SRNL-TR-2008-00280, REVISION 0

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# F-AREA PUMP TANK 1 MIXING ANALYSIS

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**NOVEMBER 2008**

Savannah River National Laboratory
Savannah River Nuclear Solutions
Aiken, SC 29808

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# REVIEWS AND APPROVALS

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# NOMENCLATURE

| | |
|---|---|
| $C$ | Empirical parameter for the Weber number |
| $C_c$ | Cunningham slip correction factor |
| CFD | Computational Fluid Dynamics |
| $d_{imp}$ | Impinging diameter; $d_{imp} = \sqrt{\frac{4}{\pi} \cdot \frac{Q_o}{W_{imp}}}$ |
| $d_o$ | Orifice diameter (pipe ID) |
| $d_p$ | Particle diameter |
| FPT1 | F-area Pump Tank 1 |
| $g$ | Acceleration due to gravity |
| $H$ | Plunge height |
| HPT7 | H-area Pump Tank 7 |
| $L_c$ | Jet break-up length; $L_c = C \cdot d_o \cdot We^{\frac{1}{2}}$ |
| $Q_o$ | Volumetric flow rate |
| RI | Recirculation Inlet into FPT1 |
| RO | Recirculation Outlet out of FPT1 |
| SRNL | Savannah River National Laboratory |
| $t$ | Free-fall time; $t = \sqrt{\frac{2 \cdot H}{g}}$ |
| TI | Transfer Inlet into FPT1 |
| TO | Transfer Outlet out of FPT1 |
| $U$ | $x$-component of velocity |
| $U_o$ | Horizontal component of the orifice velocity |
| $V$ | $y$-component of velocity |
| $V_o$ | Total velocity at the orifice |
| $V_{total}$ | Total velocity magnitude; $V_{total} = \sqrt{U^2 + V^2 + W^2}$ |
| $V_{ts}$ | Particle terminal settling velocity; $V_{ts} = \frac{(\rho_p - \rho_f) \cdot d_p^2 \cdot g \cdot C_c}{18\mu}$ |
| $W$ | $z$-component of velocity |

| | |
|---|---|
| $We$ | Weber number; $We = \frac{\rho_f \cdot V_o^2 \cdot d_o}{\sigma}$ |
| $W_{imp}$ | Vertical component of the impinging velocity; $W_{imp} = \sqrt{W_o^2 + 2 \cdot g \cdot H}$ |
| $W_o$ | Vertical component of the orifice velocity |
| $\theta$ | Plunge angle; $\theta = \tan^{-1}\left(\frac{U_o}{W_{imp}}\right)$ |
| $\mu$ | Fluid viscosity |
| $\rho_f$ | Fluid density |
| $\rho_p$ | Particle density |
| $\sigma$ | Fluid surface tension |

# 1.0 EXECUTIVE SUMMARY

The F-area pump tanks are used to transfer supernate, sludge, and other materials to and from larger waste tanks. During the transfer process, the solution must stay well mixed without allowing any particulate matter to settle out of the liquid. Recently, the pulse jet mixing in F-area Pump Tank 1 has been removed. An analysis of the transfer operation in F-area Pump Tank 1 has been performed using computational fluid dynamics methods to assess the mixing and sedimentation characteristic using only transfer and recirculation pumps.

The analysis results show that the recirculation and transfer pumps will keep the tank adequately mixed without the use of the pulse tube agitator for transfers over 70 gpm. In addition, the minimum velocities for these conditions remain higher than the terminal settling velocity for 25 μm particles, which act as an upper bound based on particle size sampling in the literature.

# 2.0 INTRODUCTION

The F-area pump tanks are used to transfer supernate, sludge, and other materials. In any transfer, the solution must stay well mixed without allowing particulate matter to settle out of the liquid and, thus, accumulate in the bottom of the pump tank. Recently, the pulse jet mixing in F-area Pump Tank 1 (FPT1) has been decommissioned. An analysis of the liquid transfer through FPT1 has been performed using computational fluid dynamics (CFD) methods to assess whether or not the velocities throughout the tank will remain high enough to keep all particulate suspended using only transfer and recirculation pumps.

The following paragraph is an abbreviated synopsis of the transfer procedure for FPT1 [1, 2]. Prior to a transfer, FPT1 begins to be filled with inhibited water through the inlet transfer line (TI). When the tank liquid level reaches 52.5 inches above the absolute tank bottom, the recirculation pump (RI and RO) is activated. At a tank liquid level of 72.5 inches above the absolute tank bottom, the outlet transfer line (TO) is activated to reduce the liquid level in FPT1 and transfer inhibited water to H-area Pump Tank 7 (HPT7). The liquid level is reduced down to 39.5 inches, with an allowable range from 37.5 to 41.5 inches above the absolute tank bottom. HPT7 goes through a similar procedure as FPT1 until both have tank liquid levels of approximately 39.5 inches above the absolute tank bottom. The transfer of inhibited water continues until a steady-state has been reached in both pump tanks. At this point, the supernate/sludge transfer begins with a minimum flow rate of 70 gpm and an average flow rate of 150 gpm. After the transfer is complete, the pump tanks (both FPT1 and HPT7) are pumped down to between 20.5 and 22.5 inches (above absolute bottom) and then flushed with 25,000 gallons of inhibited water to remove any possible sludge heal. After the flushing, the pump tanks are emptied. Note that the tank liquid level is measured using dip-tubes.

Figure 2.1 provides a simplified sketch (not to scale) of FPT1 during the steady-state transfer condition, which consists of two inlet flows that impact the liquid surface as plunging jets and two outlet flows drawn from near the bottom of the tank. During the transfer, the supernate level is held at 39.5 inches above the absolute bottom of the tank [1, 2]. In addition, the FPT1 can contain up to 16.7 wt.% sludge particles within the supernate for a given transfer [2]. Test results from Tank 40 sludge Batch 3 [3] provide a typical range of particulate diameters between 0.1 and 25 μm, with approximately 20 vol.% of the sludge distribution consisting of particles less than 1 μm in diameter.

The purpose of this analysis is to estimate FPT1 flow field during the steady-state transfer conditions to ensure that the tank remains mixed and that the velocities throughout the tank are sufficient to keep all sludge particulate suspended.

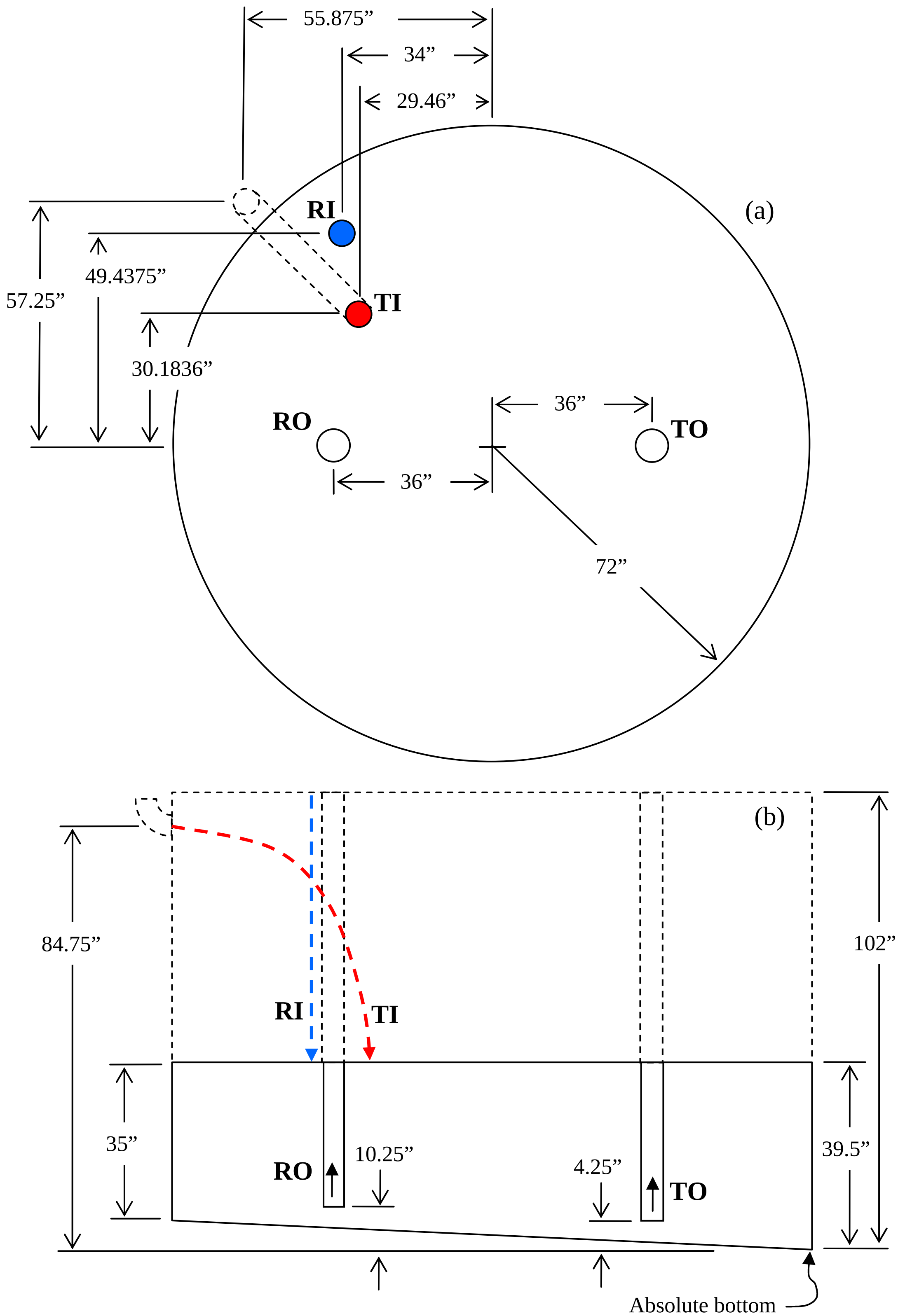


**Figure 2.1. Simplified sketch of the FPT1 geometry for the 150 gpm transfer. Top (a) and side (b) views. Not to scale.**

# 3.0 METHODOLOGY

The transfer and recirculation pump outlets and inlets are located asymmetrically within the 12' diameter F-area Pump Tank 1 (FPT1), making a three-dimensional model necessary for this analysis. The commercial CFD code FLUENT™ was used to solve the governing equations for this single-phase analysis, which include a mass balance, the three-dimensional momentum equations, and a two-equation turbulence model. The standard $k$-$\varepsilon$ turbulence model was chosen to estimate the fluid turbulence and the calculations were isothermal.

Figure 3.1 is a three-dimensional view of the modeling domain created from the sketch in Figure 2.1. The modeling domain is made up of approximately 412,000 grid elements. The following conditions are used to analyze FPT1, in coordination with Tables 3.1 and 3.2, which provide dimensional information for 150 gpm and 70 gpm transfers, respectively.

- Only the liquid within FPT1 is modeled.
- Particle motions are inferred solely based on the local fluid velocity field. In this manner, the flow of the slurry during the transfer is modeled as a single-phase, Newtonian fluid (water).
- The analysis involves only the steady-state supernate/sludge transfer after the transfer lines between F-area and H-area have been primed with the inhibited water and their steady-state condition has been achieved.
- Based on sampling test results for Tank 40 sludge Batch 3 [3], the typical range of particulate diameters is between 0.1 and 25 μm, with approximately 20 vol.% of the sludge distribution consisting of particles less than 1 μm in diameter.

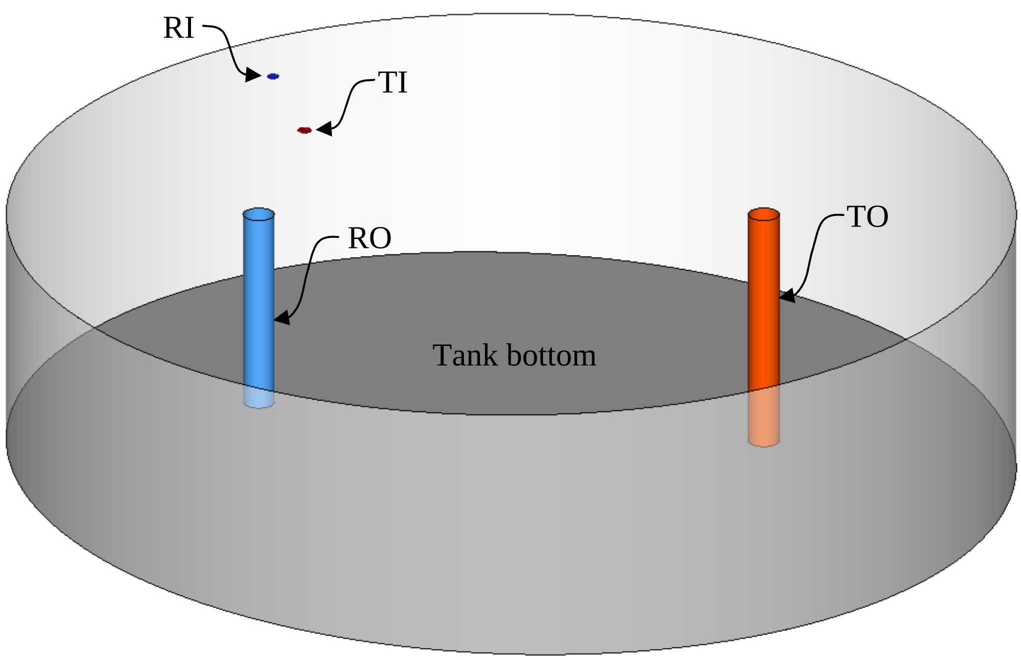


**Figure 3.1. Three-dimensional of the FPT1 liquid domain for a 150 gpm transfer.**

To create the model, the following assumptions were made:

- Internal tank structures (piping, etc.) are not included for simplification [4].
- No internal structures within the tank vapor space affect the trajectories of either the transfer inlet or recirculation inlet flows, which impact the liquid surface as plunging jets.
- The recirculation inlet and transfer inlet flows, as represented by the RI and TI are plunging jets that remain coherent until striking the supernate surface.
- The surface waves and instabilities at the supernate surface were neglected, with a pressure outlet boundary condition at the free surface.
- The fluid properties over the entire region of the tank are the same, with the supernate treated as water at 20$^o$C in the isothermal calculation. Previous calculations [5] have shown very little sensitivity to fluid temperature in the resulting flow patterns; therefore, any reasonable temperature is considered acceptable.
- There are no settled sludge solids within the tank prior to the transfer process [2].
- Fluid velocities must be greater than 0.001 m/s to avoid particle sedimentation and accumulation.

The assumption of water as the working fluid is appropriate because of its relative similarities to supernate in density and viscosity [5]. Negligible impact on the calculated flow patterns between water and supernate has been shown in previous work [6].

## 3.1 VERTICAL AND HORIZONTAL JET CHARACTERISTICS

Both the recirculation inlet flow and transfer inlet flow discharge into the air as a free jet before striking the supernate surface as a plunging jet (RI and TI, respectively). A liquid jet discharging vertically downward into a gas, e.g. recirculation inlet (RI) jet, will begin as a column of liquid but will lose coherence and break apart farther downstream below the nozzle exit. Sallam *et al*. [7] provides the following correlation, from experimental data, for the break-up length ($L_c$) for a water jet in air.

$$L_c = C \cdot d_e \cdot We^{\frac{1}{2}}, \tag{3.1}$$

where $d_e$ is the jet exit diameter, $We$ is the jet Weber number, and $C$ is an empirical parameter having a magnitude on the order of unity. Note that Equation (3.1) is applicable for water jets discharging horizontally or vertically down in air. For liquid jets with a Weber of 670 – 13,700 (as is the case for both the RI and TI), $C$ is equal to 2.1 with a standard deviation of 0.2 [7]. From Equation (3.1), the recirculation inlet (RI) has a break-up length between 345 and 417 inches with a plunge height of only 62.5 inches. Thus, RI remains a coherent column until striking the supernate surface. Similar, the transfer inlet (TI) remains a column as well with a break-up length between 179 and 216 inches at 70 gpm for a plunge height of 45.25 inches.

**Table 3.1. Dimensional information for FPT1 during the 150 gpm transfer.**

| | Transfer Inlet (TI) | Transfer Outlet (TO) | Recirculation Inlet (RI) | Recirculation Outlet (RO) |
|---|---|---|---|---|
| Nominal pipe size | 3 in SCH 40 [8] | 4 in SCH 60 [9] | 3 in SCH 40 [8] | 4 in SCH 60 [9] |
| Pipe I.D. | 3.07 in (0.078 m) | 3.94 in (0.100 m) | 3.07 in (0.078 m) | 3.94 in (0.100 m) |
| Volumetric Flow Rate | 150 gpm (568 lpm) | 150 gpm (568 lpm) | 135 gpm (511 lpm) | 135 gpm (511 lpm) |
| Velocity at pipe exit | 6.51 ft/s (1.98 m/s) | -3.95 ft/s (1.20 m/s) | 5.86 ft/s (1.79 m/s) | -3.56 ft/s (1.08 m/s) |
| Pipe opening (above absolute bottom) | 84.75 in (2.15 m) | 4.25 in (0.108 m) | 102 in (2.59 m) | 10.25 in (0.260 m) |
| Plunge height (to liquid surface) | 45.25 in (1.15 m) | n/a | 62.5 in (1.59 m) | n/a |
| Plunge velocity* (at liquid surface) | 15.6 ft/s (4.75 m/s) | n/a | 19.2 ft/s (5.86 m/s) | n/a |
| Plunge diameter* (at liquid surface) | 1.98 in (0.0504 m) | n/a | 1.69 in (0.0430 m) | n/a |
| Horizontal plunge distance* (during fall) | 37.8 in (0.961 m) | n/a | n/a | n/a |
| Plunge angle* (vertical = $0^o$) | $22.7^o$ | n/a | $0.0^o$ | n/a |
| Reynolds number | 172,000 | 134,000 | 155,000 | 121,000 |
| Weber number | 4,320 | 2,040 | 3,500 | 1,650 |
| Plunge jet break-up length* | 383 – 464 in (9.73 – 11.8m) | n/a | 345 – 417 in (8.76 – 10.6m) | n/a |

Note: * Plunge characteristics are calculated from Equations (3.1) – (3.5).

The vertical plunging jet velocity ($W_{imp}$) is derived from conservation of energy via the free fall equation.

$$W_{imp} = \sqrt{W_o^2 + 2 \cdot g \cdot H}\ , \tag{3.2}$$

where $W_o$ is the vertical velocity ($z$-component of velocity) at the jet exit, $H$ is the plunge height, and $g$ is the acceleration due to gravity. The time-averaged plunging jet diameter ($d_{imp}$) can then be found using conservation of mass.

$$d_{imp} = \sqrt{\frac{4}{\pi} \cdot \frac{Q_o}{W_{imp}}}\ , \tag{3.3}$$

where $Q_o$ is the volumetric flow rate leaving the jet exit.

**Table 3.2. Dimensional information for FPT1 during the 70 gpm transfer.**

| | Transfer Inlet (TI) | Transfer Outlet (TO) | Recirculation Inlet (RI) | Recirculation Outlet (RO) |
|---|---|---|---|---|
| Nominal pipe size | 3 in SCH 40 [8] | 4 in SCH 60 [9] | 3 in SCH 40 [8] | 4 in SCH 60 [9] |
| Pipe I.D. | 3.07 in (0.078 m) | 3.94 in (0.100 m) | 3.07 in (0.078 m) | 3.94 in (0.100 m) |
| Volumetric Flow Rate | 70 gpm (265 lpm) | 70 gpm (265 lpm) | 135 gpm (511 lpm) | 135 gpm (511 lpm) |
| Velocity at pipe exit | 3.04 ft/s (0.926 m/s) | -1.84 ft/s (0.562 m/s) | 5.86 ft/s (1.79 m/s) | -3.56 ft/s (1.08 m/s) |
| Pipe opening (above absolute bottom) | 84.75 in (2.15 m) | 4.25 in (0.108 m) | 102 in (2.59 m) | 10.25 in (0.260 m) |
| Plunge height (to liquid surface) | 45.25 in (1.15 m) | n/a | 62.5 in (1.59 m) | n/a |
| Plunge velocity* (at liquid surface) | 15.6 ft/s (4.75 m/s) | n/a | 19.2 ft/s (5.86 m/s) | n/a |
| Plunge diameter* (at liquid surface) | 1.35 in (0.0344 m) | n/a | 1.69 in (0.0430 m) | n/a |
| Horizontal plunge distance* (during fall) | 17.6 in (0.448 m) | n/a | n/a | n/a |
| Plunge angle* (vertical = 0$^o$) | 11.0$^o$ | n/a | 0.0$^o$ | n/a |
| Reynolds number | 80,500 | 62,700 | 155,000 | 121,000 |
| Weber number | 941 | 445 | 3,500 | 1,650 |
| Plunge jet break-up length* | 179 – 216 in (4.54 – 5.50m) | n/a | 345 – 417 in (8.76 – 10.6m) | n/a |

Note: * Plunge characteristics are calculated from Equations (3.1) – (3.5).

As opposed to the RI jet, the transfer inlet (TI) jet enters the tank horizontally as shown in Figure 2.1. The following equations for projectile motion, in coordination with Figure 3.2, are used to calculate the horizontal plunge distance ($x$) of the TI jet as well as the free-fall time ($t$) and the plunge angle ($\theta$) at the supernate surface.

$$t = \sqrt{\frac{2 \cdot H}{g}} . \tag{3.4}$$

The horizontal plunge distance can then be calculated by multiplying the horizontal velocity at the pipe ($U_o$) by the free-fall time. The plunge angle is then calculated using Equation (3.5).

$$\theta = \tan^{-1}\left(\frac{U_o}{W_{imp}}\right) . \tag{3.5}$$

Note that $W_o$ =0 for the TI jet so that the vertical component of the plunging jet velocity is based solely on the plunge height ($H$).

### 3.2 TERMINAL VELOCITY OF FREELY MOVING 25μm SLUDGE PARTICLES

In the present study, the sludge particles are assumed only to be present during the transfer process when the flow field has already reached steady-state. Unless the fluid velocity is held above a specific magnitude, the fluid will be unable to carry the sludge solids and they will settle out (sedimentation) and accumulate in areas of low velocity, such as along the walls. Note that the resuspension of solids that do settle to the tank bottom due to recirculation or transfer pump failure (or any other irregularities) is beyond the scope of this analysis. One method for determining the particle's terminal settling velocity ($V_{ts}$) can be derived by balancing the viscous drag, buoyancy, and gravitational forces on the particles, as shown in Equation (3.6) from Hinds (1999) [10].

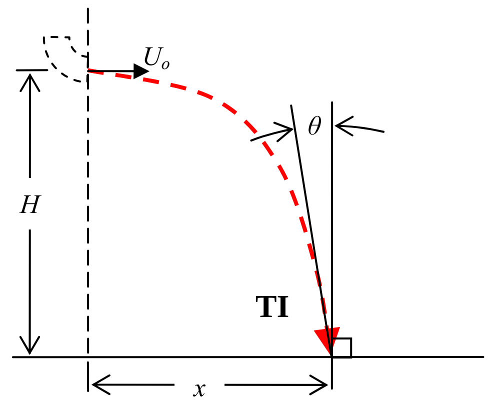


**Figure 3.2. Schematic of horizontal jet projectile motion.**

$$V_{ts} = \frac{(\rho_p - \rho_f) \cdot d_p^2 \cdot g \cdot C_c}{18\mu}, \tag{3.6}$$

where $\rho_p$ is the particle density, $\rho_f$ is the density of the fluid, $d_p$ is the particle diameter, $\mu$ is the fluid viscosity, $g$ is the acceleration due to gravity, and $C_c$ is the Cunningham slip correction factor, which is equal to 1 for spherical particles with negligible slip [11]. Eq. (3.6) assumes that the flow is in the Stokes regime and has a particle Reynolds number much less than unity, which are both true for the current small particles ($d_p \leq 25$ μm) at low speeds. Typical values of the density ratio ($\rho_p$ / $\rho_f$) for water and supernate are 2.5 and 1.67, respectively; therefore, the use of water, which is less dense, would lead to more conservative results. Using the representative particle size of 25 μm with water, the terminal settling velocity ($V_{ts}$) is found to be 0.00051 m/s. However, because the particle density and diameter could be larger, a settling velocity of 0.001 m/s (1 mm/s) is used as a bounding case. Thus, as long as the fluid velocities within FPT1 stay above 0.001 m/s, the particles are assumed to stay suspended.

## 4.0 CALCULATIONS AND RESULTS

The following results examine F-area Pump Tank 1 during its transfer operation where the supernate level is held at 39.5 inches above the absolute tank bottom. In Section 4.1, the transfer lines are activated at the typical transfer flow rate of 150 gpm. As a limiting case, the transfer flow rate is set to 70 gpm in Section 4.2. In both cases, the recirculation lines are activated at 135 gpm.

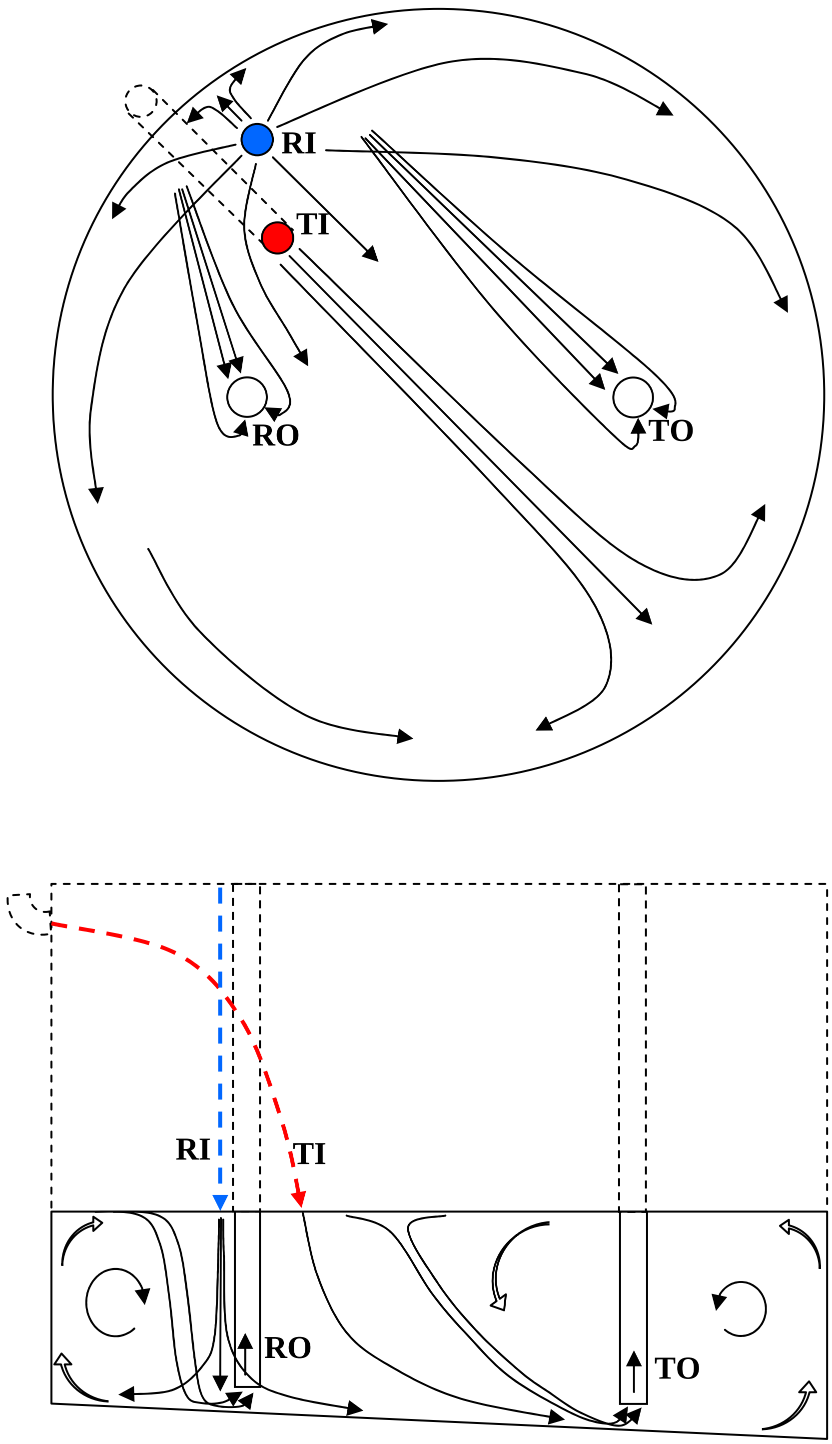


**Figure 4.1. Two-dimensional sketch of the FPT1 flow patterns during the 150 gpm transfer operation. Top (a) and side (b) views. Not to scale.**

## 4.1 TRANSFER AT 150 GPM

Figure 4.1 provides a simplified sketch of the flow patterns within FPT1 during the transfer operation when both the recirculation and transfer pumps are activated. The purpose of this sketch, which is not drawn to scale, is to highlight the affected regions within the tank that have velocities with magnitudes too small to represent in full scale. The downward flow of RI dissipates as it plunges toward the bottom of the tank. At the tank floor, the fluid fans out in all directions until it reaches the tank walls where it is turned up the wall and along the supernate surface. In this manner, recirculation regions are formed near the walls that entrain fluid around the plunging jets and essentially mix the tank, spreading the tank's contents throughout the supernate. The plunging jet formed by TI has a similar behavior, except it enters the supernate at an angle of approximately $23^o$ (with respect to the vertical) and has a greater effect on the region of the tank opposite the two inlet flows due to its angle of entry.

Figure 4.2 presents flow tracers showing the fluid flow path both originating within FPT1 and leaving out of RO and TO (Figure 4.2a) as well as originating at RI and TI and flowing throughout FPT1 (Figure 4.2b). In Figure 4.2a, there are sixty tracers that terminate within a square encompassing each tank outlet (RO & TO). Similarly, the tracers in Figure 4.2b originate within a square encompassing each tank inlet (plunging jets RI & TI). These flow tracers show that there are no direct flow paths from the tank inlets (RI & TI) to the tank outlets (RO & TO). Specifically, the fluid exiting the tank comes from the supernate surface near the entrainment region of the RI and TI, but not from the plunging jets themselves. Thus, the fluid entering from RI or TI must travel throughout the tank along one of the recirculation routes before it can be drawn out of the tank through RO or TO. This result suggests that, as long as the sludge particles remain suspended ($V_{total} > V_{ts}$) within the tank, the sludge particles at any location will eventually be drawn out of the tank through either RO or TO.

As state in the assumptions and based on Equation (3.6), the terminal settling velocity ($V_{ts}$) for sludge particulate less than 25 μm in diameter is set to 1 mm/s. To ensure that the particles remains entrained within the fluid, the fluid velocity through FPT1 must remain above $V_{ts}$. Figure 4.3 presents iso-velocity surfaces corresponding to total velocity magnitudes ($V_{total}$) of 0.012, 0.024, and 0.042 m/s, which are much higher than the terminal settling velocity of 0.001 m/s necessary to keep the particles entrained. Here the colors are shown with 50% translucency so that the lower velocity regions can be seen. All areas outside of these iso-velocity surfaces have velocity magnitudes greater than 0.042 m/s, which mean that most of the tank has velocities much greater than $V_{ts}$.

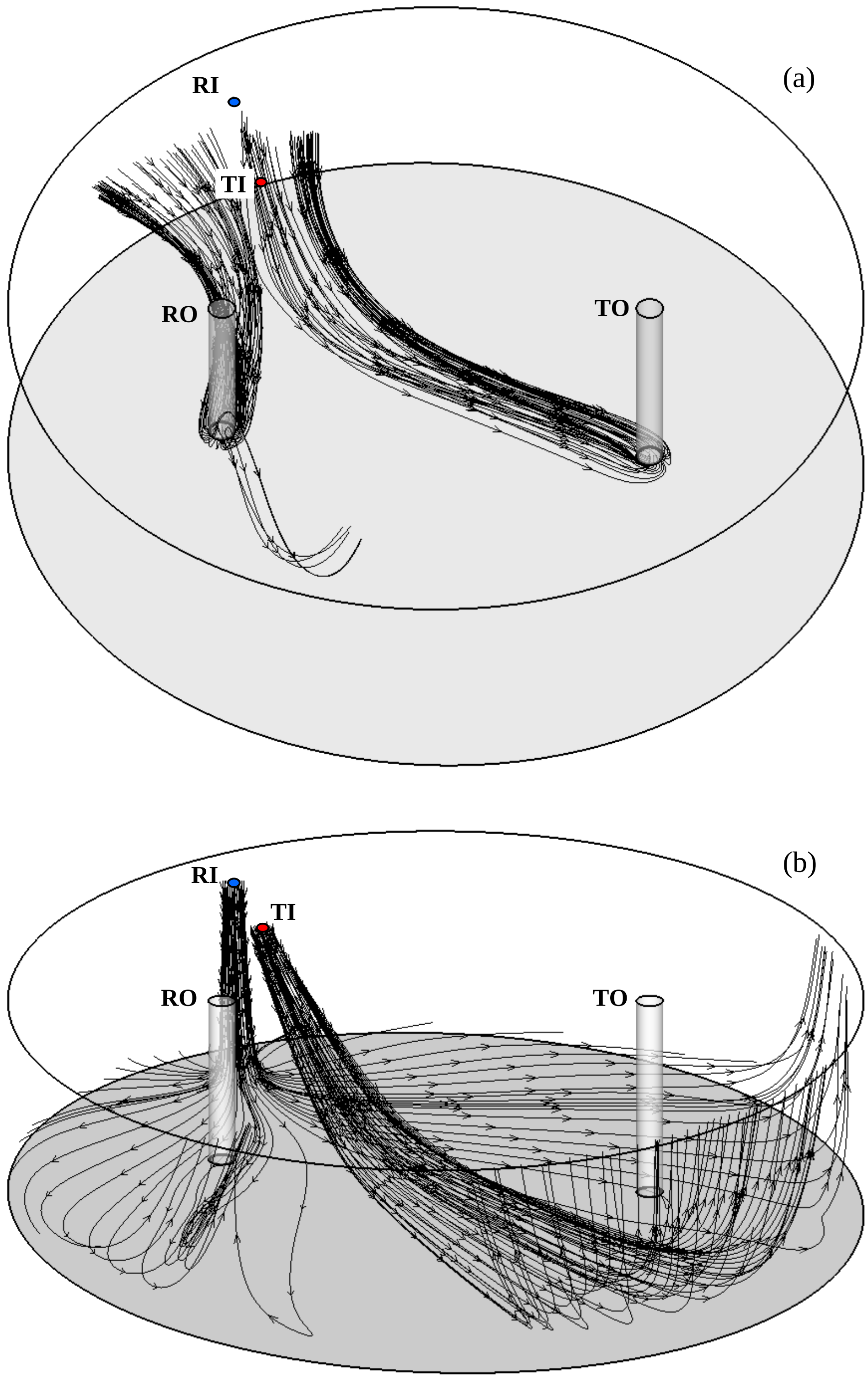


**Figure 4.2. Flow tracers for the fluid flow leaving FPT1 through RO and TO (a) and the fluid flow entering FPT1 through RI and TI (b) during the 150 gpm transfer operation.**

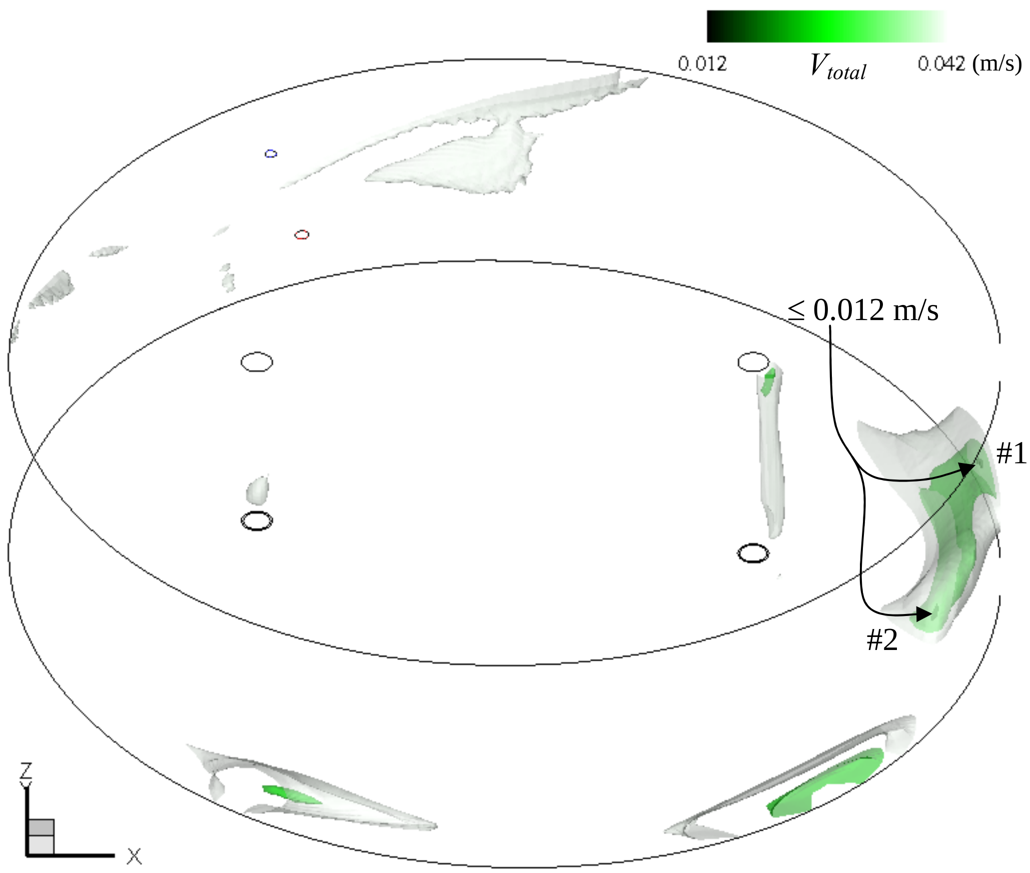


**Figure 4.3. Time-averaged, iso-velocity surfaces ($V_{total}$ = 0.012, 0.024, and 0.042 m/s) of FPT1 during the 150 gpm transfer operation.**

There are two low-velocity regions that are called out with arrows within Figure 4.3 that have velocity magnitudes less than 0.012 m/s. The region along the tank wall (Region #1) has a minimum velocity magnitude of ~0.011 m/s while the region along the tank bottom (Region #2) has a magnitude of approximately 0.002 m/s (2 mm/s). The velocity magnitude along the tank bottom is of particular interest because its magnitude is only double the minimum allowable particle settling velocity of 1 mm/s. Figure 4.4 presents a better representation of the velocity distribution along the tank bottom by providing the velocity contours. Here, black contour lines at $V_{total}$ = 0.01, 0.02, 0.03, 0.04, and 0.05 m/s used to highlight the regions of lowest velocity. Note that the tank bottom slants downward from left to right with respect to Figure 4.4. As shown, only a small fraction of the tank is within an order of magnitude of the terminal settling velocity for 25 μm diameter particles. Given that this is a bounding particle size (see assumptions), the tank velocities should be more than adequate to keep the sludge solids ($d_p \leq 25$ μm) entrained during the transfer process.

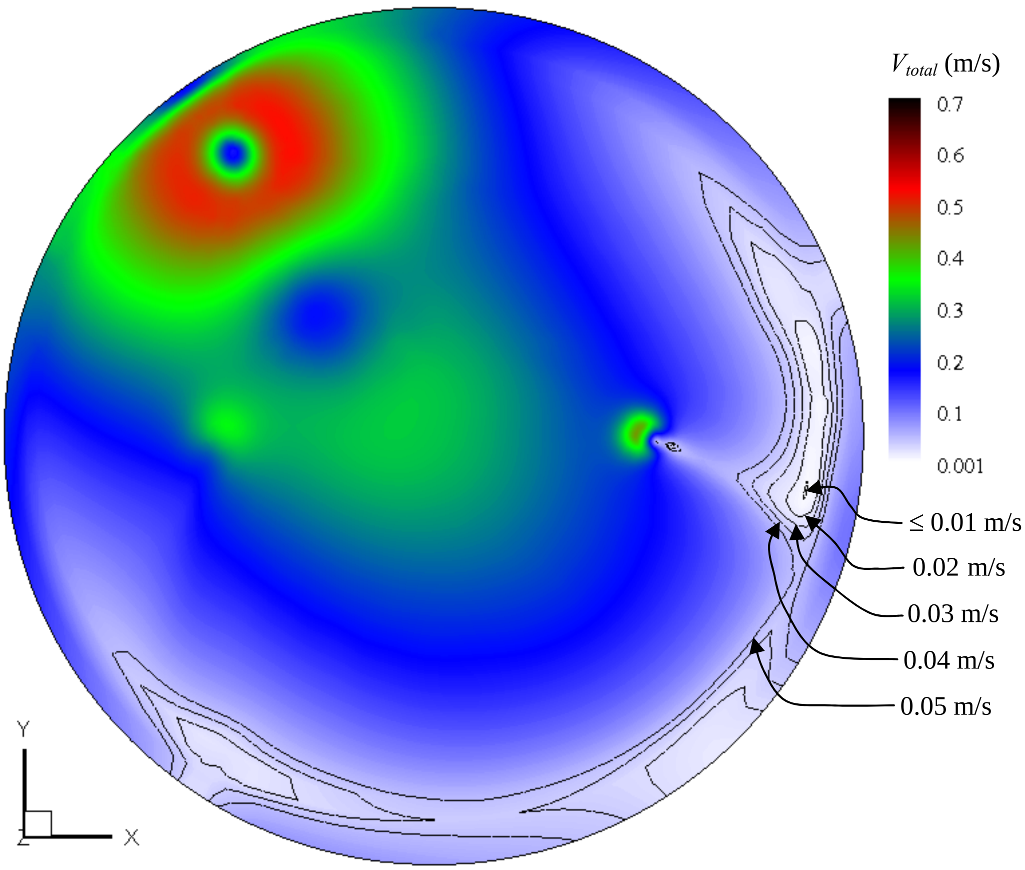


**Figure 4.4. Total velocity contours along the bottom of FPT1 during the 150 gpm transfer operation.**

## 4.2 TRANSFER AT 70 GPM

The minimum allowable flow rate for a transfer is 70 gpm. This lower flow rate (compared to the standard transfer rate of 150 gpm) will change the plunging jet trajectory as well as its resulting impingement location and velocity. Figure 4.5 shows a top view sketch (updated from Figure 2.1) with the new location of TI. In addition, Table 3.2 provides the updated dimensional information for the 70 gpm transfer. Note that the recirculation flow rate is still 135 gpm.

Similarly to the 150 gpm transfer, the flow field created by the 70 gpm transfer creates recirculation regions near the walls that entrain fluid around the plunging jets and essentially mix the tank, spreading the tank's contents throughout the supernate. However, unlike the 150 gpm transfer, there are several direct flow paths from the tank inlets (RI and TI) to the tank outlets (TO and RO, respectively).

Figure 4.6 presents flow tracers within FPT1 for the 70 gpm transfer. In Figure 4.6a, there are sixty tracers that originate within FPT1 and terminate within a square encompassing each tank outlet (RO & TO). Similarly, the tracers in Figure 4.6b originate within a square

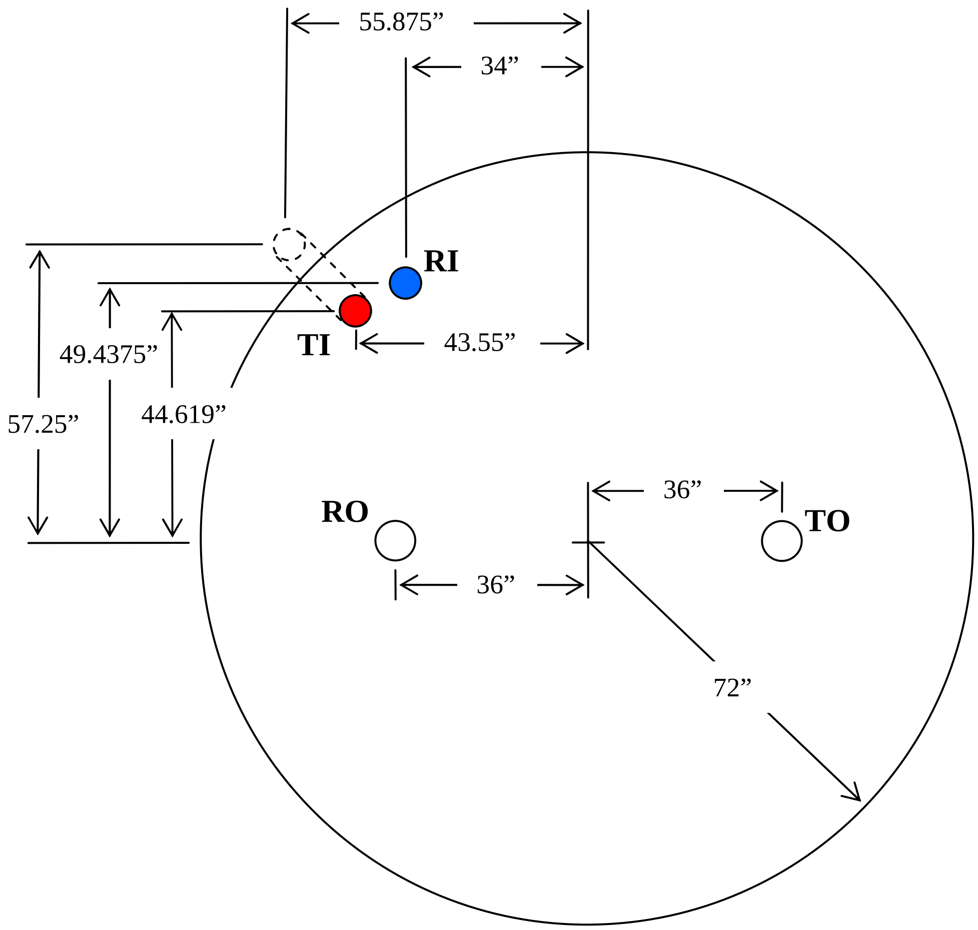


**Figure 4.5. Simplified top view sketch of the FPT1 geometry for the 70 gpm transfer. Not to scale.**

encompassing each tank inlet (plunging jets RI & TI). These flow tracers show that, while most of the fluid exiting the tank comes from the supernate surface near the entrainment region of RI and TI, some of the fluid does originate from the plunging jets themselves. A portion of the transfer fluid (from TI) entering FPT1 is drawn into the recirculation outlet (to RO); while some of the recirculation fluid (from RI) returning to the tank is transferred out (through TO). The remainder of the tank fluid still has to travel through the circulation routes within the tank before it is eventually transferred out of the tank. Thus, , as long as the sludge particles remain suspended ($V_{total} > V_{ts}$) within the tank, the sludge particles at any location will eventually be drawn out of the tank through either RO or TO.

The fluid velocity throughout FPT1 must remain above $V_{ts}$ to ensure that the particles ($d_p \leq$ 25 μm) remain suspended within the fluid. Figure 4.7 presents iso-velocity surfaces corresponding to total velocity magnitudes ($V_{total}$) of 0.012, 0.024, and 0.042 m/s, which are much higher than the terminal settling velocity of 0.001 m/s necessary to keep the particles entrained. Here the colors are shown with 50% translucency so that the lower velocity regions can be seen. All areas outside of these iso-velocity surfaces have velocity magnitudes greater than 0.042 m/s, which mean that most of the tank has velocities much greater than $V_{ts}$.

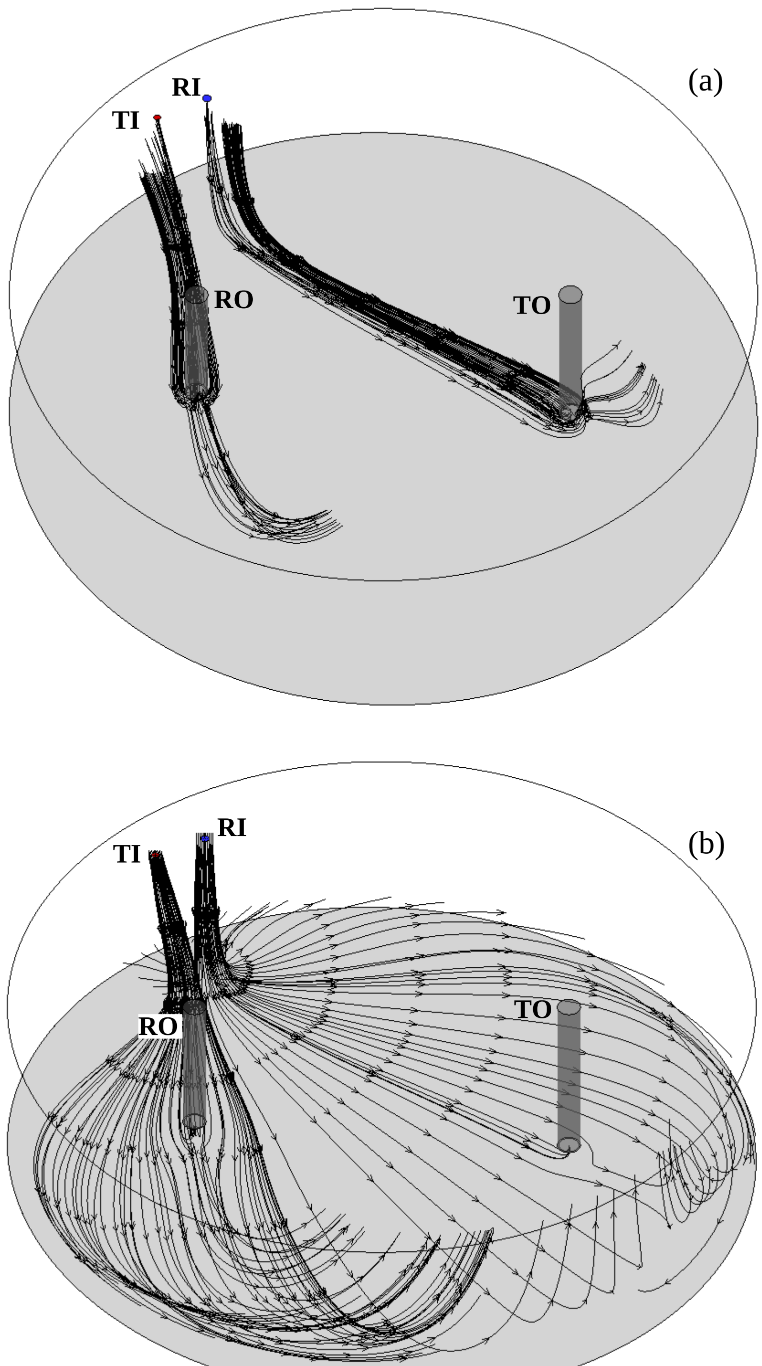


**Figure 4.6. Flow tracers for the fluid flow leaving FPT1 through RO and TO (a) and the fluid flow entering FPT1 through RI and TI (b) during the 70 gpm transfer operation.**

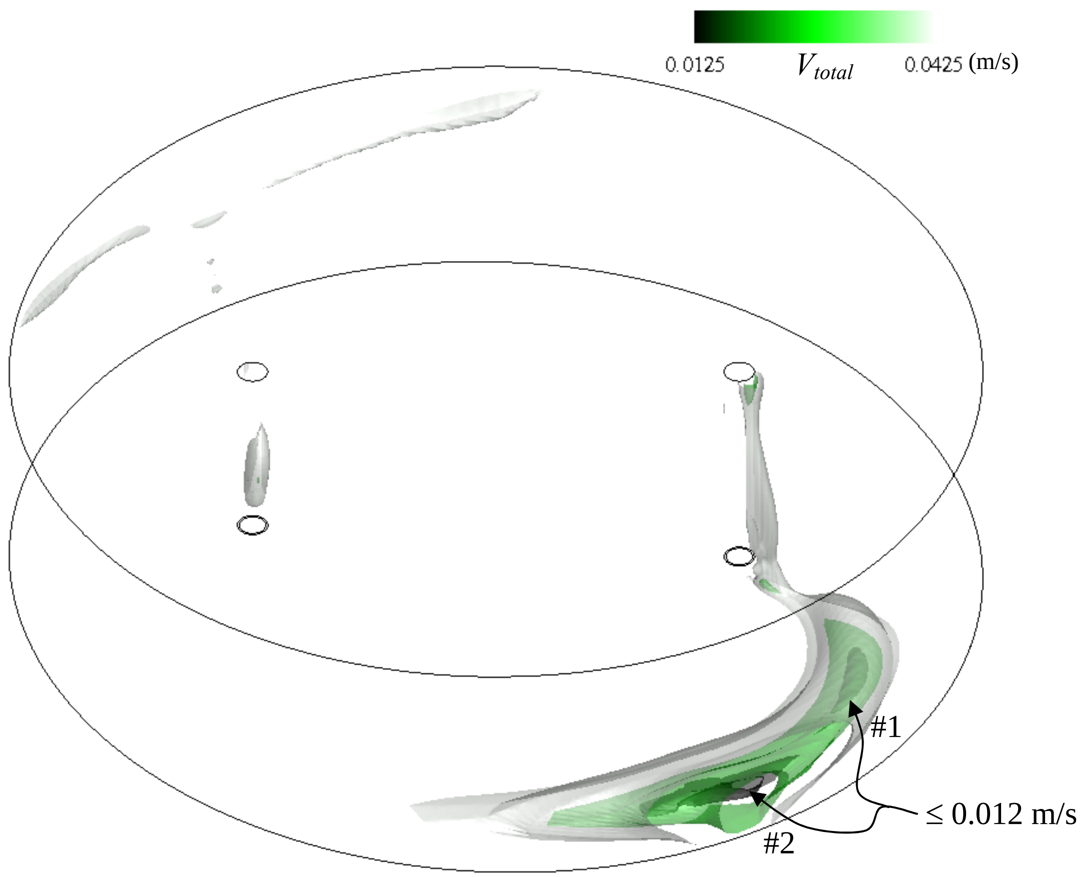


**Figure 4.7. Time-averaged, iso-velocity surfaces ($V_{total}$ = 0.012, 0.024, and 0.042 m/s) of FPT1 during the 70 gpm transfer operation.**

There are two low-velocity regions with have velocity magnitudes less than 0.012 m/s that are called out with arrows within Figure 4.7. Both regions are along the slanted tank bottom on the side farthest from RI and TI (near the absolute tank bottom). These low-velocity regions for the 70 gpm transfer have a larger area than those for the 150 gpm transfer, which is expected for the 80 gpm drop in flow rate. However, the minimum velocity magnitude for either of the 70 gpm transfer's low-velocity regions is approximately 0.002 m/s (2 mm/s), which is the same as for the 150 gpm transfer. To better represent the velocity distribution along the tank bottom as well as to better compare with the 150 gpm transfer (Figure 4.4), Figure 4.8 presents velocity contours along the tank bottom for the 70 gpm transfer. As previously, black contour lines at $V_{total}$ = 0.01, 0.02, 0.03, 0.04, and 0.05 m/s are used to highlight the regions of lowest velocity and note that the tank bottom slopes downward from left to right. While a larger surface area than the 150 gpm transfer, only a small fraction of the 70 gpm transfer's tank bottom is within an order of magnitude of the terminal settling velocity for 25 μm diameter particles. Given that this is a bounding particle size (see assumptions), the tank velocities should be more than adequate to keep the sludge solids ($d_p$ ≤ 25 μm) entrained during the transfer process, even at the minimum transfer flow rate of 70 gpm.

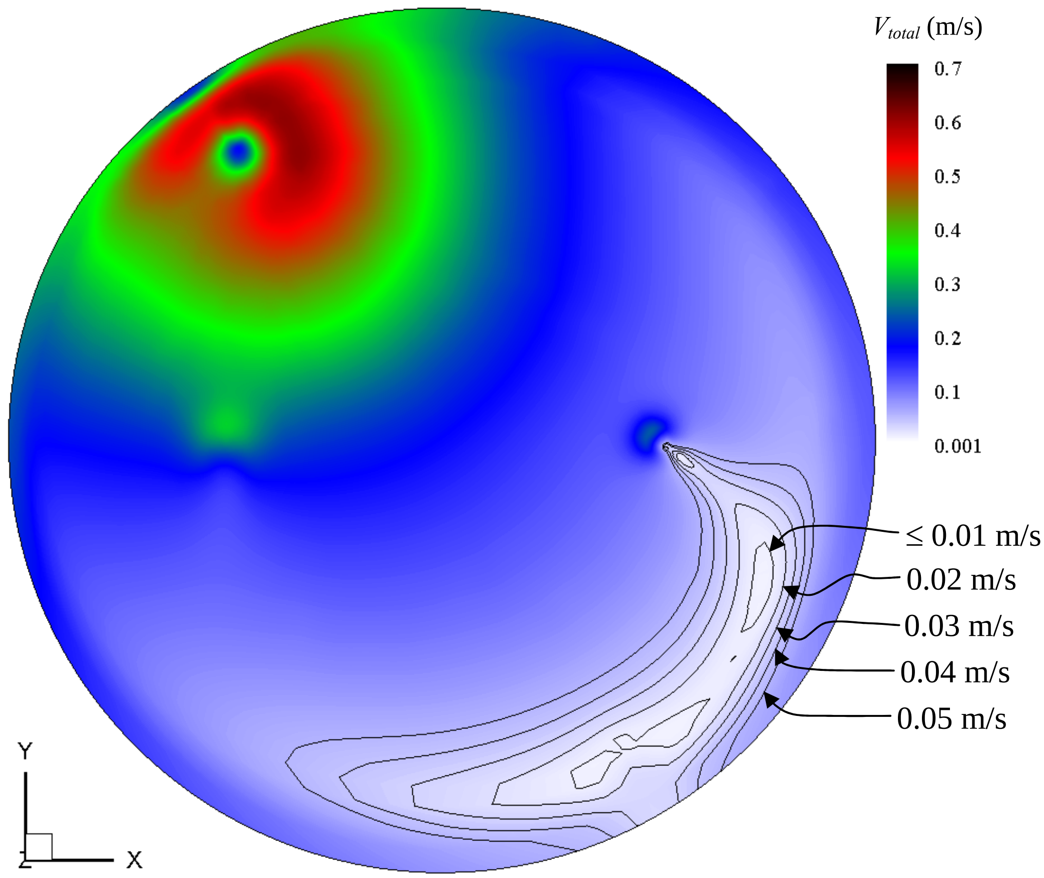


**Figure 4.8. Total velocity contours along the bottom of FPT1 during the 70 gpm transfer operation.**

# 5.0 CONCLUSIONS

During transfer operations in F-area Pump Tank 1, the recirculation pump running at 135 gpm and transfer pump running at either 70 gpm or 150 gpm will keep the tank mixed without the use of the pulse tube agitator. As such, the minimum velocities for these conditions (> 0.002 m/s) remain higher than the terminal settling velocity for 25 μm particles (0.00051 m/s), which act as an upper bound for particle size based on previous particle sampling data.

Note that, if the recirculation or transfer pumps stop while the tank still contains a slurry, the solid particles will settle to the bottom. Resuspension of the settle solids is not addressed in this analysis.

# 6.0 REFERENCES


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