank 21 configuration was developed with the horizontal discharges through the dual jets and flow return via pump suction, as shown in Fig. 1, and the operating conditions provided in Table 1. Based on the two-step approach for the pump configuration, the modeling calculations were performed for the numerical simulation similar to those conducted for the Phase 1 and 2 blending tests [1,2]. For the computational models, contaminant species were added to the tank at the fully developed flow condition, where the species was then injected for 11.5 seconds into a 3 inch hole at the top of the tank, which simulated a three inch diameter pipe. In this case, the species fluid was an acid of 1.14 specific gravity and 1.16 cp viscosity. That is, the total volume injected through a modeled 3 inch diameter, Schedule 40 pipe was about 18 gallons during the initial period of 11.5 seconds, resulting in an equilibrium steady-state mass concentration, $C_{eq} = 1.29 \times 10^{-5}$. The acid chemical species was injected at Riser NE, as shown in Fig. 1. In short, the modeling calculations were performed to estimate the blending times for the Tank 21 jet flow conditions as defined in Table 1. The transient species profile at a monitoring point was then calculated and observed as shown in Fig. 6. The results show that about 38 minutes' mixing time is required to meet homogeneity requirements of 95% blending when 1.2 million gallon tank contents are blended by 600 gpm dual horizontal jet pump in a 85-ft tank.

Figure 7 presents comparison of the transient results for fluid velocity, energy dissipation rate, flow circulation patterns, and species concentration distributions at the slurry pump discharge elevation plane at the transient time of 5.5 minutes. When velocity flow patterns during blending are determined from the CFD models at the discharge plane of the blender pump, each of the dual jets of the submersible slurry pump forms a large circulation flow pattern as fluid momentum dissipates into the tank fluid media. Thus, the pump discharge plane has two unique, least active zones due to the formation of large circulation eddies, compared with distributions of the turbulent energy dissipation rates. More detailed circulation patterns can also be shown by the Lagrangian integration method along the flow path, where Fig. 7 shows major flow path lines from the jet exit of the blending pump to the pump suction inlet. The modeling results clearly show that the turbulent jet dissipation rate and flow circulation behavior are closely related to the blending mechanism of miscible fluids within the tank fluid space. These results are consistent with the previous SRNL and literature results [3,8]. In particular, Baldyga and Bourne [10] developed an empirical correlation for blending time, t_{blend}, in terms of circulation eddy diffusivity (ν_t) and turbulent dissipation rate (ε). That is

$$t_{blend} = C\left(\frac{\nu_t}{\varepsilon}\right)^{0.5} \tag{8}$$

A constant value of C in Eq. (8) is dependent on turbulent flow conditions.

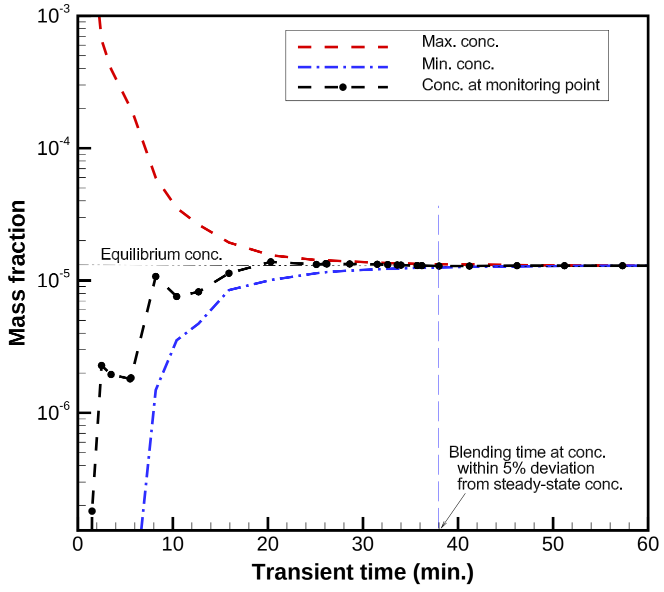
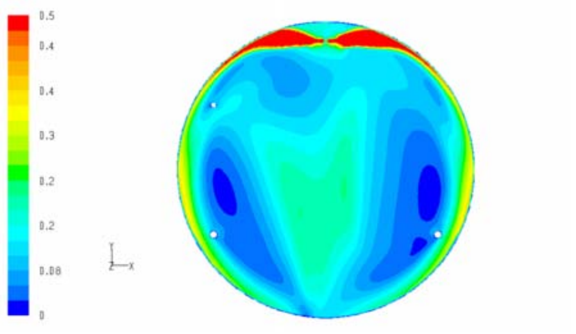
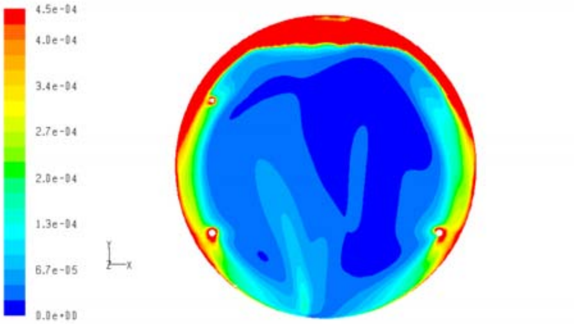


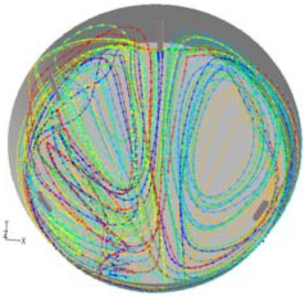
Figure 6. Transient concentrations at an observation point at the tank center and pump elevation



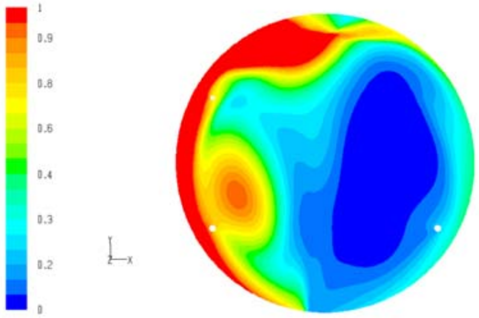
(Velocity magnitude, numbers in m/sec)



(Energy dissipation rate, numbers in m^2/sec^3)



(Lagrangian flow circulation patterns)



(Species conc. non-dimensionalized by equilibrium value)

Figure 7. Comparison of the transient results for fluid velocity, energy dissipation rate, flow circulation patterns, and nondimensional species distributions at the slurry pump discharge elevation plane at the transient time of 5.5 minutes

IV. CONCLUSION

A two-step computational model was developed for the blending analysis of the salt solution waste processing. The calculation model was benchmarked against the SRNL test results and literature data.

The validated model was applied to the quantitative performance evaluation of tank contents blending in prototypic Tank 21. The performance calculations were made under the multi-processor high performance computing platform. The calculation results show that when a dual jet pump equipped with 600 gpm per nozzle blends the 1.2 million gallon volume contained in Tank 21, about 38 minutes' blending operation is required for the 95% homogeneity concentration of tank contents.

NOMENCLATURE

A	Area
C	Concentration or constant for equation
C_1	Constant for equation
C_2	Constant for equation
C_{eq}	Equilibrium concentration
C_μ	Constant used in Eq. (2)
cp	Centipoise (= 0.001 N-sec/m^2)
D	Tank diameter
D_v	Molecular diffusion coefficient for species
d_o	Jet nozzle diameter
g	Gravitational acceleration
gallon	Liquid volume (= 0.0037854 m^3)
h_l	Liquid height
hp	Horse power (= 746 watts)
inch	Length (= 0.0254 m)
$\bar{J}_v$	Diffusion flux of species
k	Turbulent kinetic energy per unit mass
P	Production in turbulent kinetic energy transport
Sc_t	Turbulent Schmidt number
S_v	Source term in species transport equation
t	Time
t_d	Kolmogorov time
t_{blend}	Blending time
U_o	Velocity at jet inlet
U	Local velocity along the jet discharge direction
$\bar{v}$	Local velocity vector
u_i	Local turbulent fluctuation velocity (i = 1 for x-axis, i = 2 for y-axis, i = 3 for z-axis)
< >	Time-averaging symbol for a parameter inside a sharp bracket
v_{rms}	Root-mean-square velocity
x	Local distance along the x-axis
Y_v	Tracer mass fraction of the mixture at a local point
ε	Turbulent energy dissipation rate per unit mass
ε_m	Relative error

ρ	Fluid density
λ	Turbulent length scale
λ_{dif}	Diffusion length
μ_t	Turbulent dynamic viscosity (= $\rho\nu_t$)
ν	Kinematic viscosity
ν_{t}	Turbulent eddy diffusion coefficient
Re	Reynolds number
$\mathrm{Re}_{\mathrm{jet}}$	Reynolds number based on jet diameter
SRS	Savannah River Site
SRNL	Savannah River National Laboratory
wt	Weight

REFERENCES

1. Leishear, R. A., Poirier, M. R., and Fowley, M. D., “SDI Blend and Feed Blending Pump Design Phase 1 (U)”, Savannah River National Laboratory, SRNL-STI-2010-00054, March 2010, pp. 1-100.
2. Leishear, R. A., Poirier, M. R., and Fowley, M. D., “Blending Study for SRR Salt Disposition Integration: Tank 50H Scale-Modeling and Computer-Modeling for Blending Pump Design, Phase 2 (U)”, Savannah River National Laboratory, SRNL-STI-2010-00151, May 2011.
3. Leishear, R. A., Poirier, M. R., Fowley, M. D., Lee, S. Y., abd Steeper, T. J.., 2011, “Comparison of Experimental Results to CFD Models for Blending in a Tank Using Dual Opposing Nozzles”, IMECE 2011-62042, International Mechanical Engineers Congress and Exposition, American Society of Mechanical Engineers, New York, New York, pp. 1-12.
4. Leishear, R. A., Fowley, M. D., Poirier, M. R., Lee, S. Y., and Steeper, T. J., 2011, “Blending Time and Velocity Variations During Blending in a Tank Using Dual Opposing Jets”, IMECE2011-62116, International Mechanical Engineers Congress and Exposition, American Society of Mechanical Engineers, New York, New York, pp. 1-11.
5. Kiser, K. M., “Material and Momentum Transport in Axisymmetric Turbulent Jets of Water”, *A.I.Ch.E. Journal*, Vol. 9, No. 3, pp. 386-390, 1963.
6. Post, S., 1998, “A Computational and Experimental Study of Near-Field Entrainment in Steady Gas Jets,” MSME thesis, Purdue University.
7. Lee, S. Y., Dimenna, R. A., Leishear, R. A., and Stefanko, D. B., “Analysis of Turbulent Mixing Jets in a Large Scale Tank”, ASME *Journal of Fluids Engineering*, Vol. 130, Number 1, pp. 011104, 2008.
8. Grenville, R. K. and Tilton, J. N., “Turbulent Flow or Flow as a Predictor of Blend Time in Turbulent Jet Mixed Vessels”, Proceedings of 9th European Conf. on Mixing, pp. 67-74, 1997.
9. Lee, S. Y. and Armstrong, B. W., “SDI CFD Modeling Analysis”, SRNL-STI-2011-00025, April 2011.
10. Baldyga, J. and Bourne, J. R., “A Fluid Mechanical Approach To Turbulent Mixing and Chemical Reaction, Part III Computational and Experimental Results for the New Micromixing Model”, *Chem. Eng. Commun*., Vol. 28, pp. 259-281, 1984.
11. W. P. Jones, and B. E. Launder, “The Prediction of Laminarization with a Two-Equation Model of Turbulence”, *Int. J. of Heat Mass Transfer*, vol. 15, 1972, pp. 301-314.