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Plunging jets
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TANK 26 EVAPORATOR FEED PUMP TRANSFER ANALYSIS

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SEPTEMBER 2008

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Savannah River Nuclear Solutions
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SRNL™

Printed in the United States of America

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REVIEWS AND APPROVALS

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NOMENCLATURE

C	Empirical parameter for the Weber number
CFD	Computational fluid dynamics
EFP	Evaporator Feed Pump
d_{imp}	Impinging diameter
$d_{imp,a}$	Impinging diameter for the inner column of a “broken” jet
$d_{imp,b}$	Impinging diameter for a broken jet; $d_{imp,b} = \sqrt{\frac{4}{\pi} \cdot \frac{Q_o}{V_{imp}}} + K \cdot T_u^* \cdot V_o \cdot \frac{V_{imp} - V_o}{g}$
d_o	Orifice diameter
d_p	Particle diameter
g	Acceleration due to gravity
h	Tank liquid level (above the sludge layer)
H	Plunge height
k	Turbulent kinetic energy
K	Empirical constant for $d_{imp,b}$
L_c	Jet break-up length; $L_c = C \cdot d_o \cdot We^{\frac{1}{2}}$
Q_o	Volumetric flow rate
Q_{sludge}	Volume of sludge entrained into the supernate
Q_{tank}	Volume of the tank
SRNL	Savannah River National Laboratory
T_u^*	Normalized streamwise turbulence of a free-falling liquid jet in a gas
V_{min}	Minimum particle scour velocity; $V_{\min} = \left(\frac{d_p}{h}\right)^{-0.1} \cdot \sqrt{2.5 \cdot g \cdot d_p \cdot \left(\frac{\rho_p}{\rho_f} - 1\right)}$
V_{imp}	Impinging velocity; $V_{imp} = \sqrt{V_o^2 + 2 \cdot g \cdot H}$
$V_{imp,a}$	Impinging Velocity for the inner column of a broken jet; $V_{imp,a} = V_{imp}$
$V_{imp,b}$	Impinging Velocity for a broken jet
V_o	Orifice velocity
V_{total}	Total velocity magnitude; $V_{total} = \sqrt{V_x^2 + V_y^2 + V_z^2}$
V_x	x-component of velocity

V_y	*y*-component of velocity
V_z	*z*-component of velocity
We	Weber number; $We = \frac{\rho_f \cdot V_o^2 \cdot d_o}{\sigma}$
ε	Turbulent energy dissipation
ρ_f	Fluid density
ρ_p	Particle density
σ	Fluid surface tension

1.0 EXECUTIVE SUMMARY

The transfer of liquid salt solution from Tank 26 to an evaporator is to be accomplished by activating the evaporator feed pump, located approximately 72 inches above the sludge layer, while simultaneously turning on the downcomer. Previously, activation of the evaporator feed pump was an isolated event without any other components running at the same time. An analysis of the dissolved solution transfer has been performed using computational fluid dynamics methods to determine the amount of entrained sludge solids pumped out of the tank to the evaporator with the downcomer turned on.

The analysis results showed that, for the maximum and minimum supernate levels in Tank 26 (252.5 and 72 inches above the sludge layer, respectively), the evaporator feed pump will entrain between 0.05 and 0.1 wt% sludge solids weight fraction into the eductor, respectively. Lower tank liquid levels, with respect to the sludge layer, result in higher amounts of sludge entrainment due to the increased velocity of the plunging jets from the downcomer and evaporator feed pump bypass as well as decreased dissipation depth.

2.0 INTRODUCTION

Tank 26 is a feed tank to transfer supernate to another tank or to an evaporator. In either of these transfers, the discharge stream must contain less than a maximum weight percent of sludge solids at any time during the transfer process. An analysis of the liquid transfer to the evaporator has been performed using computational fluid dynamics (CFD) methods to estimate the amount of sludge drawn from Tank 26 through the evaporator feed pump when the downcomer is activated during the transfer process.

Figure 2.1 provides a simplified sketch (not to scale) of Tank 26, which consists of a supernate solution with a settled sludge layer on the bottom of the tank that is approximately 89 inches deep. The sludge particle range in size from 0.1 to 25 μm in diameter, with 20 vol.% of the particulate having diameters less than 1 μm [1, 2]. The supernate layer has a maximum height of 341.5 inches above the tank bottom that corresponds to the downcomer discharge height and results in a supernate layer height of approximately 252.5 inches above the sludge. Note that higher liquid levels are possible, but will have little to no influence on the fluid flow patterns near the sludge layer. The minimum supernate layer height is 161 inches above the tank bottom (corresponding to the evaporator eductor orifice height).

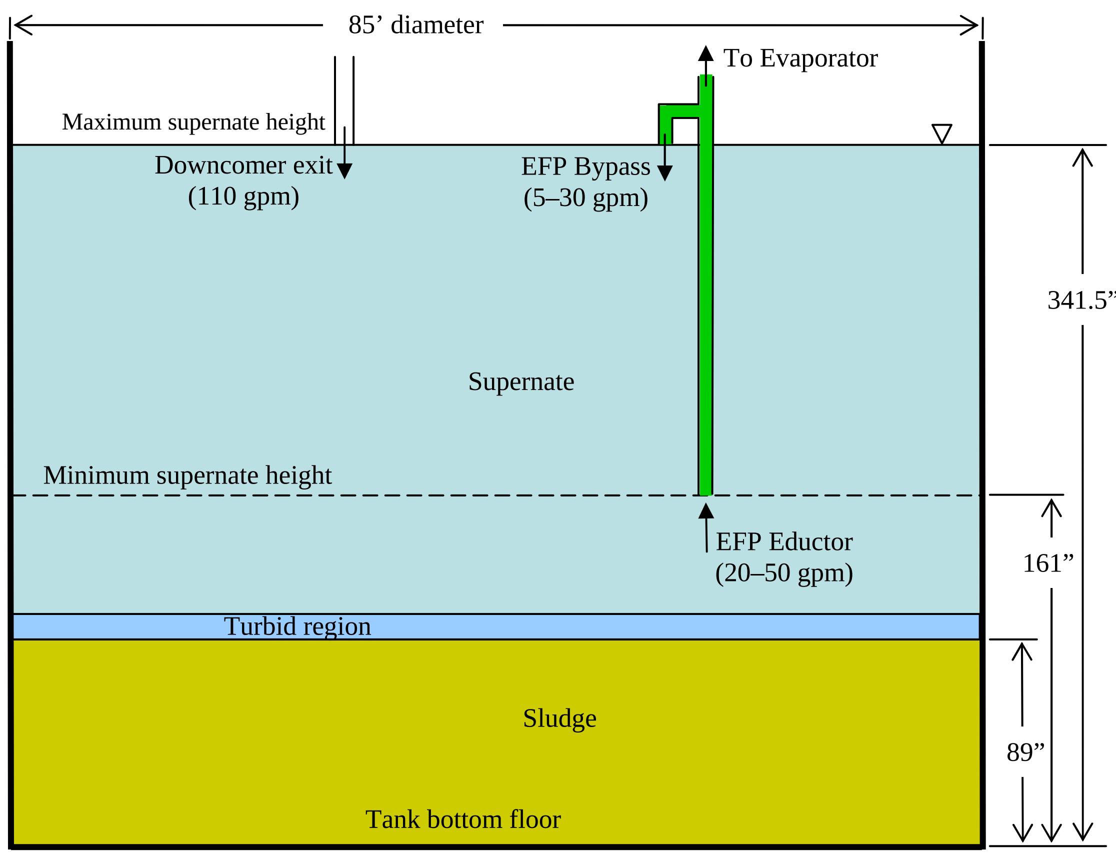

Figure 2.1. Two-dimensional sketch of the simplified modeling geometry. Not to scale.

Under normal conditions, the downcomer would first add liquid to Tank 26. Then, after any sludge particulate that had been stirred up by the downcomer had been allowed to resettle to the bottom of the tank, the evaporator feed pump (EFP) would be activated to transfer supernate to the evaporator. A limit of 1.0 wt.% sludge particulate is imposed on fluid drawn out of Tank 26 through the EFP eductor for transfers to the evaporator [3]. As a time-saving (and cost-saving) measure, it has been proposed that both the downcomer and the EFP could be activated simultaneously without violating the sludge limit of 1.0 wt%.

The purpose of this analysis is to estimate the amount of sludge solids in the EFP during the transfer through the eductor located 72 inches above the sludge layer (161 inches above the tank bottom).

3.0 METHODOLOGY

The downcomer and evaporator feed pump are located asymmetrically within the Tank 26, which makes a three-dimensional model appropriate for this calculation. The governing equations solved for each analysis included a mass balance, the three-dimensional momentum equations, and two turbulence equations. The standard, two-equation, k-ε model was used to estimate the fluid turbulence. Figure 2.1 provides a sketch (not to scale) of the geometry that was modeled using the FLUENT™ CFD code, while Table 3.1 lists the modeling conditions that were used.

Figure 3.1 presents a three-dimensional view of the modeling domain created from the sketch in Figure 2.1. For the high supernate level (case 1), the modeling domain is made of approximately 3 million grid elements. Additionally, for the low supernate level (case 2), the modeling domain is made of approximately 1.3 million grid elements.

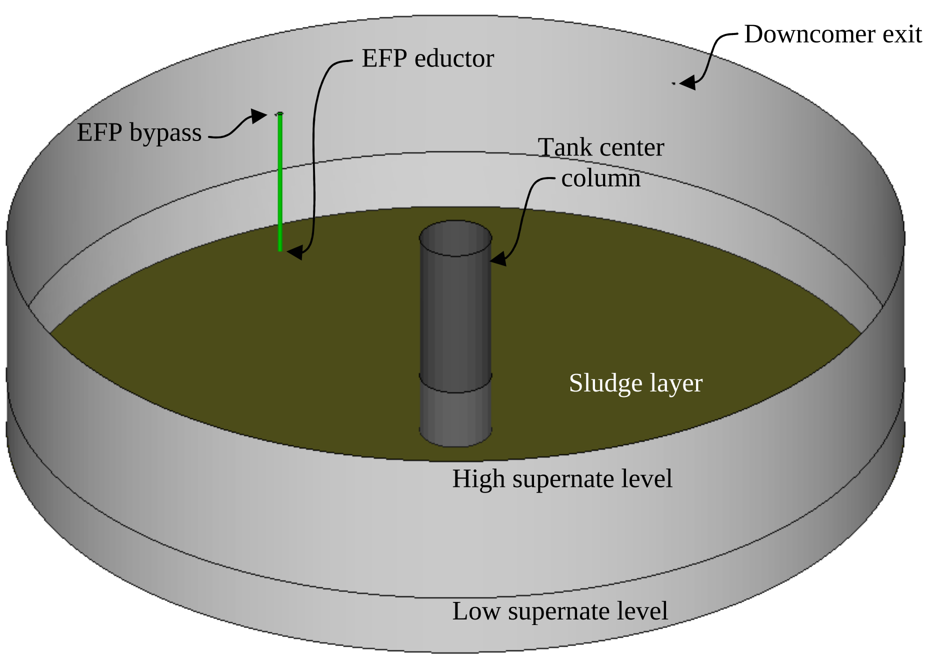

Figure 3.1. Three-dimensional view of the high supernate level model domain.

The following conditions, in coordination with Table 3.1, are used to analyze Tank 26:

- Only the liquid within Tank 26 is modeled. Particle motions are inferred based on the velocity field and the interactions (entrainment, settling, etc.) that would occur because of those velocities.
- Flow rates are set to the highest values for the evaporator feed pump eductor and bypass, which have ranges of 20 – 50 gpm and 5 – 30 gpm, respectively [4].
- When the supernate liquid level is below the downcomer orifice, the downcomer flow and EFP bypass are treated as plunging jets.
- Tank 26 contains primarily cohesive, densely-packed sludge, with a turbid layer approximately 6 inches deep of loosely-packed solids above the sludge layer [3].
- Based on sampling test results for Tank 40 sludge Batch 3 [2], 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.

The following assumptions were made to create this model:

- Internal tank structures (piping, etc.) are not included for simplification [5].
- The surface waves and instabilities at the supernate surface were neglected, with a pressure outlet boundary condition of atmospheric pressure at the free surface.
- The liquid volume in Tank 26 is assumed to stay relatively constant during the transfer process because the downcomer, which adds liquid at 110 gpm, will increase the fluid height by a maximum of 0.031 inches per minute.
- 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 calculation. Previous calculations [6] have shown very little sensitivity to fluid temperature in the resulting flow patterns.
- The sludge layer is modeled as a solid, level surface with a free slip condition.
- Loosely-packed sludge solids in the turbid region are assumed to contain approximately 99 wt% supernate and 1 wt% particulate.
- Solids in the sludge layer are homogeneously distributed and are picked up into the flow when the local velocity at the sludge layer surface (at the solid boundary) exceeds the minimum scour velocity required to transport sludge solids.
- The plunging jet created by the EFP bypass retains 50% of its fluid flow within the intact center column with the remaining 50% striking the supernate surface as fluid globules in random patterns within the impinging area ($d_{imp,b}$).
- The liquid in Tank 26 is homogeneously mixed based on previous results [1] and the resulting flow patterns.

The assumptions listed above warrant some clarification. The assumption of water as the working fluid is appropriate because of its relative similarity to supernate in density and viscosity [6]. Previous work for similar analyzes [1] has shown negligible impact on the calculated flow patterns between water and supernate.

Table 3.1. Modeling conditions used for the calculations.

Parameter	Values	
	Case 1: High tank level	Case 2: Low tank level
Supernate liquid level	341.5 in tank level	161 in tank level
Sludge layer at tank bottom	89 in tank level	89 in tank level
Downcomer jet flow rate (Q_o)	110 gpm	110 gpm
Downcomer exit diameter (d_o) [7]	3 in SCH 10S Pipe (3.26 in ID)	3 in SCH 10S Pipe (3.26 in ID)
Downcomer exit velocity (V_o)	4.23 ft/s (1.29 m/s)	4.23 ft/s (1.29 m/s)
Downcomer plunge height (H)	0.0 in	180.5 in (4.58 m)
Downcomer break-up length (L_c)	0.0 in	309 in – 374 in (7.85 m – 9.50 m)
Downcomer impinging diameter (d_{imp})	3.26 in (82.8 mm)	1.20 in (30.4 mm)
Downcomer impinging velocity (V_{imp})	4.23 ft/s (1.29 m/s)	31.4 ft/s (9.57 m/s)
EFP eductor flow rate (Q_o)	50 gpm	50 gpm
EFP eductor diameter (d_o) [8]	Penberthy LL 2.0 eductor (1.69 in ID)	Penberthy LL 2.0 eductor (1.69 in ID)
EFP eductor velocity (V_o)	-7.15 ft/s (2.18 m/s)	-7.15 ft/s (2.18 m/s)
EFP bypass flow rate (Q_o)	30 gpm	30 gpm
EFP bypass exit diameter (d_o) [8]	1 1/2 in SCH 40 Pipe (1.61 in ID)	1 1/2 in SCH 40 Pipe (1.61 in ID)
EFP bypass exit velocity (V_o)	4.73 ft/s (1.44 m/s)	4.73 ft/s (1.44 m/s)
EFP bypass plunge height (H)	0.0 in	180.5 in (4.58 m)
EFP bypass break-up length (L_c)	0.0 in	95 in – 105 in (2.41 m – 2.67 m)
EFP bypass impinging diameter (d_{imp})	1.61 in (40.9 mm)	a = 0.221 in (5.61 mm); b = 3.312 in (84.13 mm)
EFP bypass impinging velocity (V_{imp})	4.73 ft/s (1.44 m/s)	a = 31.5 ft/s (9.60 m/s); b = 0.732 ft/s (0.223 m/s)

Cohesively packed sludge will behave like a solid surface if the fluid velocity is too low to break the bonds holding the sludge solids together. Any loosely-packed solids along the sludge surface will move along with the fluid in a free slip fashion. The sludge in Tank 26 is primarily composed of cohesive, densely-packed sludge, with a turbid layer of loosely-packed solids (approximately 6 in deep) along the top of the sludge layer [3]. A turbidity probe can reach its maximum value with as little as 0.4 wt% sludge particles and is unable to measure higher values [9]. Thus, the turbid layer could have a wide range of values. However, given the inactivity of Tank 26, a more realistic estimate would be on the order of 1 wt% particulate in the turbid region, as is assumed for this study. This is a conservative estimate given that a higher weight percentage of sludge would result in more larger particles, which tend to settle more readily and are not as susceptible to the small driving flow expected in these tanks at the sludge layer.

In the present study, the sludge solids are not scoured unless the liquid velocity is greater than the minimum scouring velocity (V_{min}) necessary to pick up solids deposited at the sludge layer. For cohesive sludge solids, the minimum scouring velocity is 0.7 m/s (2.27 ft/s) [6, 10]. For loosely-packed solid, the minimum scouring velocity is dependent upon several factors, including: flow velocity, particle size, and the density ratio between the particulate and the carrier fluid. Graf [11] published the following empirical correlation for the minimum scour velocity using data available in the literature.

$$V_{\min} = \left(\frac{d_p}{h}\right)^{-0.1} \cdot \sqrt{2.5 \cdot g \cdot d_p \cdot \left(\frac{\rho_p}{\rho_f} - 1\right)}, \qquad (3.1)$$

where d_p is the particle diameter, h is the tank liquid level, g is the acceleration due to gravity, ρ_p is the density of the sludge particulate, and ρ_f is the density of the fluid. Typical values of the density ratio (ρ_p / ρ_f) for water and supernate are 2.5 and 1.67, respectively. A range of minimum scouring velocities for sludge particles ranging between 0.1 and 25.0 μm in diameter is provided in Table 3.2.

According to previous work [1, 2], the sludge layer in the tanks at SRS has a typical range of particulate sizes between 0.1 and 25 μm. According to the literature [1, 2], submicron particles such as 0.1 μm solids do not settle readily since Brownian motion becomes significant for particles with diameters less than 0.5 μm. SRNL test results [2] show that approximately 20 vol.% of sludge for Tank 40 Batch 3 consists of particles less than 1 μm in diameter. Thus, the present study assumes a representative particle size of 1 μm in diameter as a conservative estimate of the sludge layer solids.

Table 3.2. Minimum velocities of supernate required to transport solid particles.

Particle size	Case 1 -- High supernate level	Case 2 -- Low supernate level
0.1 μm	0.0254 ft/s (0.00774 m/s)	0.0224 ft/s (0.00682 m/s)
0.5 μm	0.0483 ft/s (0.0147 m/s)	0.0427 ft/s (0.0130 m/s)
1.0 μm	**0.0637 ft/s (0.0194 m/s)**	**0.0561 ft/s (0.0171 m/s)**
5.0 μm	0.122 ft/s (0.0370 m/s)	0.107 ft/s (0.0326 m/s)
10.0 μm	0.160 ft/s (0.0488 m/s)	0.142 ft/s (0.0431 m/s)
15.0 μm	0.188 ft/s (0.0574 m/s)	0.166 ft/s (0.0506 m/s)
20.0 μm	0.212 ft/s (0.0644 m/s)	0.187 ft/s (0.0568 m/s)
25.0 μm	0.231 ft/s (0.0704 m/s)	0.204 ft/s (0.0621 m/s)
Cohesive sludge [6, 10]	2.27 ft/s (0.692 m/s)	2.27 ft/s (0.692 m/s)

For the low supernate level model (case 2), both the downcomer and EFP bypass discharge into the air as a free jet before striking the supernate surface as a plunging jet. A liquid jet discharging vertically downward into a gas will begin as a liquid column but will lose coherence and break apart farther downstream below the nozzle exit. Sallam *et al.* [12] provides the following correlation for this distance, known as the break-up length (L_c), for water jet in air.

$$L_c = C \cdot d_o \cdot We^{\frac{1}{2}}, \qquad (3.2)$$

where *We* is the jet Weber number and *C* is an empirical parameter having a magnitude on the order of unity. For liquid jets with a Weber of 670 – 13,700 (*We* = 2000 and 1200 for the downcomer and EFP bypass, respectively), *C* is equal to 2.1 with a standard deviation of 0.2 [12]. From Equation (3.2), the downcomer has a break-up length between 309 and 374 inches and, thus, should remain a column until striking the supernate surface because the maximum plunge height is 180.5 inches. Conversely, the EFP bypass at 30 gpm has a break-up length between 95 and 105 inches and, thus, will break apart into large globules of liquid prior to impacting the supernate surface.

For the downcomer, the plunging jet's impinging velocity (V_{imp}) is derived from conservation of energy via the free fall equation.

$$V_{imp} = \sqrt{V_o^2 + 2 \cdot g \cdot H} \, , \tag{3.3}$$

where V_o is the velocity at the jet exit. The time-averaged plunging jet's impinging diameter (d_{imp}) can then be found using conservation of mass.

$$d_{imp} = \sqrt{\frac{4}{\pi} \cdot \frac{Q_o}{V_{imp}}} \, , \tag{3.4}$$

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

Figure 3.2 provides a schematic of a free-falling liquid jet, which was used to describe the EFP bypass plunging jet that does not remain coherent at the supernate surface. Below the jet break-up length, globules of fluid break off from the jet column—due to gravity, turbulent eddies, and surface tension—as the jet column itself forms breaks at varying distances [12]. From a time-averaged standpoint, the jet column forms a steady pattern as it strikes the supernate surface, with a much smaller diameter than the remainder of the liquid jet. Outside of the inner column, the globules of liquid strike the supernate surface with varying sizes and random locations. However, no data are reported that measure the fraction of liquid remaining in the center column. To avoid underestimating this fraction, and based on the additional fall after break-up length coupled with the break-down process [12], the authors assumed that half of the original flow remained within the column at the supernate surface while the other half fell randomly within the outside diameter of the plunging jet. Castillo [13] published an empirical correlation for the plunging jet thickness at the liquid surface

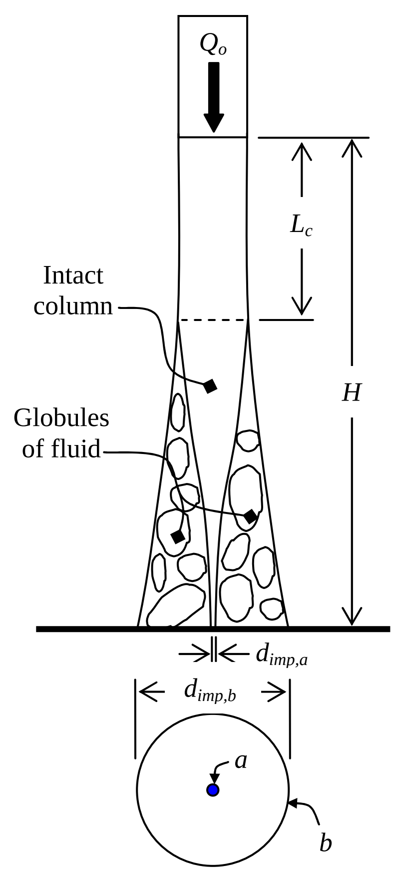

Figure 3.2. Plunging jet schematic.

(impinging diameter, d_{imp}) in terms of the geometric dimensions of the jet exit, the fall height, and the relative turbulence of the jet at the jet exit using waterfall data.

$$d_{imp,b} = \sqrt{\frac{4}{\pi} \cdot \frac{Q_o}{V_{imp}}} + K \cdot T_u^* \cdot V_o \cdot \frac{V_{imp} - V_o}{g}, \tag{3.5}$$

where $d_{imp,b}$ is the total plunge jet diameter (outer circle), K is an empirical constant equal to approximately 1.14 for a circular jet [13], T^*_u is normalized streamwise turbulence of the free falling jet, and V_{imp} is the plunge jet's impinging velocity as found using Equation (3.3). Equation (3.4) can be used to find the diameter of the center column of the plunging jet ($d_{imp,a}$) by assuming that half of the volumetric flow rate is used in the calculation. The velocity of this intact center column ($V_{imp,a}$) is assumed to remain at the plunge jet velocity found using Equation (3.3). The effective velocity outside of the center column ($V_{imp,b}$) is found by averaging the other half of the flow rate across the plunge jet area outside of the center column.

In the present work, the weight percentage of sludge solids will be predicted from the ratio of the volume of sludge (Q_{sludge}) to the volume of supernate (Q_{tank}) for a conservative evaluation of the sludge carryover during the operation of the EFP and the downcomer. The volume of sludge is calculated as the scour area at the bottom of the tank times the depth of loosely-packed sludge solids, as will be shown in the following section. The scour area for a given particle size is defined as the area at the sludge layer where the velocity is higher than the V_{min} for that particle and, thus, would scour that particle size.

4.0 CALCULATIONS AND RESULTS

The results for this work can be broken into two sections, which represent the minimum and maximum supernate levels within Tank 26. Section 4.1 presents results for case 1 with the supernate level at the maximum height of 341.5 inches above the bottom of the tank. Results from case 2 where the supernate level is at the minimum height of 161 inches above the tank floor are described in Section 4.2. Note, the aforementioned analysis was done for an eductor and bypass flows set at 50 and 30 gpm, respectively, but that additional cases were examined where the volumetric flow rates for the evaporator feed pump eductor and bypass were set to their minimums (20 gpm and 5 gpm, respectively), but only negligible changes in the flow patterns were seen.

4.1 CASE 1 – HIGH SUPERNATE LEVEL

Figure 4.1 shows a sketch of the flow patterns created by the downcomer and the evaporator feed pump for the high supernate level model (case 1). The sketch is not drawn to scale to highlight the affected regions within the tank, which are too small to represent in full scale. The downward flow from the downcomer dissipates as it impinges upon the sludge layer at the bottom of the tank. At the sludge layer, the fluid scours particulate (from the sludge layer where the fluid velocity is greater than V_{min}) as it flows outward in all directions until it reaches the tank walls. The fluid then flows up the wall and along the supernate surface until it is entrained back downward toward the bottom of the tank. In this manner, large

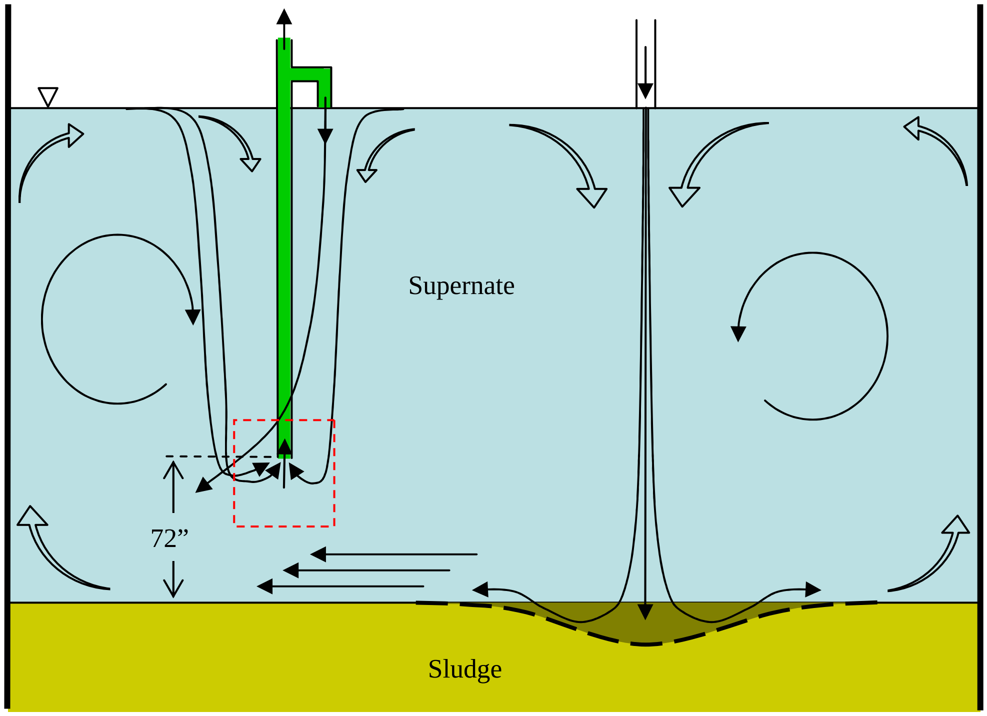

Figure 4.1. Two-dimensional sketch of the flow patterns produced by the downcomer and evaporator feed pump eductor and bypass for the high supernate level model. Not to scale.

recirculation regions are formed that essentially mix the tank, spreading any scoured particulate throughout the tank. The EFP bypass creates similar flow patterns, although to a smaller extent due to the lower momentum (1.36 kg-m/s vs. 4.46 kg-m/s for the EFP bypass and downcomer, respectively).

Figure 4.2 shows the steady-state flow patterns near the EFP eductor corresponding to the red dashed box within Figure 4.1. Here the color of the velocity vector corresponds to the total velocity magnitude (V_{total}). Note that the velocity vectors more than four eductor diameters downstream of the eductor orifice are not being turned toward the eductor. In addition, all of the fluid traveling into the eductor can be traced back toward the supernate surface.

There are two important points to make from Figures 4.1 and 4.2:

1. The recirculation regions will mix the tank fairly well so that any solids that are picked up from the sludge layer will be spread throughout the tank.
2. Most of the flow entering the EFP eductor comes from the supernate surface, not the bottom of the tank, because of the recirculation regions created by the downcomer and the EFP bypass.

Total velocity contours at the sludge layer for the high supernate model are presented in Figure 4.3. Note that the EFP (representing the bypass and eductor) and downcomer are marked by white circles within the contours. The highest velocity achieved at the sludge layer is 0.190 ft/s (0.058 m/s), which is much less than the minimum scour velocity of 2.27 ft/s (0.7 m/s), see Table 3.1, necessary to scour cohesive, densely-packed particles.

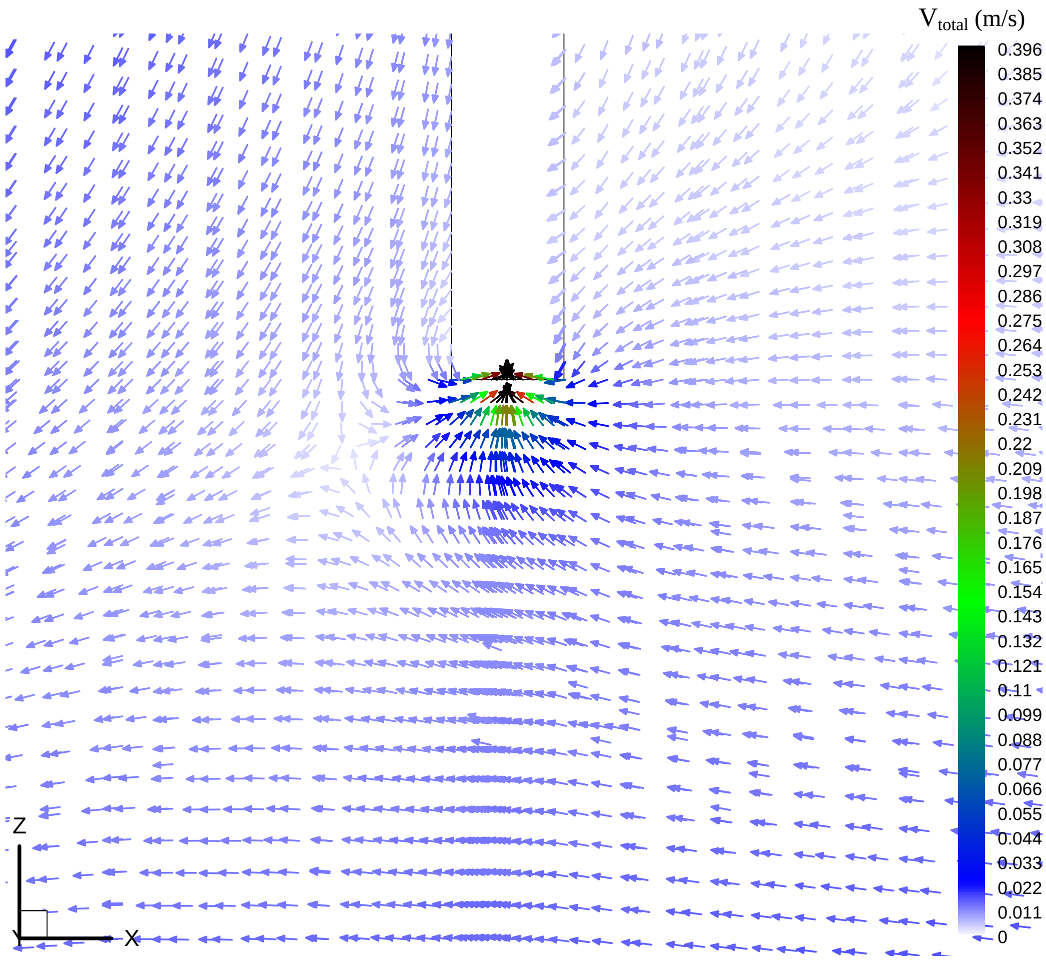

Figure 4.2. Velocity vector field showing the flow patterns at the evaporator feed pump educator for the high supernate level model corresponding to the red dashed box in Figure 4.1.

However, above the densely packed sludge layer is a turbid layer of loosely-packed particles. Based on past experience and laboratory turbidity measurements [3, 9], this layer is estimated to be approximately 6 inches deep and have a solids weight-percentage on the order of 1%. By using the minimum scour velocities provided in Table 3.2 in coordination with Figure 4.3, the volume of sludge entrained from the turbid region can be estimated. Using the characteristic particle size of 1 μm, the evaporator feed transfer into the eductor will contain approximately 0.0275 vol%, or 0.0460 wt%, sludge solids. Table 4.1 provides additional values based on several weight-percentage solids and characteristic particle diameters within the turbid region.

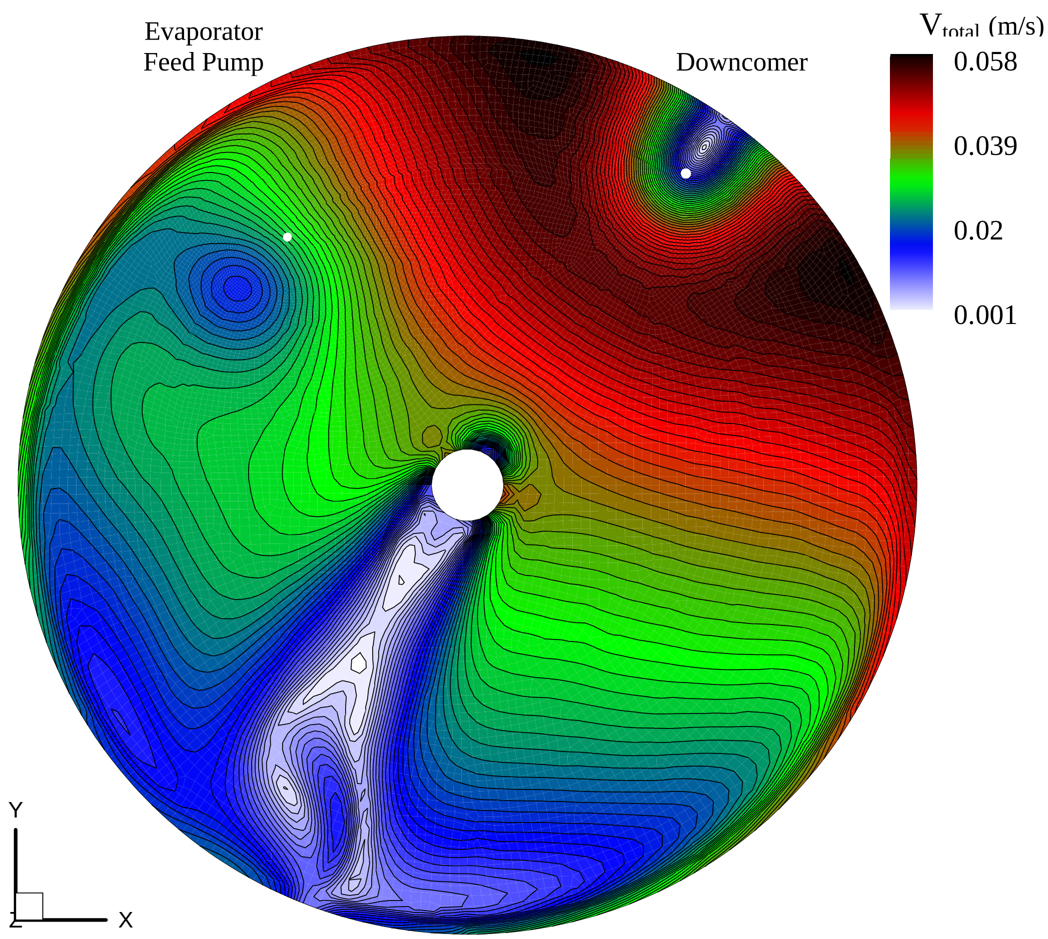

Figure 4.3. Total velocity contours at the sludge layer for the high supernate level model.

Table 4.1. Volume- and weight-percentage of solid particles drawn into the eductor by the evaporator feed pump based on the estimated weight-percentage of sludge particles within the turbid layer above the coherent sludge for the high supernate case.

Particle size (µm)	Assumed wt% solids in the turbid layer					Percentages
	0.1	0.5	1.0	5.0	10.0	
0.1	0.0034	0.0169	0.0339	0.1695	0.3389	Volume-percent of solids
0.5	0.0031	0.0156	0.0311	0.1557	0.3114	
1.0	0.0028	0.0138	**0.0275**	0.1377	0.2754	
5.0	0.0012	0.0060	0.0120	0.0599	0.1198	
10.0	0.0005	0.0027	0.0054	0.0271	0.0543	
0.1	0.0057	0.0283	0.0566	0.283	0.566	Weight-percent of solids
0.5	0.0052	0.0260	0.0520	0.260	0.520	
1.0	0.0046	0.0230	**0.0460**	0.230	0.460	
5.0	0.0020	0.0100	0.0200	0.100	0.200	
10.0	0.0009	0.0045	0.0091	0.0453	0.0907	

4.2 CASE 2 – LOW SUPERNATE LEVEL

Figure 4.4 presents a sketch (not to scale) of the flow patterns created in Tank 26 when the supernate level is at its minimum of 161 inches above the bottom of the tank (case 2). At this height, the downcomer and EFP bypass are both plunging jets that fall 180.5 in (4.58 m) before impacting the supernate surface at approximately 31.5 ft/s (9.6 m/s). At this impact velocity, the downcomer plunging jet will maintain much of its strength throughout the 72 inches of supernate above the sludge layer. The EFP bypass plunging jet will still penetrate the supernate with an appreciable amount of force, but to a lesser effect compared to the downcomer due to its break-up length after approximately 100 inches. The recirculation regions seen for the high supernate model are still present here, but with larger velocities and smaller sizes. Thus, their scouring ability is much higher than that seen in Section 4.1.

The steady-state flow pattern near the EFP eductor corresponding to the red dashed box within Figure 4.4 is shown in Figure 4.5. Again, the two main points from the high supernate model are valid for the low supernate level model:

1. The recirculation regions mix the tank fairly well so that any solids scoured from the sludge layer will be spread throughout the tank.
2. The flow entering the EFP eductor comes from the supernate surface rather than the sludge layer directly because of the recirculation regions.

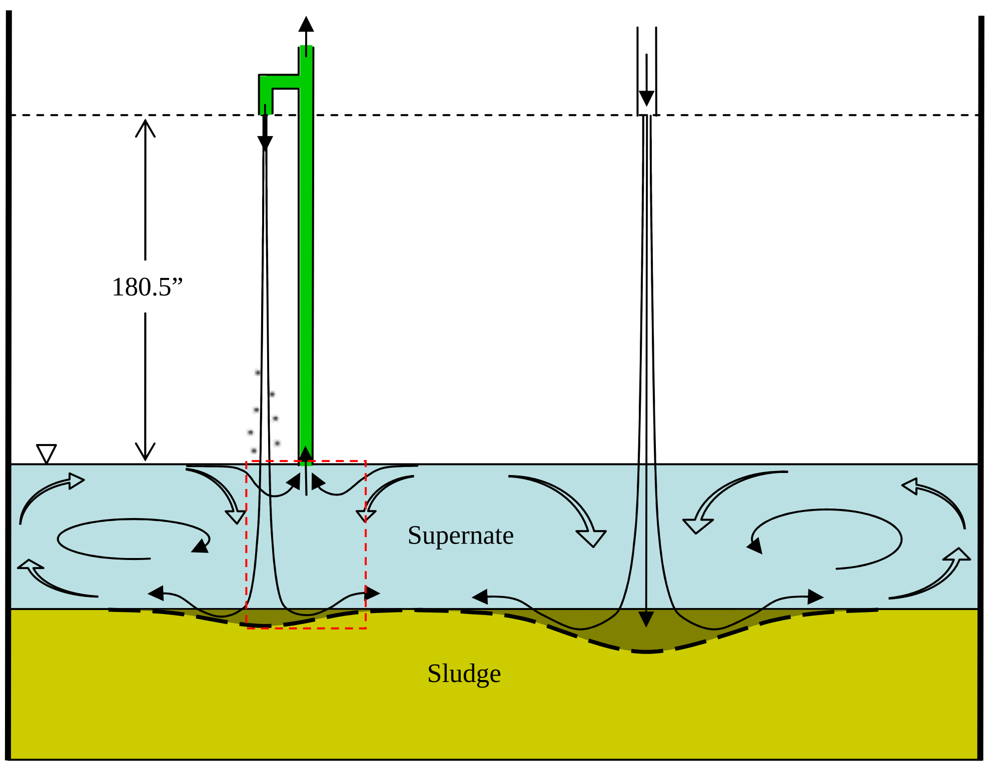

Figure 4.4. Two-dimensional sketch of the flow patterns produced by the downcomer and evaporator feed pump eductor and bypass for the low supernate level model. Not to scale.

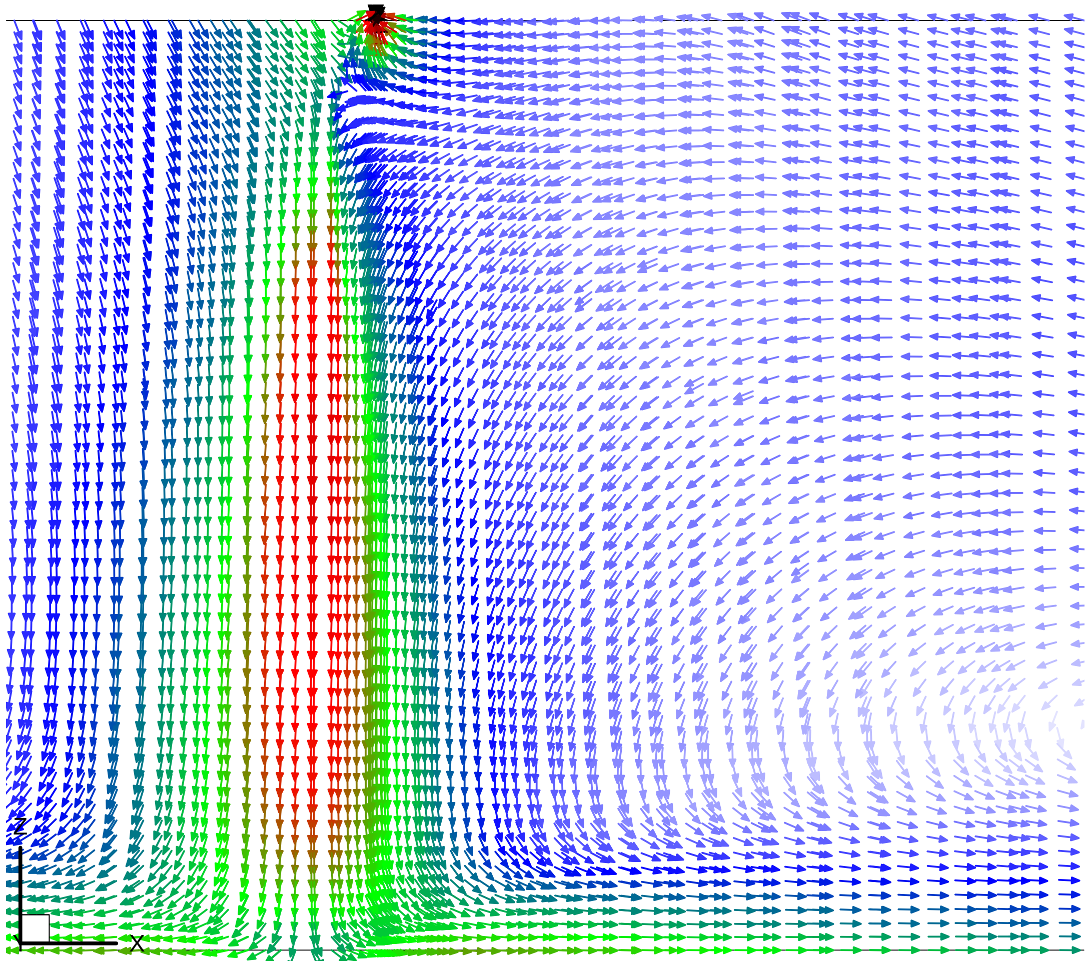

Figure 4.5. Velocity vector field showing the flow patterns at the evaporator feed pump eductor for the low supernate level model corresponding to the red dashed box in Figure 4.4. (See Figure 4.2 for scale)

However, unlike the high supernate level case, the velocity at the sludge layer is an order of magnitude higher with a maximum total velocity of 1.87 ft/s (0.571 m/s) below the downcomer. While this is not higher than the 2.27 ft/s (0.692 m/s) necessary to scour cohesive sludge, it is rather close. However, the velocity across the sludge layer drops off quickly with increasing distance from the downcomer, as seen in the velocity contour plot in Figure 4.6. Note that the EFP and downcomer are marked by white circles within the contours. Also note that the contour lines are not equally spaced.

While the downcomer and EFP bypass have the same freefall distance, their velocities at the sludge layer as well as their effected regions within the turbid layer are not equal. This can be attributed to the difference in momentum (1.36 kg-m/s vs. 4.46 kg-m/s for the EFP bypass and downcomer, respectively) as well as the condition of the plunging jets at the supernate surface. The downcomer remains coherent, which allows its impulse to cut through the liquid down to the sludge layer while keeping a high velocity. In contrast, the EFP bypass does not remain coherent and, thus, much of its momentum is spread throughout a large area of the surface in the form of globules of liquid. The remaining intact column of fluid (approximately half) dissipates more quickly as it plunges through the supernate, resulting in smaller velocities. Even with the lower velocities, the EFP bypass does entrain some sludge from the turbid region as shown in Figure 4.6. This is a significant change compared to the high supernate level case where the EFP bypass impedes the downcomer's ability to scour, as shown by comparing the area below the EFP in Figures 4.3 and 4.6 for the low and high supernate levels, respectively.

Additional cases (not shown) were attempted with the EFP bypass discharging the minimum volumetric flow rate of 5 gpm. Because the plunging jet height did not change, the lower flow rate resulted in similar flow patters to those shown in Figure 4.6 with the maximum flow rate (30 gpm). Thus, the plunging jet height of the EFP bypass is more significant with regards to sludge scour.

At the minimum supernate level, the velocity magnitude is too low to scour the densely-packed, cohesive particles. Thus, only the loosely-packed particles within the turbid layer will be affected. Using the characteristic particle size of 1 μm with 1 wt% solids in the 6-inch deep turbid layer, the evaporator feed transfer into the eductor will contain approximately 0.0560 vol%, or 0.0935 wt%, sludge solids. Tables 4.1 and 4.2 provide additional values based on several weight-percentage solids and characteristic particle diameters within the turbid layer.

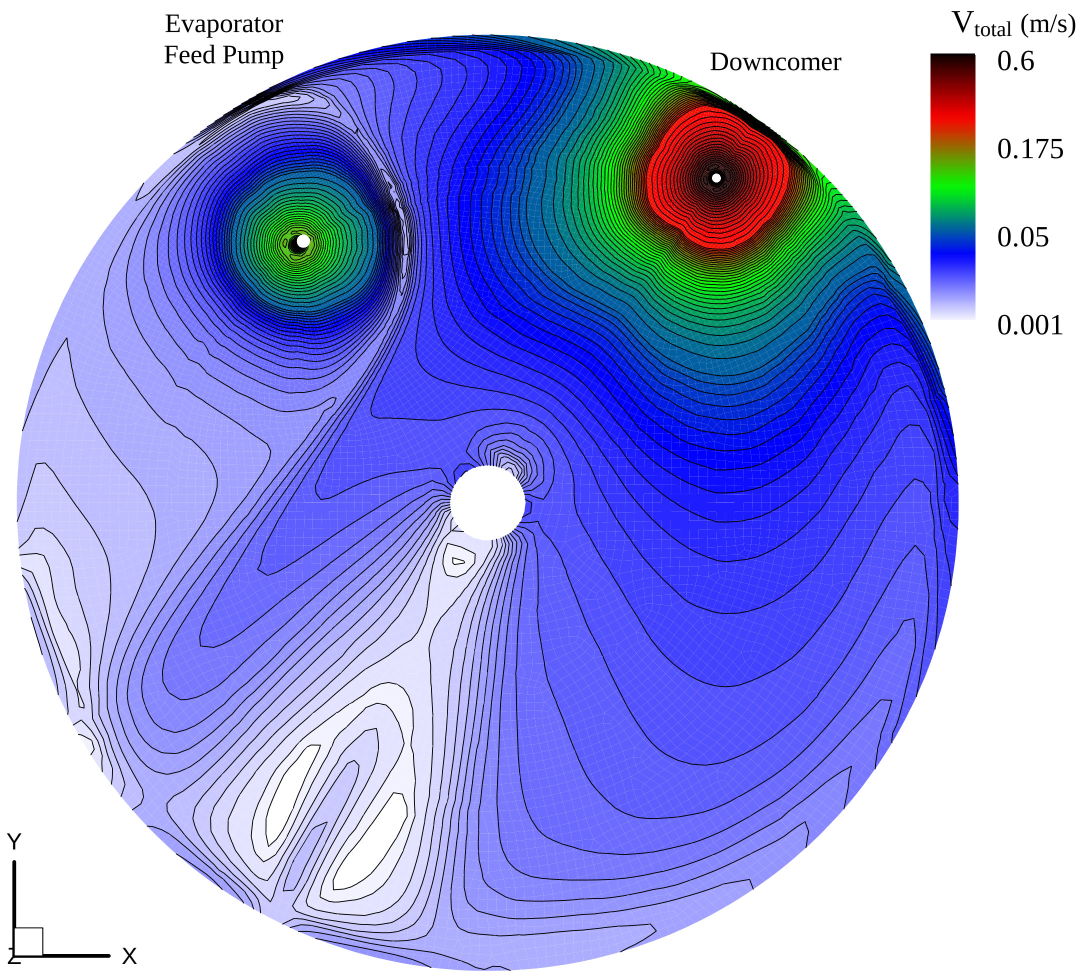

Figure 4.6. Total velocity contours at the sludge layer for the low supernate level model.

Table 4.2. Volume- and weight-percentage of solid particles drawn out of the tank by the evaporator feed pump based on the estimated weight-percentage of sludge particles within the turbid layer above the coherent sludge for the low supernate case.

Particle size (μm)	Assumed wt% solids in the turbid layer					Percentages
	0.1	0.5	1.0	5.0	10.0	
0.1	0.0075	0.0377	0.0754	0.3772	0.7545	Volume-percent of solids
0.5	0.0063	0.0314	0.0629	0.3144	0.6287	
1.0	0.0056	0.0280	**0.0560**	0.2802	0.5599	
5.0	0.0022	0.0108	0.0217	0.1084	0.2168	
10.0	0.0013	0.0067	0.0134	0.0671	0.1341	
0.1	0.0126	0.0630	0.126	0.630	1.26	Weight-percent of solids
0.5	0.0105	0.0525	0.105	0.525	1.05	
1.0	0.0094	0.0468	**0.0935**	0.468	0.935	
5.0	0.0036	0.0181	0.0362	0.181	0.362	
10.0	0.0022	0.0112	0.0224	0.112	0.224	

5.0 CONCLUSIONS

The preceding analysis of Tank 26 was based on the following conditions, in coordination with Table 3.1:

- Only the liquid within Tank 26 is modeled. Particle motions are inferred based on the velocity field and the interactions (entrainment, settling, etc.) that would occur because of those velocities.
- Flow rates are set to the highest values for the evaporator feed pump eductor and bypass, which have ranges of 20 – 50 gpm and 5 – 30 gpm, respectively [4].
- When the supernate liquid level is below the downcomer orifice, the downcomer flow and EFP bypass are treated as plunging jets.
- Tank 26 contains primarily cohesive, densely-packed sludge, with a turbid layer approximately 6 inches deep of loosely-packed solids above the sludge layer [3].
- Based on sampling test results for Tank 40 sludge Batch 3 [2], 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.

The preceding analysis was also based on the following assumptions:

- Internal tank structures (piping, etc.) are not included for simplification [5].
- The surface waves and instabilities at the supernate surface were neglected, with a pressure outlet boundary condition of atmospheric pressure at the free surface.
- The liquid volume in Tank 26 is assumed to stay relatively constant during the transfer process because the downcomer, which adds liquid at 110 gpm, will increase the fluid height by a maximum of 0.031 inches per minute.

- 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 calculation. Previous calculations [6] have shown very little sensitivity to fluid temperature in the resulting flow patterns.
- The sludge layer is modeled as a solid, level surface with a free slip condition.
- Loosely-packed sludge solids in the turbid region are assumed to contain approximately 99 wt% supernate and 1 wt% particulate.
- Solids in the sludge layer are homogeneously distributed and are picked up into the flow when the local velocity at the sludge layer surface (at the solid boundary) exceeds the minimum scour velocity required to transport sludge solids.
- The plunging jet created by the EFP bypass retains 50% of its fluid flow within the intact center column with the remaining 50% striking the supernate surface as fluid globules in random patterns within the impinging area ($d_{imp,b}$).
- The liquid in Tank 26 is homogeneously mixed based on previous results [1] and the resulting flow patterns.

From these conditions and assumptions, the evaporator feed pump will draw between 0.05 and 0.1 wt% sludge solids into the eductor depending upon the tank liquid level (252.5 and 72 inches above the sludge layer, respectively). Lower tank liquid levels, with respect to the sludge layer, result in higher amounts of sludge entrainment due to the increased plunging jet velocities as well as decreased dissipation depth.

The preceding work has helped to quantify the behavior of plunging jets for future work.

6.0 REFERENCES

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