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# Tank Mixing Study with Flow Recirculation

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## INTRODUCTION

Savannah River National Laboratory (SRNL) evaluate methods to mix and blend the solution contents of the SRS JT-71/72 tanks to ensure the contents are properly mixed. This work focuses on the estimate of mechanical mixing time of two miscible liquids related to the turbulent dispersion circulated by the pump, while ensuring that the solutions are mixed adequately.

The primary objective of this work is to quantify the mixing time when two miscible fluids are mixed by one recirculation pump and to evaluate adequacy of 2.5 hours of pump recirculation to be considered well mixed in SRS tanks, JT-71/72. The work scope described here consists of two modeling analyses. They are the steady state flow pattern analysis during pump recirculation operation of the tank liquid and transient species transport calculations based on the initial steady state flow patterns. The modeling calculations for the mixing time are performed by using the 99% homogeneity criterion for the entire domain of the tank contents.

The tank geometry for JT-71/72 tanks equipped with one recirculation pump is provided in Fig. 1. This tank has 7-turn helical cooling coils with 2 inches in coil diameter and 42 inches in loop diameter. Tank fluid is pumped out by the submerged nozzle inlet with 2.125 inches diameter located at about 1.5 inches above the tank floor, and it is discharged back to the top surface of the tank liquid. The tank contents are dispersed and mixed mainly by 15 gpm recirculation flow through the submerged nozzle inlet.

All modeling calculations for the mixing operations are performed by a three-dimensional Computational Fluid Dynamics (CFD) approach. The CFD modeling results are benchmarked against the literature results [2] and the previous SRNL test results [3] to validate the model. Final performance calculations were performed by using the validated model to quantify the mixing time for the HB-Line tanks JT-71/72 and to demonstrate the adequacy of 2.5 hours' mixing time of the tank contents by one recirculation pump to get well mixed.

## DESCRIPTION OF THE ACTUAL WORK

For the present analysis, a three-dimensional computational fluid dynamics (CFD) approach was taken

to calculate flow velocity distributions, and to estimate mixing time for two miscible liquids; such as, solution and acid, for Tank JT-71/72 as illustrated in Fig. 1. The results are benchmarked against both the literature data and SRNL test data [3]. The commercial finite volume code, FLUENT, was used to create a full scale geometry file in a non-orthogonal mesh environment by using the body-fitted coordinate system and structured multi-block grids.

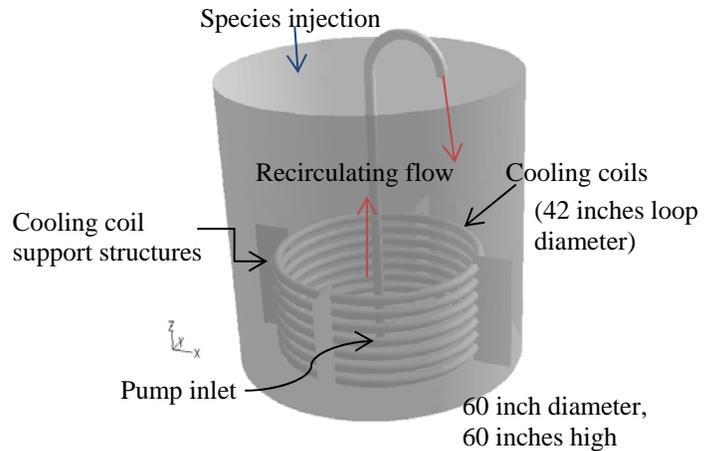


Fig. 1. Geometry for SRS JT-71/72 tanks

For the mixing performance analysis, the reference design conditions were considered as shown in Fig. 1 and Table 1. The circulation pump is submerged for the mixing inside a cylindrical tank that is 60 in high and about 60 in diameter. The 15 gpm flowrate is pulled through 2.125-inch nozzle inlet installed at about 1.5 inches above the tank floor, and it is discharged back to the top surface of the tank liquid. This tank has 7-turn helical cooling coils with 2 inches in coil diameter and 42 inches in loop diameter.

For the calculations, the transient governing equations consisting of one mass balance, three momentum equations along the Cartesian coordinate system, two turbulence transport equations for kinetic energy ( $k$ ) and dissipation rate ( $\epsilon$ ) [4], and one species transport equation were 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

$$t_m = \left| \frac{C - C_{eq}}{C} \right| < 0.01 \quad (1)$$

The steady-state flow solutions for the entire tank fluid were used for the initial conditions.

Table 1. Modeling conditions used for the present analysis

Parameters	Values
Tank diameter x tank level (inches)	60 x 60
Cooling coil loop diameter (inches)	42
Cooling coil diameter (inches)	2
Number of cooling coil turns	7
Cooling coil pitch height (inches)	3
Bulk fluid density (kg/m <sup>3</sup> )	1150, 1235
Bulk fluid viscosity (cp)	1.0, 3.0
Tracer fluid species density (kg/m <sup>3</sup> )	1000, 1100, 1235
Tracer fluid species viscosity (cp)	1.0, 3.0
Recirculation pump flowrate (gpm)	15
Pump suction diameter (inches)	2.125
Pump discharge diameter (inches)	1.5

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 in a deep tank.
- The flow conditions for the pump operations are assumed to be fully turbulent since Reynolds numbers for typical operating conditions are in the neighborhood of  $3.0 \times 10^4$  based on the pump nozzle inlet conditions (2.125 inch inlet diameter).
- Cooling coils and their supporting structures are considered as major flow obstructions, assuming that detailed small objects attached to the inner wall of the tank have negligible impact on the mixing time due to flow recirculation

The governing equations to be solved for the present work are composed of one continuity equation, three momentum equations for the three component directions (x, y, and z directions), and two constitutive equations for the turbulence descriptions. The detailed descriptions for the governing equations and computational methods are provided in the previous work [3].

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

$$\frac{\partial \rho Y_v}{\partial t} + \nabla \cdot (\rho \bar{v} Y_v) = -\nabla \cdot \bar{J}_v + S_v \quad (2)$$

$Y_v$  is local mass fraction of tracer species in the continuous fluid.  $\bar{J}_v$  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 diffusion and convective concentration gradient. Typical molecular diffusion coefficient of liquid species in the liquid domain is about  $1 \times 10^{-9}$  (m<sup>2</sup>/sec), which is much smaller than gas species.

The governing equations described above are solved over the entire tank domain with and without cooling coil supports as shown in Fig. 2. For the calculations, the domain was meshed by a hexahedral meshing technique. The number of mesh nodes for the domain with cooling coils was established as about  $5 \times 10^5$  nodes. The number of mesh nodes for the model with cooling coils and support structure was about  $6 \times 10^5$ .

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]. A pump connected with vertical pipe is located near the tank bottom 1.5 inches above the tank, and the pumped flow returns to the tank through the 1.5 inch pipe submerged on top liquid surface. In this case, the species fluid was an acid of 1.235 specific gravity and 3 cp viscosity, and total volume injected through the 2.125 inch hole was about 0.6 gallons for the initial period of 10 seconds. The acid was injected at the middle of tank radius as schematically shown in Fig. 1. The transient species profile was then calculated and observed for estimation of the mixing time.

The modeling results were benchmarked against the literature data [2] and the previous SRNL test results [3]. The validated model was applied for a series of the modeling calculations to estimate the mixing times for nominal operating conditions and to investigate the impact of the flow obstructions and fluid properties on the mixing time. The mixing calculations for two separate cases were performed. The first case is the transient calculations of the species concentration in a tank with cooling coils. The second calculations are for the tank fluid with cooling coils combined with supporting structures as built in JT-71/72 tank. In each case, three different property models for a combination of high/low end densities and viscosities were developed. All detailed modeling conditions considered here are summarized in Table 1.

## RESULTS

Based the two-step approach, the modeling calculations were made for the numerical simulation as performed for the mixing operation. The first step is to establish the steady-state flow patterns of submersible pump flows as performed for the pump recirculation. The second step is to perform the transient modeling calculations starting with another set of species balance equation in addition to the continuity, momentum, and two turbulence equations. In this approach, the transient calculations were started from the fully developed flow distribution of the first step steady-state runs as initial conditions. For the second step, a transient run was started with acid species injected into the fully-developed flow pattern established by the first step, and run until the species was mixed with continuous bulk phase in a homogeneous way within 99%. A contaminant species started from the fully developed condition of the first step in which the species was injected for 10 seconds into the 2 inch hole at the top of the tank. In this case, the species fluid has properties of 1.0 specific gravity and 1.0 cp viscosity, and total volume injected through the hole was about 0.6 gallons for the initial period of 10 seconds. The transient contaminant profile was calculated and observed.

The benchmarking tests are chosen as two typical areas representing the turbulent pump dissipations, and flow dispersion 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 obstructions. One is the momentum dissipation area directly impacted by the submerged flow parameter, product of pump inlet velocity and pump diameter  $U_o d_o$ , and the other one is the remote area near the flow obstructions indirectly influenced by forced convective circulation. 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.

### Benchmarking Results for Mixing Model

A benchmarking tank geometry was developed with the return path reflecting the actual tank configuration as described by Grenville and Tilton [2]. A jet pump with 42.6° upward angle is located at the tank bottom, and the jetted flow returns to the pump through the tank bottom. Based on this model, the present two-step method was applied to estimate the blending time for benchmarking of Grenville's experimental work. In this approach, the transient calculations were again started from the fully developed flow distribution of the first step runs as initial conditions. The second step simulated the mixing tests as performed by Grenville and Tilton. 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. The Tank A system in the literature [2] has 1.68 m in diameter and 1.55m in tank liquid level, and the tank liquid is recirculated by inlet velocity of 19.8 m/sec through 26.1 mm jet diameter located at the corner of tank bottom. The transient species profile was then calculated and observed.

The modeling calculations indicate that the tank blending time is shown to be about 33 seconds, which is in agreement with Grenville's measured results of 32 seconds to within about 3%. The results show very clearly that the injected contaminant species follows the velocity profile and that the propagation of the contaminant species develops over the same time period as both the bulk flow and the eddy flow patterns. From the previous results [3], the benchmarking results for blending time are shown in Fig. 2. These results demonstrated that the CFD models predicted the test results for a range of jet  $U_o d_o$  operating conditions within about 20%.

### Performance Results for Mixing Calculations in JT-71/72 Tanks

The CFD modeling predictions for the mixing time due to the recirculated mainstream velocities along the principal flow direction driven by the pump were benchmarked against the literature results. 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 2.5 hours of pump recirculation for tank species to be well mixed in HB-Line tanks, JT-71/72.

A series of calculations were performed to determine mixing time for potential operating conditions as shown in Table 1. All cases modeled for the analysis are summarized in Table 2. For the performance analysis, the modeling calculations were based on the 15 gpm pump recirculation to evaluate the mixing operations. The results show that the maximum speed is about 2.3 ft/sec at inlet of the pump located at 1.5 inches above the tank floor, corresponding to 15 gpm circulation flowrate. In this case, the pump is installed at the center of the tank as shown in Fig. 1.

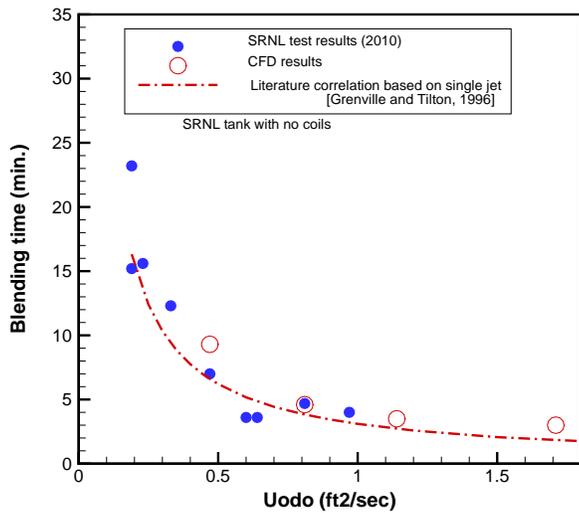


Fig. 2. Benchmarking results of theoretical tank blending time compared to experimental test results [3]

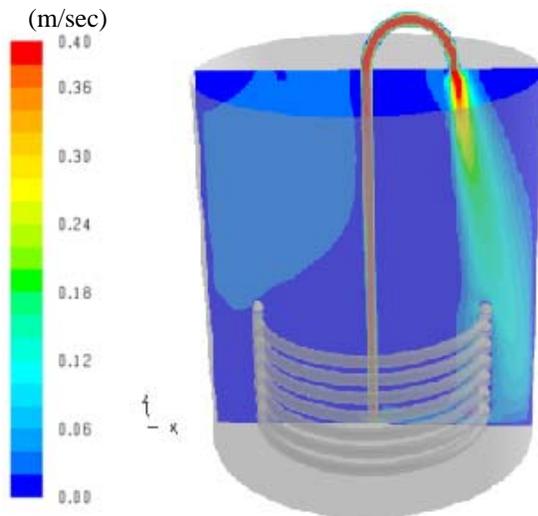


Fig. 3. Circulation flow patterns and flow distributions before species injection (Case A1)

Fig. 3 shows steady state circulation flow patterns and flow distributions before species injection for Case A1, which has low-end density and low-end viscosity of bulk solution and species as shown in Table 2. Maximum and minimum values of transient species mass fractions are observed during the mixing period.

The results for all of the modeling cases considered for the analysis are summarized in a quantitative way in Table 2. As shown in the table, a maximum mixing time of 35 minutes will be required when two miscible fluids are mixed by one recirculation pump. The addition of the supports to the model adds only a small amount of time

to the end result. Any other small obstructions not modeled, such as the air sparge ring, will have a negligible impact on the adequacy of the 2.5 hours of mixing. The modeling calculation results verify adequacy of 2.5 hours of pump recirculation to be considered well mixed in SRS tanks, JT-71/72.

Table 2. Results for the modeling cases considered for the analysis

Modeling cases	Modeling geometry	Operating conditions		Mixing time (min.)
		Bulk fluid	Spg*: viscosity	
Case A1	Cooling coils included	Bulk fluid	Spg*: 1.150 viscosity: 1 cp	28
		Species to be mixed	Spg*: 1.100 viscosity: 1 cp	
Case A2	Cooling coils included	Bulk fluid	Spg*: 1.235 viscosity: 3 cp	31
		Species to be mixed	Spg*: 1.235 viscosity: 3 cp	
Case A3	Cooling coils included	Bulk fluid	Spg*: 1.235 viscosity: 3 cp	29
		Species to be mixed	Spg*: 1.0 viscosity: 1 cp	
Case B	Cooling coils & supporting structures included	Bulk fluid	Spg*: 1.235 viscosity: 3 cp	35
		Species to be mixed	Spg*: 1.0 viscosity: 1 cp	

Note: \*specific gravity

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