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HYDRAULIC AND MIXING EVALUATIONS FOR SRS MISCIBLE LIQUID SOLUTIONS

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ABSTRACT

The hydraulic results demonstrate that pump head pressure of 20 psi recirculates about 5.6 liters/min flowrate through the existing 0.131-inch orifice when a valve connected to NT-41 is closed. In case of the valve open to NT-41, the solution flowrates to Savannah River Site (SRS) tanks, NT-21 and NT-41, are found to be about 0.5 lpm and 5.2 lpm, respectively.

The modeling calculations for the mixing operations of miscible fluids contained in the HB-Line tank NT-21 were performed by taking a three-dimensional Computational Fluid Dynamics (CFD) approach. The CFD modeling results were benchmarked against the literature results and the previous SRNL test results to validate the model. Final performance calculations were performed for the nominal case by using the validated model to quantify the mixing time for the HB-Line tank. The results demonstrate that when a pump recirculates a solution volume of 5.7 liters every minute out of the 72-liter tank contents containing two acid solutions of 2.7 M and 0 M concentrations (i.e., water), a minimum mixing time of 1.5 hours is adequate for the tank contents to get the tank contents adequately mixed. In addition, the sensitivity results for the tank contents of 8 M existing solution and 1.5 M incoming species show that the mixing time takes about 2 hours to get the solutions mixed.

KEYWORDS
Hydraulic Circulation Loop, Species Transport, Fluid Mixing Model, Hydraulic Mixing

1. INTRODUCTION

Savannah River National Laboratory (SRNL) evaluated the methods to mix and blend the solution contents of the Savannah River Site (SRS) NT-21 tank to ensure the tank contents are properly mixed when the solution fluid was recirculated by a hydraulic pump through the flow loop of the tank. This work focused on the estimate of hydraulic recirculation flowrate and mixing time of two miscible liquids due to the hydraulic recirculation driven by a pump, while ensuring that the solutions were mixed adequately.

The work scope described here consists of two areas to investigate two modeling studies. One area is to estimate the hydraulic flowrate of solution liquid driven by the pump head of 45 feet (~20 psi) through the flow circulation loop connected to two HB-Line tanks, NT-21 and NT-41, as shown in Fig. 1. The other one is to assess the operational time to mix and blend the solution contents of the blend tank to ensure the contents are properly mixed before they are transferred

from the blend tank such as NT-21 to the NT-41 tank. The modeling calculations for estimate of the mixing time are performed by using the 99% homogeneity criterion for the entire liquid domain of the tank. For the work, a hydraulic flow system connected to the NT-21 tank is comprised of 1-inch and 0.402-inch pipes, two valves, one orifice, 10 elbows, and one T-junction. The fluid flow of 5.7 liters/min is recirculated by a pump through the piping loop during the nominal conditions. The tank contents in NT-21 consist of two different forms of fluids. One fluid is heavier than the other due to different acid molarities.

The circulation loops and tank dimensions used for the flowrate evaluations are schematically presented in Figs. 1 and 2. Prior to the transfer of the NT-21 contents to NT-41, the tank contents are supposed to be adequately mixed by the flow recirculation driven by the hydraulic pump head with Valve 1 closed so that the transfer flow to NT-41 is blocked for the mixing operation. The mixing tank, NT-21, has a thin slab tank of 3.25 inches wide and 63.25 inches long as shown in Fig. 2. After the solutions in NT-21are properly mixed, most of them will be transferred to NT-41 by opening Valve 1. In case of the valve opening, the orifice located between the points 21 and 22 in Fig. 1 controls the flowrate returning to NT-21 in terms of the pressure loss. The recirculated flowrate is determined by the first work scope of the hydraulic analysis.

The cases considered for the hydraulic analysis are:

- Case-1: Estimate of the circulation flowrate for orifice diameter 0.131 inches and Valve 1 closed.
- Case-2: Estimate of the circulation flowrate for orifice diameter 0.131 inches and Valve 1 open.
- Case-3: Estimate of the circulation flowrate for orifice diameter 0.25 inches and Valve 1 closed.
- Case-4: Estimate of the circulation flowrate for orifice diameter 0.25 inches and Valve 1 open.

Tank fluid is pumped out by the exit pipe with 1 inch diameter located at the bottom floor of the tank side, and it is discharged back to the tank thorough the 60° elbow located at 0.25 inches above the tank floor. The tank contents are dispersed and mixed mainly by the recirculation flow established by the hydraulic head through the submerged elbow pipe of 0.402 inches in diameter. The detailed dimensions and geometrical shape of the tank NT-21 are shown in Fig. 2.

The hydraulic calculations for the circulation loops connected to NT-21 and NT-41 were made by using spread sheet software under Window-7 platform. Modeling conditions for the hydraulic estimate are shown in Table 1. All mixing calculations for the NT-21 tank were performed by a three-dimensional Computational Fluid Dynamics (CFD) approach coupled with species transport equation. The modeling domain and geometry of the mixing tank are shown in Fig. 2.

The CFD modeling results are benchmarked against the literature results [2] and the previous SRNL test results [5] to validate the model. Final performance calculations were performed by using the validated model to quantify the mixing time for the HB-Line tank NT-21 and to demonstrate the adequacy of hydraulic flowrate driven by one recirculation pump to get the tank contents well mixed.

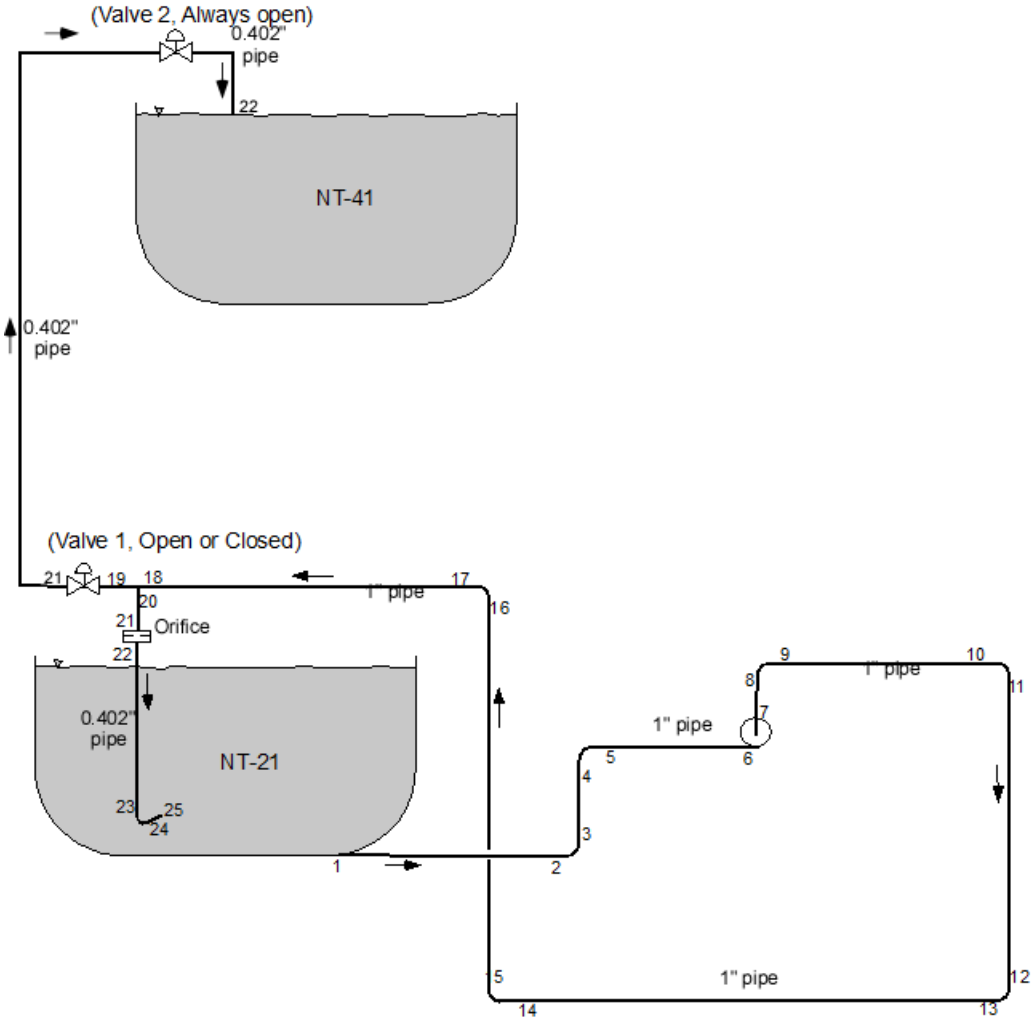


Figure 1. Flow diagram for HB-Line tanks, NT-21 and NT-41 (Numerical number is a node number referred to as a location identifier.)

2. MODELING ASSUMPTIONS AND APPROACH

2.1 Hydraulic Analysis

The present calculation uses one-dimensional steady-state approach for a given pump flow boundary. The modeling assumptions are made as follows:

- The connection pipe is completely filled with flowing fluid without plugging. The 20-psi pump head corresponding to hydraulic head of 45 feet is supplied to the circulation loop, and the fluid exits the pipe as a free jet inside the tanks with a free surface, NT-21 and NT-41.
- No leakage is allowed within circulation loop.
- The fluid is a single-phase incompressible fluid, assuming that slurry fluid is homogeneously mixed and isothermal.
- Slurry follows Newtonian fluid behavior.

The governing equation can be derived from one-dimensional steady-state integral momentum equations for incompressible flow. That is,

$$0=\int\left\{\left(\frac{dp}{dx}\right)_{friction}\right\}dx+\int\left\{\left(\frac{dp}{dx}\right)_{acceleration}\right\}dx+\int\left\{\left(\frac{dp}{dx}\right)_{gravity}\right\}dx+(\Delta P)_{Pump}$$

$$=-\left(\frac{P_w}{A}\right)\tau_w+0-\rho gH+(\Delta P)_{Pump} \qquad (1)$$

$$=-\left(\sum_{i=1}^{I}\Delta P_{i-j}\right)_{Friction}-\left(\sum_{i=1}^{J}\Delta P_{i-j}\right)_{Elevation}+(\Delta P)_{Pump}$$

In eq. (1) P_w and A are wetted wall area and flow area of the pipe, respectively. The parameter τ_w and H in the eq. (1) are wall shear stress and elevation height for the flow system. The wall shear stress can be expressed in terms of a friction factor and hydraulic mean diameter (d_h).

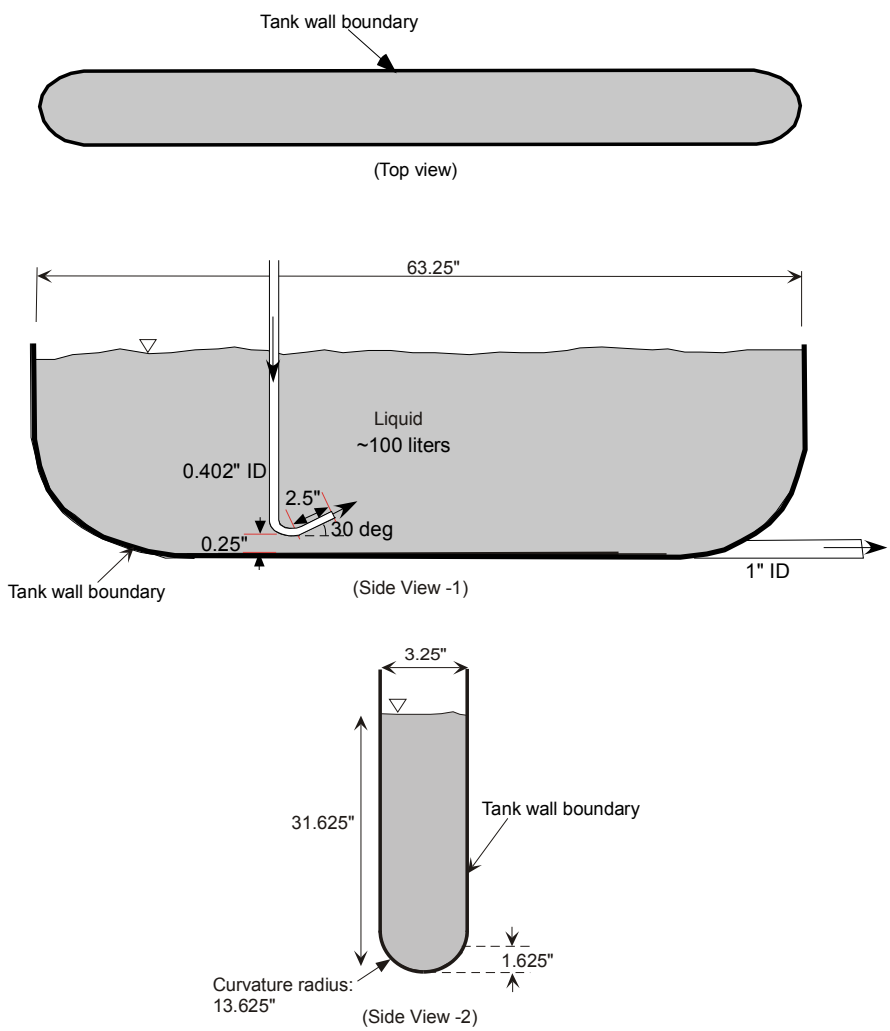


Figure 2. Geometrical dimensions for NT-21.

Table 1. Modeling conditions used for the hydraulic analysis

a. Circulation loop for NT-21	
Bulk slurry density	1177.8 kg/m^3
Viscosity	1 cp
Pipe diameter (shown in Fig. 1)	• 1 inch for the connection pipe between pump and orifice • 0.402 inches for the pipe between downstream side of the orifice
Pipe length for NT-21 loop	255 inches
Orifice diameter = 0.131 or 0.25 inches	0.131* or 0.25 inches
Number of elbows for NT-21 loop	10 elbows
Net elevation head	33 inches
NT-21 hydraulic head	36 inches
Pump supply head available	45 ft (~ 20psid)
b. Circulation loop for NT-41	
Slurry density = 1177.8 kg/m3	1177.8 kg/m^3
Viscosity = 1 cp	1 cp
Number of elbows for NT-41 loop	25 elbows
Pipe length for NT-41 loop	670 inches
Net elevation head	233 inches
Pipe diameter (as shown in Fig. 1)	0.402 inches (Downstream side of T-junction)
Number of valves (as shown in Fig. 1)	2

Note:*Nominal case

The resulting equation consists of total frictional pressure loss $\Delta P_{Friction}$, elevation pressure $\Delta P_{Elevation}$, and pumping head source ΔP_{Pump}. The average wall shear stress is

$$\tau_w = \frac{1}{2} f \rho u^2 \tag{2}$$

In eq. (2) f is called Fanning friction factor and it is obtained from an empirical correlation. The ratio of the wetted perimeter (P_w) to flow area (A) for a given pipe becomes

$$\frac{P_w}{A} = \frac{\pi d}{0.25 \pi d_h^2} = \frac{4}{d_h} \tag{3}$$

Using eqs. (1), (2), and (3), the resulting equation can be written in terms of volumetric flowrate (q) and hydraulic head (H), which is equivalent to net elevation of the fluid between the inlet and the exit. Elevation head pressure in eq. (1) is dependent on net elevation difference ΔH between the supply and the discharge exit. That is

$$\Delta P_{Elevation} = \rho g (\Delta H) \tag{4}$$

Total frictional pressure loss for the loop connected to the tanks, NT-21 and NT-41, becomes

$$\Delta P_{Friction} = \Delta P_{pipe} + \Delta P_{elbow} + \Delta P_{T-jun} + \Delta P_{orifice} \tag{5}$$

When volumetric flowrate q is expressed in terms of hydraulic diameter (d_h) and pipe length between the nodes i and j (L_{ij}) as indicated in Fig. 1, the frictional pressure drop between the nodes i and j for the pipe region becomes

$$\left(\Delta P_{i-j}\right)_{pipe} = \frac{8}{\pi^2}(4f)\left(\frac{L_{ij}}{d_h^{\,5}}\right)\rho q^2 \qquad (6)$$

The frictional pressure drop through elbow component is expressed in terms of hydraulic diameter (d_h) and pipe length between the nodes i and j (L_{ij}), the frictional pressure drop for flowrate q through the I component in the loop such as elbow, T-junction, and orifice becomes

$$(\Delta P)_I = \frac{8}{\pi^2}\left(\frac{K_I}{d_h^{\,4}}\right)\rho q^2 \qquad (7)$$

K_I in the above equations represents flow resistance for I component of the loop in terms of friction factor and geometrical dimensions. For the calculation of flow resistance, the Fanning friction factor (f) correlation is required. The flow resistance (K) values for the flow direction changes and elbows etc. were provided by the literature [Crane, 1976, Idelchik et al., 1986].

The Fanning friction factor for turbulent flow (greater than 2,000 Reynolds number for the present work) is

$$f = \left(\frac{0.079}{Re^{0.25}}\right) \qquad (8)$$

Reynolds number Re is given in terms of flowrate q as follows:

$$Re = \left(\frac{4}{\pi}\right)\left(\frac{\rho}{\mu d_h}\right)q \qquad (9)$$

When pump supply head through the flow loops to NT-21 and NT-41 is given, the governing equation is complete for estimating flowrate q by using eq. (1).

2.2 Mixing Calculations

For the mixing analysis, a three-dimensional computational fluid dynamics (CFD) approach was taken to calculate flow velocity distributions for the modeling domain, and to estimate mixing time for two miscible liquids; such as, solution and acid, for HB-Line tank NT-21 as illustrated in Fig. 2. The results are benchmarked against both literature data and SRNL test data [2]. A commercial finite volume code, FLUENT, was used to create a full scale geometry file in a non-orthogonal mesh environment.

The prototypic model geometry was created on the computational domain by using the body-fitted coordinate system and structured multi-block grids. For the mixing performance analysis, the reference design conditions were considered as shown in Fig. 1 and Table 1. As shown in Table 2, the circulation flow of 5.7 liters/min is jetted into the contents of a slab tank through the 60° elbow pipe for the mixing. The same flowrate is pulled through the 1-inch pipe exit installed at the tank floor of NT-21, and it is discharged back into the tank liquid through the 0.402-inch

elbow pipe that is located about 0.25 inches above the tank floor. This elbow inlet is directed at a 30° angle toward top liquid surface as shown in Figs 2 and 3. The hydraulic calculation results show that about 5.6 liters per minute is recirculated through NT-21 during the mixing period. This flow rate is very close to the nominal flowrate of 5.7 liters/min, which was used for the estimate of the mixing calculations. However, the mixing time change due to the difference between these two flowrates was found to be negligible from the mixing sensitivity analysis.

For the mixing calculations, the transient governing equations consist of one mass balance, three momentum equations along the Cartesian coordinate system, two turbulence transport equations for kinetic energy (k) and dissipation rate (ε), and one species transport. The equations were transiently solved by an iterative technique until the species concentrations of tank fluid were reached at equilibrium concentration within 1% relative error. For C_{eq} the equilibrium concentration and C the transient concentration at a monitoring point, the 99% mixing time t_m was defined by

$$t_m = \left| \frac{C - C_{eq}}{C} \right| < 0.01 \qquad (10)$$

The present work used the assumptions as follows:

- Top tank liquid surface 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 slurry region in a deep tank.
- The fluid properties of water or acid solution were evaluated at values to conservatively evaluate the system.
- The flow conditions for the pump operations are assumed to be fully turbulent since Reynolds numbers for typical operating conditions are in the range of 1 $x10^4$ to 3.0 $x10^4$ based on the nozzle inlet conditions (0.402 inch inlet diameter).
- Inlet pipe was considered as major flow obstruction, assuming that detailed small objects attached to the inner wall of the tank have negligible impact on the mixing time due to flow recirculation

A standard two-equation turbulence model, the κ–ε model [3], was used to capture the turbulent flow evolution driven by the blending circulation pump since the previous work [2, 3] showed that the two-equation model predicts the flow evolution of turbulent jet in a large stagnant fluid domain with reasonable accuracy. This model specifies the turbulent or "eddy" viscosity ν_t by the empirical equation.

$$\upsilon_t = \frac{\mu_t}{\rho_f} = \left(\frac{C_\mu k^2}{\varepsilon} \right) \qquad (11)$$

In Eq. (11), C_μ is an empirical constant. In the present calculations, C_μ is 0.09 [7]. Thus, the turbulent viscosity 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 timescale (k/ε), a quantity of turbulent eddy diffusivity (k^2/ε), can be formed without specification of flow-dependent mixing length scale λ [7]. 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:

$$k = \frac{1}{2}\left\{\overline{(u_x)^2} + \overline{(u_y)^2} + \overline{(u_z)^2}\right\} \tag{12}$$

k can be produced by fluid shear, friction or buoyancy, or through external forcing at low-frequency eddy 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 k transport balance in the two-equation turbulence model can be expressed as:

$$\frac{Dk}{Dt} = \nabla \bullet \left(\frac{\upsilon_T}{\sigma_k}\nabla k\right) + P - \varepsilon \tag{13}$$

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. The eddies are continuously evolving, and the superposition of their induced motions leads to the 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 the turbulence, a constant supply of energy must be fed to the turbulent fluctuations at the largest scales from the mean motions, where it is driven by a jet pump or mechanical agitator. Thus, turbulent energy dissipation rate ε is viewed as the energy-flow rate in the cascade, and it is determined by the large-scale motions, independent of the viscosity at high Reynolds number. Consequently, the transport equation for ε is best considered as being entirely empirical. That is,

$$\frac{D\varepsilon}{Dt} = \nabla \bullet \left(\frac{\upsilon_t}{\sigma_\varepsilon}\nabla \varepsilon\right) + C_1\left(\frac{\varepsilon}{k}\right)P - C_2\frac{\varepsilon^2}{k} \tag{14}$$

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

$$\frac{\partial \rho Y_v}{\partial t} + \nabla \cdot \left(\rho \bar{v} Y_v\right) = -\nabla \cdot \vec{J}_v + S_v \tag{15}$$

Y_v is local mass fraction of tracer species in the continuous fluid. $\vec{J}_v$ is diffusion flux of 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 tracer under turbulent fluid flow is computed by

$$\vec{J}_v = -\left(\rho D_v + \frac{\mu_t}{Sc_t}\right)\nabla Y_v \tag{16}$$

D_v is molecular diffusion coefficient of tracer in the continuous fluid medium. Typical molecular diffusion coefficient of liquid species in the liquid domain is about 1 x 10^{-9} (m^2/sec), which is much smaller than gas species.

The governing equations described above are solved over the entire tank domain as shown in Fig. 2. For the calculations, the domain was meshed by a hexahedral meshing technique. The number of mesh nodes for the slab domain was established as about 1.2 x 10^6 nodes. Figure 3 shows three-dimensional computational volume meshes for the domain including the pipe structures.

A mixing model of the tank configuration was set up with the return path reflecting the actual tank configuration as defined in engineering drawing [1]. The modeling domain and configurations for the tank with the loop structures of elbow pipe and exit pipe are shown in Fig. 2. As shown in the figure, a discharge elbow connected with vertical pipe is located near the tank bottom 0.25 inches above the tank floor, and the exit flow leaves the tank through the 1 inch pipe connected to the bottom side of the slab tank. In this case, the heavier fluid, Fluid 1, was an acid of 1.11specific gravity and 1 cp viscosity, and total volume Fluid 1 settled on tank floor was about 12 liters for the initial period. In this period, total volume 60 liters of the lighter fluid, Fluid 2, are placed on the top of Fluid 1 inside the slab tank, NT-21. Fluid properties for both of the two fluids to be mixed are shown in Table 1. Based on the modeling conditions of Table 2, the transient species profile of fluid species Fluid 2 was then calculated and observed for estimation of the mixing time.

The modeling results were benchmarked against the literature data and the previous SRNL test results [2]. The validated model was applied for the modeling calculations to estimate the mixing time for nominal operating conditions of a thin slab tank, NT-21.

Table 2. CFD modeling conditions used for the mixing analysis

Nominal case	Fluid 1 (2.7 M acid)	Density	1108 kg/m^3
		Viscosity	1 cp
		Volume of fluid	12 liters
	Species fluid to be mixed (Fluid 2: Water)	Density	994 kg/m^3
		Viscosity	1 cp
		Volume of fluid	60 liters
Sensitivity case	Fluid 1 (8 M acid)	Density	1268 kg/m^3
		Viscosity	1.4 cp
		Volume of fluid	12 liters
	Species fluid to be mixed (Fluid 2: 1.5 M acid)	Density	1075 kg/m^3
		Viscosity	1 cp
		Volume of fluid	60 liters
Pipe diameter (shown in Fig. 1)			1 inch for exit pipe 0.402 inches for inlet pipe
Circulation flowrate			5.7 liters/min
Velocity for incoming flow			1.16 m/sec

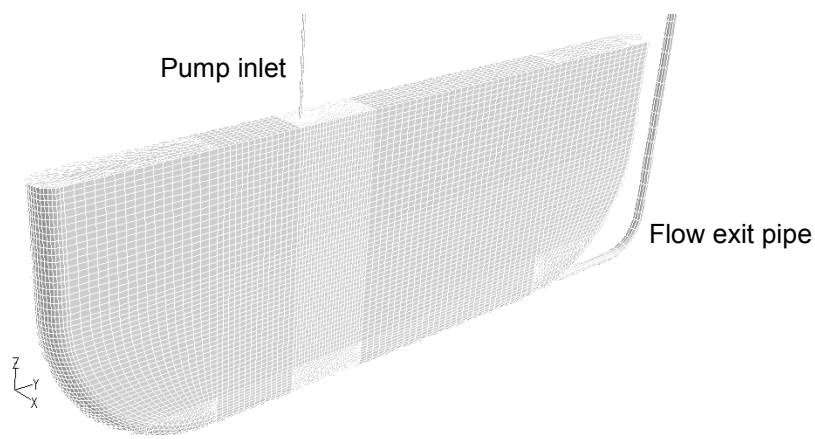


Figure 3. Computational meshes for the NT-21 tank mixing analysis (1.2 x 10^6 meshes)

3. CALCULATIONS AND RESULTS

3.1 Results for Hydraulic Calculations

Based on the modeling assumptions and governing equations provided in section 2.1 along with physical dimensions and fluid properties as shown in Table 1, the calculations have been made by using Microsoft Excel spread sheet to evaluate the slurry flowrate driven by the 45 ft pump head (or 20 psi) for different operating conditions.

The calculations were based on the slurry flow assumption without air entrainment and the piping layout information as shown in Fig. 1. Total pipe lengths are about 255 inches for the circulation loop of NT-21 and about 670 inches for the circulation loop of NT-41 as provided in

Table 1. Two cases were considered for the circulation loops connected to two tanks, NT-21 and NT-41. One case is for the T-junction valve (Valve 1 in Fig. 1) closed to allow the fluid flow to be recirculated through NT-21 and to be performed for the species mixing of NT-21 contents, while the other is for the valve open to allow the mixed slurry fluid to be transferred to NT-21.

The calculation results demonstrate that pump head pressure of 20 psi recirculates about 5.6 liters/min (lpm) flowrate through 0.131-inch orifice when a valve connected to NT-41 is closed. In case of the valve open to NT-41, the solution flowrates to NT-21 and NT-41 are found to be about 0.5 lpm and 5.2 lpm, respectively. The calculations are based on the slurry density of 1.1778 gm/cc. The results for two different orifice sizes of 0.131" and 0.25" are summarized in Table 3.

Table 3. Results for the modeling cases considered for the hydraulic analysis

Modeling cases	Modeling conditions		Flowrate (liters/min)	
	Orifice size (inches)	Valve 1* open or close	Return flow to NT-21	Flowrate to NT-41
Case-1	0.131	close	5.6	0
Case-2	0.131	open	0.5	5.2
Case-3	0.25	close	17.9	0
Case-4	0.25	open	13.7	5

Note:*Valve 1 location shown in Fig. 1

3.2 Results for Mixing Performance Calculations

Using the CFD approach described above, FLUENT modeling calculations were made to numericaly simulate the mixing operation. The transient modeling calculations starting with another set of species balance equation in addition to the continuity, momentum, and two turbulence equations were performed for the time estimate to mix the tank contents that consist of two different miscible acid solutions in NT-21. In this approach, the transient calculations were started from the initial species distribution as shown in Fig. 5 along with the modeling conditions of Table 1 for the discretized computational domain as shown in Fig. 3. A transient run was started with 5.7 liters/min recirculation flowrate jetted into the tank solution through the 0.402 inch pipe, and run until the lighter species, Fluid 2, was mixed with the Fluid 1 species in a homogeneous way within 99%. In this case, the Fluid 2 species has properties of 1.0 specific gravity and 1.0 cp viscosity, and total volume injected through the discharge pipe was 5.7 liters every minute. The transient species profile for the lighter solution of Fluid 2 was calculated and observed to estimate the time to get homogeneously mixed.

The benchmarking tests are chosen as two typical areas representing the turbulent flow dissipations, and flow pattern behavior since these two phenomena are closely related to the miscible fluid mixing and species dispersion mechanisms within the bulk fluid space of the tank with flow recirculation. Both of the benchmarking areas are closely related to the mixing times of the miscible tank contents, and the spread behavior of the injected species. The detailed results are provided in the subsequent section.

Literature Benchmarking Results for Mixing

A benchmarking model of the Tank A configuration was developed with the return path reflecting the actual tank configuration as described by Grenville and Tilton [5]. The model configuration is shown in Figure 6. As shown in the figure, a jet pump with 42.6^o upward angle is located at the tank bottom, and the jetted flow returns to the pump through the tank bottom. Based on this model, a two-step method was applied to estimate the blending time for benchmarking of Grenville's experimental work. In this approach, the transient mixing calculations were started from the fully developed flow distribution of the first step runs as initial conditions. The second step simulated the mixing tests performed by Grenville and Tilton [5]. Based on the fully developed flow patterns established by the first step, the second step was a transient calculation for a contaminant species started from the fully developed condition of the first run in which the species was injected for 10 seconds into the inlet jet. In this case, the species fluid was an acid with a 1.14 specific gravity and a 1.16 cp viscosity, where the total volume injected through a 10 mm hole was approximately 0.21 gallons for an initial period of 10 seconds. Detailed test configurations and the computational domain of the Tank A system are shown in Fig. 4. The transient species profile was then calculated and observed.

Comparison of transient snapshots between species concentration and flow patterns at a vertical central plane crossing the pump nozzle exit was made, indicating that the tank mixing time was found to be about 33 seconds, which is in agreement with Grenville's measured results of 32 seconds to within about 3%. The results showed very clearly that the injected contaminant species followed the velocity profile and that the propagation of the contaminant species was developed over the same time period as both the bulk flow and the eddy flow patterns. From the previous results [6], the benchmarking results for blending time are shown in Fig. 5. These results demonstrated that the CFD models predicted the test results within about 20% for a range of jet operating conditions, namely, product of jet velocity and jet exit diameter, $U_o d_o$.

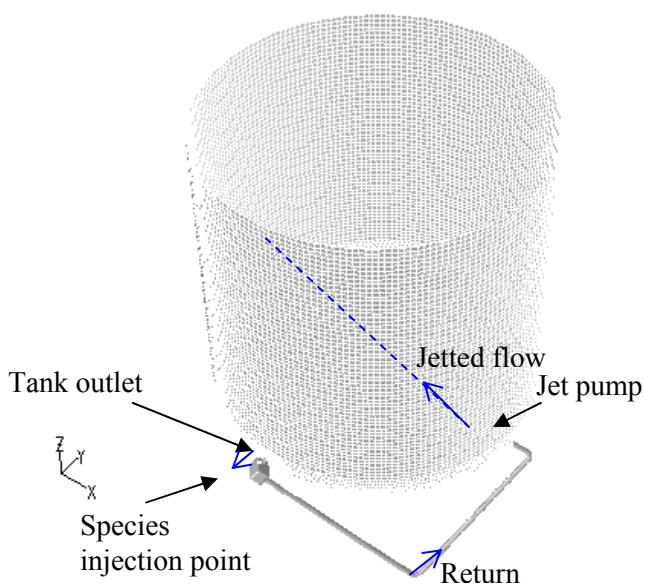


Figure 4. Tank A, geometry for the demonstration runs based on two different approaches of transient flow pattern and species transport calculations

Table 4. Test conditions and literature mixing times [5] for transient CFD calculations

D (Tank dia., m)	h_l (liquid height)	Inclination angle of Jet*	d_o (jet dia., mm)	U_o m/sec	Re_{jet}	Model prediction	Literature mixing time [5]
1.68	1.55 m	42.6°	26.1	19.8	516,780	33 sec.	32 sec.

Note: *Jet is located at the corner of tank bottom.

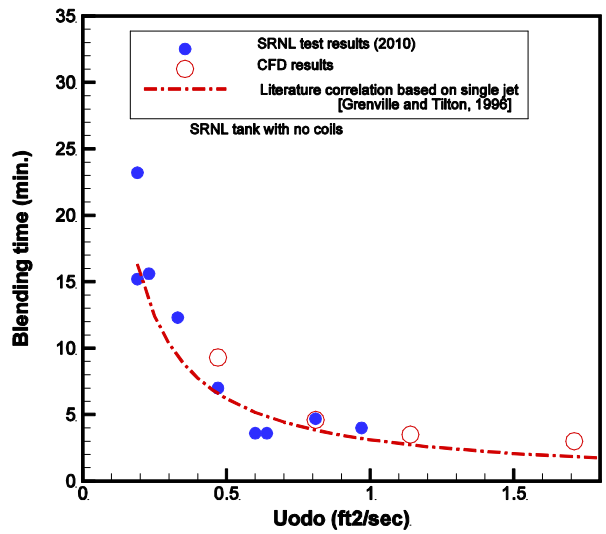


Figure 5. Benchmarking results of theoretical tank blending time compared to experimental test results [6]

Performance Results for Mixing Calculations in NT-21 Tank

Based on the validated CFD model, the current work consists of two main goals. One goal is to quantify the mixing operation time that will adequately blend and mix two miscible liquids to obtain a uniform composition in the tank with a minimum level of nonuniform species contents. The other is to verify adequacy of 1.5 hours of pump recirculation for tank species to be well mixed in HB-Line tank, NT-21.

The CFD modeling calculations were performed to determine mixing time for potential operating conditions as shown in Table 2. The calculations were performed two cases as shown in the table. One is the nominal case for the tank solutions consisting of the existing 2.5 M acid solution and incoming water species. The other case is for the sensitivity run consisting of two acid solutions of 8M existing solution and 1.5 M incoming species. For the performance analysis, the modeling calculations were based on the 5.7 liters/min pump recirculation to evaluate the mixing time in NT-21. The results show that the maximum speed is about 1.1 m/sec at inlet of the pipe located at about 1.5 inches above the tank floor, corresponding to 5.7 liters/min circulation flowrate. In this case, the inlet nozzle is installed at a distance of 22.25 inches from the wider side wall and at the center of the narrower side of the slab tank as shown in Fig. 2. Figure 6 shows the circulation flow patterns at 90 minutes' transient time for the center plane of the slab tank.

The snapshots of the transient mass fractions for the modeling conditions of Table 2 are shown in Fig. 7. As shown in the figure, the lighter species is stratified during the mixing period since convective motion is not large enough to overcome the gravity along the vertical depth of the tank solution. As shown in Fig. 7, a mixing time of 90 minutes for the nominal case is required when two miscible fluids are mixed by one recirculation pump. The calculation results demonstrate that when a pump recirculates the solution volume of 5.7 liters every minute out of the total volume of 72 liters in the NT-21 tank containing two acid solutions of 2.7 M and 0 M concentrations (i.e., water), a minimum mixing time of 1.5 hours is adequate for the tank contents to get adequately mixed. The sensitivity results for the tank contents of 8 M existing solution and 1.5 M incoming species show that the mixing time takes about 2 hours to get the solutions mixed. Table 5 summarizes the results of the nominal and sensitivity cases.

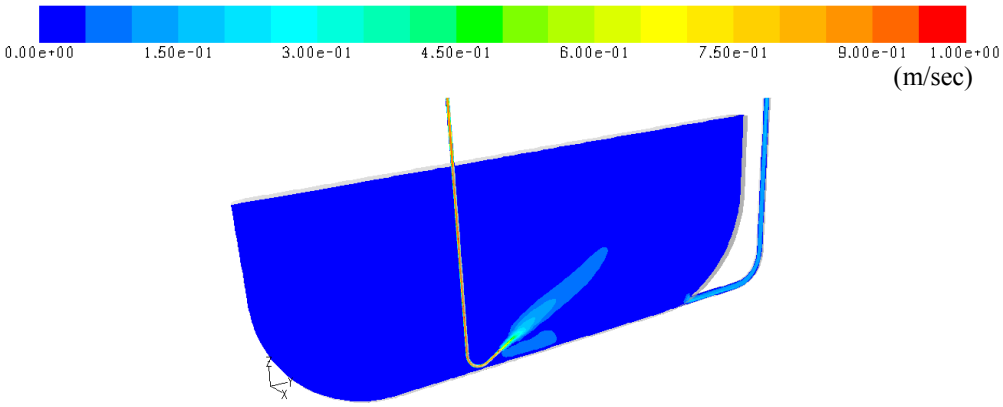
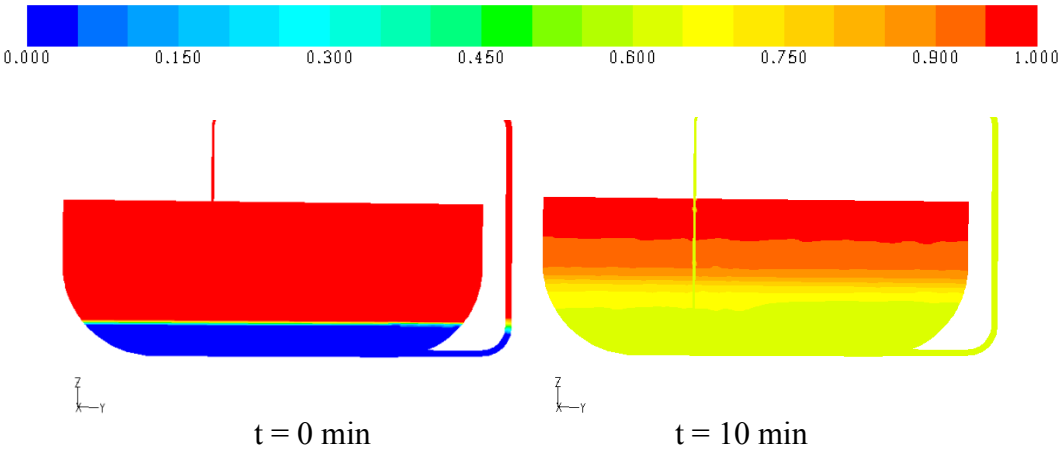
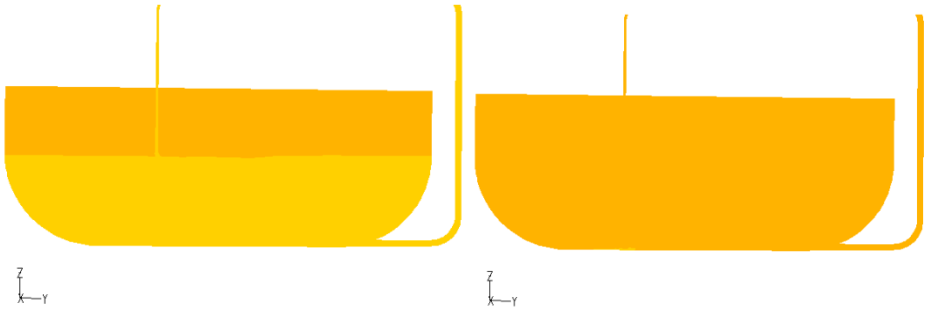


Figure 6. Flow velocity distributions for the central plane at 90 min. transient time





t = 60 min t = 90 min

Figure 7. Transient non-dimensional mass fractions for Nominal case.

Table 5. CFD modeling results used for the mixing analysis

Case	Molarities	Mixing time (min.)
Nominal case	Fluid 1 (2.7 M acid)	90
	Species fluid to be mixed (Fluid 2: Water)	
Sensitivity case	Fluid 1 (8 M acid)	120
	Species fluid to be mixed (Fluid 2: 1.5 M acid)	

4. CONCLUSIONS

The hydraulic results demonstrate that a pump head pressure of 20 psi recirculates about 5.6 liters/min (lpm) flowrate through the existing 0.131-inch orifice when a valve connected to NT-41 is closed. In case of the valve open to NT-41, the solution flowrates to HB-Line tanks, NT-21 and NT-41, are found to be about 0.5 lpm and 5.2 lpm, respectively.

The modeling calculations for the mixing operations of miscible fluids contained in NT-21 were performed by taking a three-dimensional Computational Fluid Dynamics (CFD) approach. The CFD modeling results were benchmarked against the literature results [5] and the previous SRNL test results [6] to validate the model. Final performance calculations were performed by using the validated model to quantify the mixing time for the HB-Line tank. The mixing study results for the NT-21 tank show that, for the nominal case modeled, the mixing time adequate for the blending of tank contents is at least 90 minutes when nominal flowrate of 5.7 liters/min is recirculated through the tank. The sensitivity results for the tank contents of 8 M existing solution and 1.5 M incoming species show that the solution mixing takes about 2 hours to get the solutions mixed.

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