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EROSION MODELING ANALYSIS FOR MODIFIED DWPF SME TANK

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Acronyms

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CFD	Computational Fluid Dynamics
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
HLWE	High Level Waste Engineering
MFT	Melter Feed Tank
rpm	Rotations Per Minute
sg	Specific Gravity
SME	Slurry Mix Evaporator

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Abstract

In support of an erosion evaluation for the modified cooling coil guide and its supporting structure in the DWPF SME vessel, a computational model was developed to identify potential sites of high erosion using the same methodology established by previous work. The erosion mechanism identified in the previous work was applied to the evaluation of high erosion locations representative of the actual flow process in the modified coil guide of the SME vessel, abrasive erosion which occurs by high wall shear of viscous liquid.

The results show that primary locations of the highest erosion due to the abrasive wall erosion are at the leading edge of the guide, external surface of the insert plate, the tank floor next to the insert plate of the coil guide support, and the upstream lead-in plate. The present modeling results show a good comparison between the original and the modified cases in terms of high erosion sites, as well as the degree of erosion and the calculated shear stress. Wall shear of the tank floor is reduced by about 30% because of the new coil support plate.

Calculations for the impeller speed lower than 103 rpm in the SME showed similar erosion patterns but significantly reduced wall shear stresses and reduced overall erosion. Comparisons of the 103 rpm results with SME measurements indicated that no significant erosion of the tank floor in the SME is to be expected. Thus, it is recommended that the agitator speed of SME does not exceed 103 rpm.

1. Introduction

A recent visual inspection of the Slurry Mixer Evaporator (SME) tank interior revealed significant areas of erosion of the tank floor where the cooling coil guides are located [1]. DWPF Engineering has continued to investigate the tank erosion in an attempt to identify the root cause so that corrective actions can be taken. As result, the coil guide and support structure of the SME vessel were modified recently. Figure 1 is based on the modified geometry of the SME, and the present model includes the cooling coil guide pins and geometrical shapes of the guide structure. The tank was modified by placing a ¼ in thick plate of stainless steel at the bottom of each guide where significant erosion of tank floor occurred.

The primary cause of the tank leakage was identified as material degradation due to wear [1, 2]. Erosion in the SME has occurred in localized areas around the coil guides. There are four coil guides located in the bottom of the tank. One of the four guides is shown in Fig. 1. Each coil guide has similar erosion characteristics. A recent inspection conducted by DWPF Engineering identified severe erosion to the leading edge of the guide, scouring of the base metal, and loss of the top lead-in plate. The guides protrude into the flow stream and can cause a vortex that can tend to scour the exposed surfaces of the guides. This generates secondary flow circulation and results in waste fluid staying in contact with the downstream horizontal surface below the coil support insert (see Fig. 1). When slurry comes in contact with the wall surface, it can remove wall material. This phenomenon is called erosion. It is caused by mechanical interactions of the ambient fluid and solids against the wall surface.

In the previous work [2, 3] a literature survey was performed to identify the principal mechanisms of wear for a solids laden fluid and to find out what other wear studies and experiments have been done. Available evidence suggests that the key to understanding erosion in flow systems is a detailed knowledge of the coupled phenomena of solids circulation and fluid motion. One problem arising from slurry flow is the wear it creates on the tank floor. Wear occurs from the abrasive solids in the slurry and the wall shear of viscous liquid. The chemicals in the slurry may also cause corrosion and a synergistic effect of both erosion and corrosion. In this work, the erosion mechanism without any chemical reactions is considered as the primary cause of wear. This simplification is justified by a material study done on the damaged tank surface which concluded that corrosion was unlikely [4].

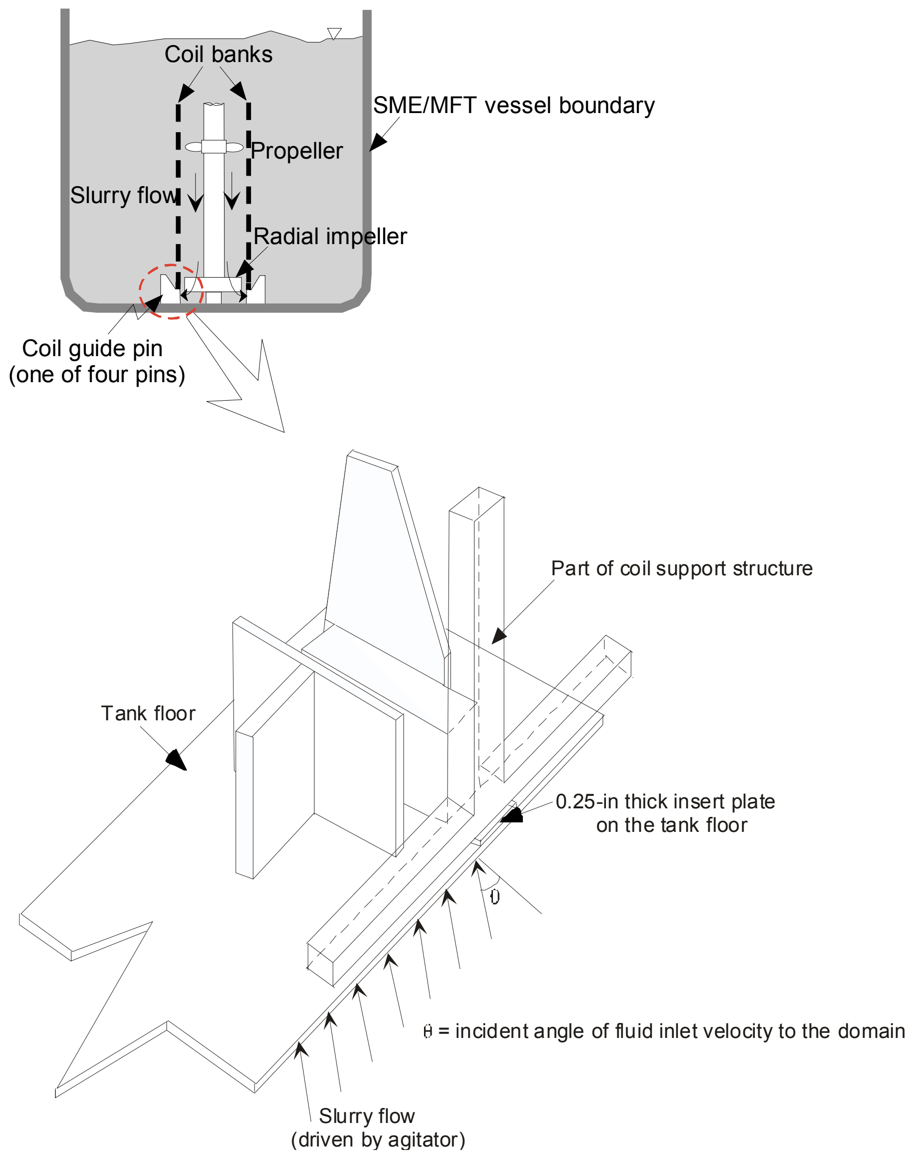


Figure 1. Modeling geometry of the modified coil support structure in SME tank for the present erosion analysis

This report presents the application of computational fluid dynamics (CFD) methods to evaluate the erosion phenomena expected in the actual SME by calculating erosion drivers. Ductile material such as stainless steel is damaged by wall mechanism when particles impinge on the ductile surface of the present coil guide at attack angles near 30^o. Previous results [2, 3] showed that the primary locations of high erosion due to particle impingement are at the occurrence of sudden change of flow direction, sudden contraction, and flow obstruction. Transport equations that govern slurry flow, and the erosion mechanism established by the previous work [2] were used to evaluate the high erosion sites and the primary cause of erosion damage created by the SME mixing process. The primary erosion mechanism is created by high wall shear stress of viscous liquid.

For the present work, Eulerian continuous transport equations are used for the stream flow. The mixing process of the SME at an agitation speed of 130 rpm creates a Reynolds number of about 10^5. This Reynolds number corresponds to a fully turbulent flow regime. A two-equation turbulence model was used to consider the dispersion effect of particles due to turbulent eddies. In the analysis, flow patterns, wall shear, and vorticity distributions were considered as the key parameters for capturing flow characteristics and providing information on potential damage sites caused by abrasive erosion.

The primary objective of the present work is to identify potential locations of high erosion for the SME coil guide and its support structures as shown in Fig. 1. The present analysis is mainly concerned with the erosion predictions for the tank floor. The agitator is located at the center of the tank and has two impellers. The upper blade is a propeller to circulate fluid in the axial downward direction. The lower blade is a Rushton-type flat-plate impeller. This type of impeller directs flow in the radial direction. The SME agitator operates at 130 and 65 rpm.

Table 1 shows typical conditions for key operating parameters. This information will be used in the present modeling calculations, and three agitation speeds are used: 65 rpm, 103 rpm, and 130 rpm.

Table 1. Input parameters for the present calculations

Parameters	Input data
Bulk fluid specific gravity	1.35 sg
Fluid viscosity	10 cp
Fluid velocity at the model boundary (agitator speed)	0.65 m/sec (65 rpm), 1.8 m/sec (130 rpm), and 1.3 m/sec (103 rpm)

2. Analysis Approach and Methodology

The present analysis focuses on the flow behavior in the vicinity of the coil guide and its supporting structure for the modified SME vessel. The analysis work took a Computational Fluid Dynamics (CFD) approach by using a commercial software package, Fluent^{TM}. Due to the complexities of the erosion process, accurate quantitative results are not expected from the CFD model without tests against which to compare. However, the modeling results will be used to evaluate the potential for excessive erosion at the base of the coil guide. The present CFD modeling is used in a qualitative way to investigate the high erosion locations near the cooling coil guide and its supporting structure by observing the existence of erosion drivers.

Figure 2 shows the modeling and computational domains used for the present analysis including the eroded guide pin geometry and recently-modified coil support structure in the SME tank. The computational domain was deliberately kept small to minimize the size of the numerical model and the associated computational time. Nonetheless, upstream flow information was included from the global model to ensure the flow pattern reaching the domain boundary of the SME guide pin would be close to that actually occurring in the tank mixed with agitator. Because of the close proximity of the coil guides to the discharge of the radial impeller, the inlet flow to the guide pin model is not affected by the flow past the guide pin. Therefore, the global model gives a good approximation to the boundary flow for the current model.

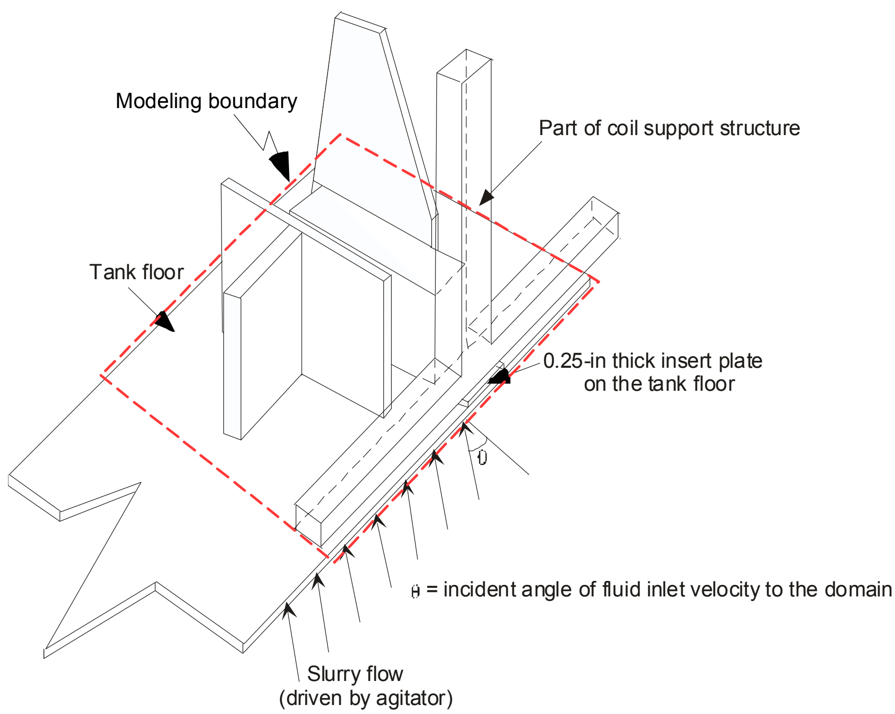


Figure 2. Modeling domains considered for the present analysis

Two stages of modeling efforts were made using the same basic solution method as the previous work [2]. One is the global model, which includes the mechanical agitator and tank boundary in the computational domain to evaluate upstream flow field of each coil guide and to estimate overall flow patterns near the boundary of the cooling coil guide under different rotational speeds agitator. The flow field calculations of the global model were performed by the Fluent™ MixSim code. The second stage created a detailed model to evaluate the flow field surrounding the coil guide. The boundary conditions for this model were based on the information provided from the first model. The modeling results performed here were used in identifying the potential locations of high erosion for the SME coil guide and its support structure.

Based on the modeling domains defined in Fig. 2 and the operating conditions shown in Table 1, the erosion evaluations for three different modeling cases of the agitator speeds were performed to provide information on erosion damage for the areas near the four cooling coil guides and to compare flow patterns and high erosion locations between the original and the modified coil support structures due to the presence of flow obstructions such as the insert plate on the tank floor.

2.1 Principal Mechanisms for the Present Analysis

As established in the previous work [2], the principal mechanism of erosion for a slurry was identified as abrasive wall friction under the current geometrical and operating conditions. This is associated with regions of secondary flow recirculation and regions of high wall shear.

The current erosion analysis addresses flow patterns expected for the coil guide geometry, as well as the specific erosion mechanisms for a slurry flow, wall shear stress. The average primary flow velocity is in the range of 0.65 to 1.8 m/sec corresponding to three different agitating speeds as shown in Table 1. These velocities were derived from the flow field results of the global model. The suspension slurry is assumed to flow like a single-phase flow since the flow regime is fully turbulent.

Ductile material such as Hastalloy or stainless steel is damaged by wall mechanism when particles impinged on the surface. The previous results [2] show that the primary locations of high erosion due to particle impingement are at the occurrence of sudden change of flow direction, sudden contraction, and flow obstruction. Thus, for a slurry flow, the particle impingement process may not be important compared to the abrasive shear-driven erosion mechanism. The solid-fluid mixture flows like a homogeneous fluid due to the high interfacial drag, so particles don't tend to separate from the flow and impinge on the wall. In addition, the present coil guide geometry has a large open space without any sudden change of flow direction.

2.2 Computational Fluid Dynamics Methodology

As discussed earlier, main mechanisms for erosion were identified to develop simulation methods using a CFD approach and the commercial CFD code, Fluent^{TM} [6]. The present model relies on the previous methodology [2] that material erosion is governed primarily by the wall shear mechanism when particles are homogeneously distributed in the slurry flow and the impingement angles of the particles against the wall surface are small. The wall shear model will be used to provide qualitative information on flow patterns and potential erosion damage locations.

For the calculations of the continuous slurry flow field, three-dimensional transport and continuity equations were solved in an Eulerian reference system. Detailed governing equations for the continuous phase were provided in the previous work [2, 3]. Reynolds number for the flow condition is found to be in the range of about 10^5, which corresponds to a fully turbulent regime. A two-equation turbulence model with turbulent kinetic energy and dissipation equations, the $k-\varepsilon$ model, was used to include the effects of particle dispersion due to turbulent eddies in the continuous phase. For the wall shear model, field solutions for the Eulerian equations of the continuous slurry flow were applied to estimate wall shear stress. All converged solutions for the governing equations were achieved using the segregated and iterative solution technique.

As discussed above, abrasive erosion mechanism was considered to evaluate the high erosion locations and investigate the primary cause of wear damage in the modeling domain representing flow in the region of the cooling coil guide. Flow patterns, wall shear, and vorticity distributions were considered key parameters for capturing flow characteristics and potential leakage sites caused by erosion damage.

3. Modeling Assumptions and Computational Domains

Assumptions in the erosion calculations were as follows:

- The present models consider only mechanical erosion related to the loss of material from the wall surface, but they do not consider the moving boundary effects due to the material loss.

- The present analysis deals with pure erosion due to the hydrodynamic interactions of waste flow against the wall boundary. Chemical corrosion was not considered.

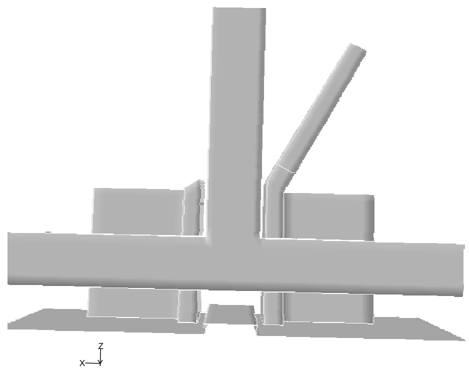
- The waste flow regime is assumed to be fully turbulent, and particles are distributed homogeneously. Reynolds number is in the range of 10^5 based on the design and operating conditions, and average flow velocity of fluid-solid flow is much larger than the critical entrainment velocity of solid particle.

- Waste fluid is assumed to have Newtonian behavior.

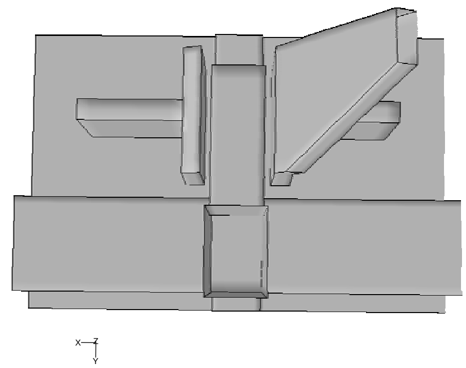
- The entire domain is isothermal so that no energy balance equation is considered. Steam condensation within the modeling boundary is assumed to be negligible since cooling across the modeling boundary is small.

Three-dimensional computational mesh for the modeling domain, as shown in Figs. 2 and 3, is presented in Fig. 4. A finer non-uniform grid was used in the corner zones and joint sections at which potential flow direction changes and flow splits might occur. From a nodalization study, an optimum number of about 200,000 nodes was established for the final analysis of the three-dimensional flow model. As shown in the figures, very fine meshes, less than 0.05 in long, were used near the misalignment and connection joints to capture the high velocity gradient. Flow boundary conditions at the inlet of the computational flow domain used uniform homogeneous flow since the distance upstream of the inlet of the present modeling domain was long enough to reach fully-developed flow.

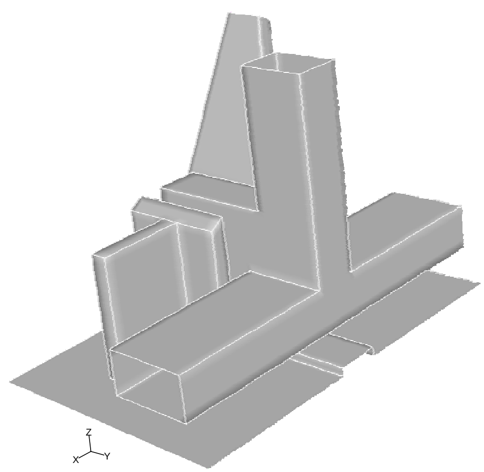
Based on the modeling assumptions, the continuity and momentum equations are coupled to compute the flow patterns and find the locations of high wall shear where the highest abrasive erosion is assumed to occur. The three-dimensional computational model was developed and solved with Fluent™ [6]. All converged solutions were achieved using the segregated and iterative solution technique.



(Side view)



(Top view)



(Three-dimensional view)

Figure 3. One-pin SME cooling coil guide simulating the eroded geometry identified by the recent inspection

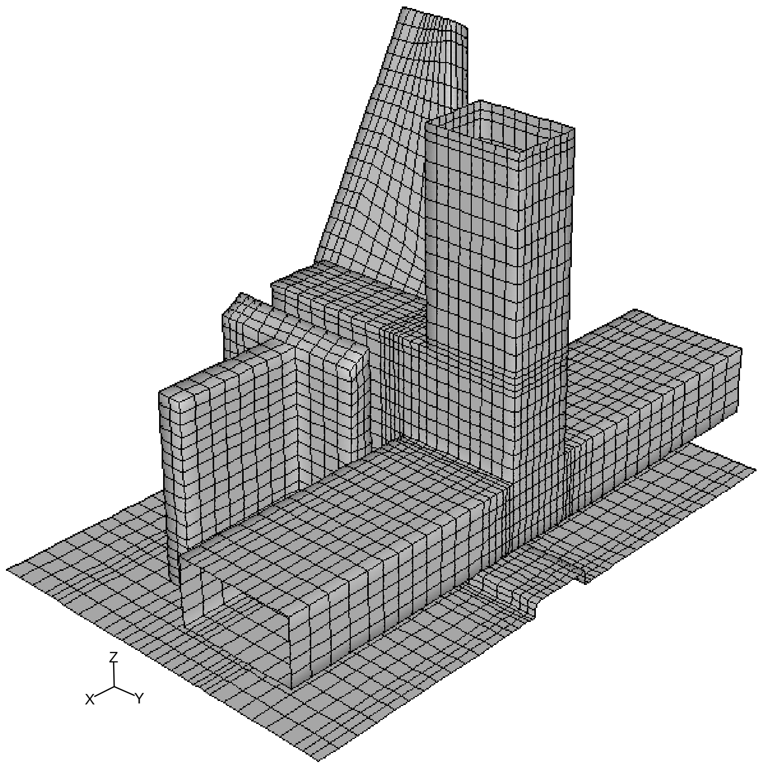


Figure 4. Three-dimensional meshes used for the present computations

4. Results and Discussions

Based on the modeling domain defined in Figs. 3 and the operating conditions shown in Table 1, the erosion evaluations for the modeling domain of the SME coil guide were performed by a computational approach to provide information on erosion areas near one of the four coil guides. The boundary conditions provided in Table 1 were based on the results of the tank flow model, which considered the rotational motion of the agitator. In this case 30^o incident angle into the region of the coil guide was established by the previous study [2] since the sensitivity results show that the 30^o incident flow field creates an overall erosion pattern close to the one observed by the recent inspections. In addition, the literature data [2, 3] shows that ductile wall surface is mostly damaged by abrasive erosion near 30^o attack angle. The results are compared under the original configurations of the coil guide shown in Fig. 5.

The modeling calculations for three different agitator speeds 65, 103, and 130 rpm were performed. The results of wall shear distributions for the three agitation speeds are shown in Figs. 6 to 8. The results show that the locations of high erosion sites are not changed when the agitation speed is changed. They also show that the locations are not sensitive to the variations of incident angles.

Flow patterns for the modified coil guide area are shown in Fig. 9. The figure shows that the region near the tank floor area between coil support structure and floor insert plate has the highest flow corresponding to one of the high erosion sites as observed by the recent inspections.

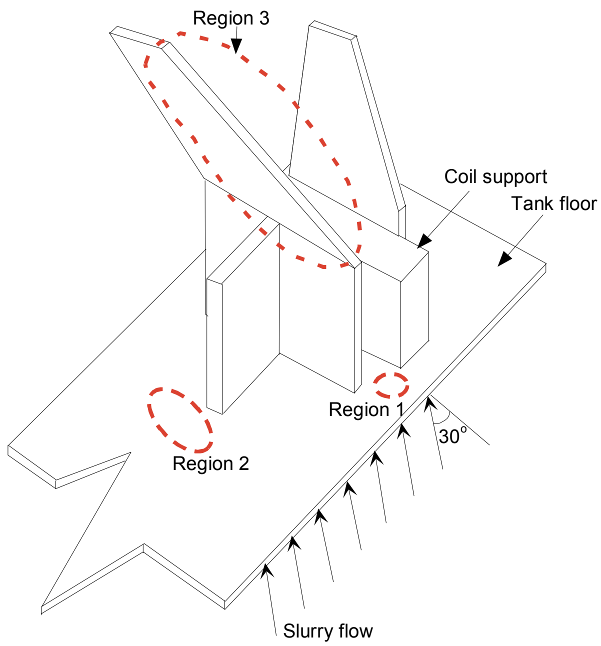
It is noted that when the erosion patterns are compared between the original and the modified geometries, they are not changed significantly as shown in Figs. 5 and 6. The flow patterns and fluid vorticity distributions for the 130 rpm case around the structures of the modified coil guide are compared in Figs. 10 and 11. In these figures the downstream regions of the guide support and floor insert plate have the highest velocity magnitudes and flow rotations.

The present analysis is mainly concerned with the erosion estimations for the tank floor. The results show that serious erosion damages can occur to the tank floor as well as the 0.25-in thick insert plate when the agitator impeller operates continuously at 130 rpm, even though the wall shear at the tank floor is reduced by about 30% compared to the original geometry results. The sites of high abrasive erosion and the degree of erosion-driven damage at the floor of the SME tank due to wall shear mechanism for three typical flow conditions shown in Table 1 are compared in Fig. 12.

The previous results [2] for three high erosion sites are compared among three different agitator speeds of the original SME vessel in Table 2. The results demonstrate that when the agitator impeller operates between 65 rpm and 103 rpm, the leading edge of the coil guide will be damaged by the abrasive wall erosion, but maximum wall shear for the tank floor below the coil tab is about 87 Pa, which is well below the seriously eroding value of about 169 Pa for the leading-edge component as observed in the recent inspections of the SME vessel coil guide [2]. The present results for several high erosion sites are compared among the three different agitator speeds of the modified SME tank in Table 3. The results clearly show that maximum wall shear at the tank floor is reduced from 127 Pa to 98 Pa due to the insertion of the coil support plate on the tank floor, but maximum wall shear of the coil support structure is increased to 177 Pa.

Measurements and observations of erosion in the SME showed the upstream coil lead-in completely removed, tank floor erosion in Region 1 of about 3/8-in, and floor erosion in Region 2 of about 1/16 – 1/8-in. The wall shear stresses shown in Table 3 indicate that the maximum shear stress expected in Region 1 (103 rpm) is slightly less than that observed in Region 2 (130 rpm). Therefore, while the coil guide lead-in might be eroded, the tank floor would not be eroded any more than the degree observed in Region 2, viz., no more than 1/8-in. A linear extrapolation of the data based on wall shear stress would indicate an erosion of about 0.05 in in Region 1 and none in Region 2. Table 3 also indicates that virtually no erosion from wall abrasion would be expected for agitator speeds of 65 rpm.

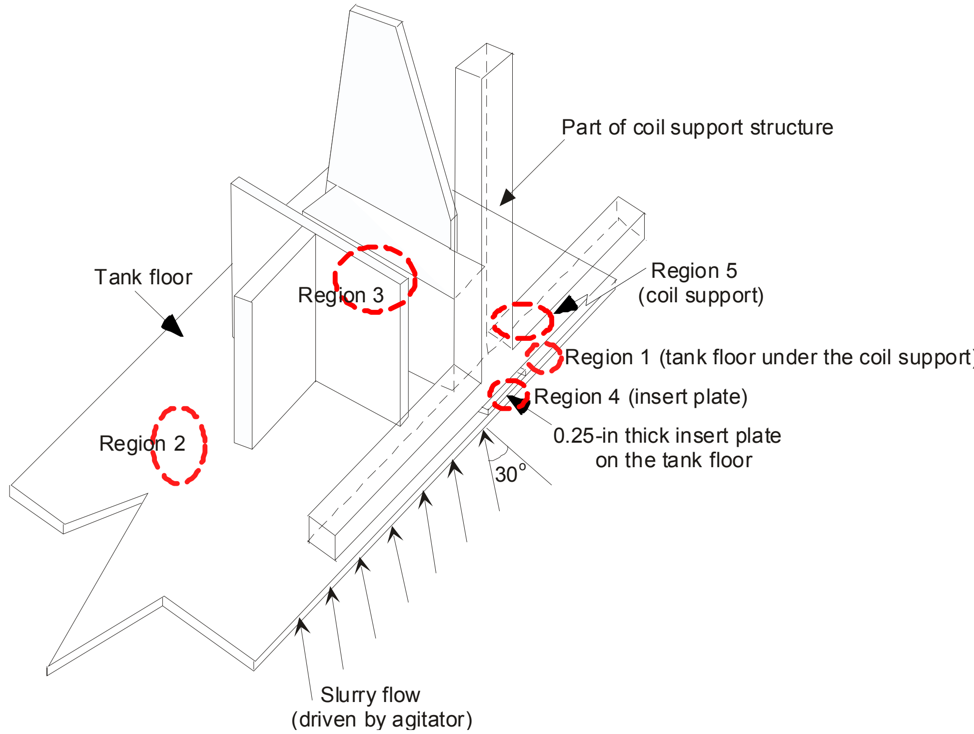
Table 2. Maximum wall shears for three major erosion locations observed by the recent SME inspections and CFD modeling results for SME coil guide (Refer to Fig. 18 of the previous report [2])



Slurry velocity magnitude for 30° incident into coil guide region (agitator speed)	Max. wall shear at Region 1	Max. wall shear at Region 2	Max. wall shear at Region 3
0.65 m/sec (65 rpm)	39 Pa	29 Pa	41 Pa
1.3 m/sec (103 rpm)	87 Pa	65 Pa	107 Pa
1.8 m/sec (130 rpm)	127 Pa**	96 Pa***	169 Pa*

Note: *Severe damage due to erosion (observed)
** High erosion (observed)
*** Visibly noticeable erosion (observed)

Table 3. Maximum wall shears for three major erosion locations observed by the recent SME inspections and CFD modeling results for the modified SME coil guide (Refer to Figs. 6 through 8)



Slurry velocity magnitude for 30° incident into coil guide region (agitator speed)	Max. wall shear at Region 1	Max. wall shear at Region 2	Max. wall shear at Region 3	Max. wall shear at Region 4	Max. wall shear at Region 5
0.65 m/sec (65 rpm)	27 Pa	21 Pa	28 Pa	37 Pa	50 Pa
1.3 m/sec (103 rpm)	63 Pa	46 Pa	76 Pa	92 Pa	119 Pa
1.8 m/sec (130 rpm)	98 Pa	72 Pa	123 Pa	139 Pa	177 Pa

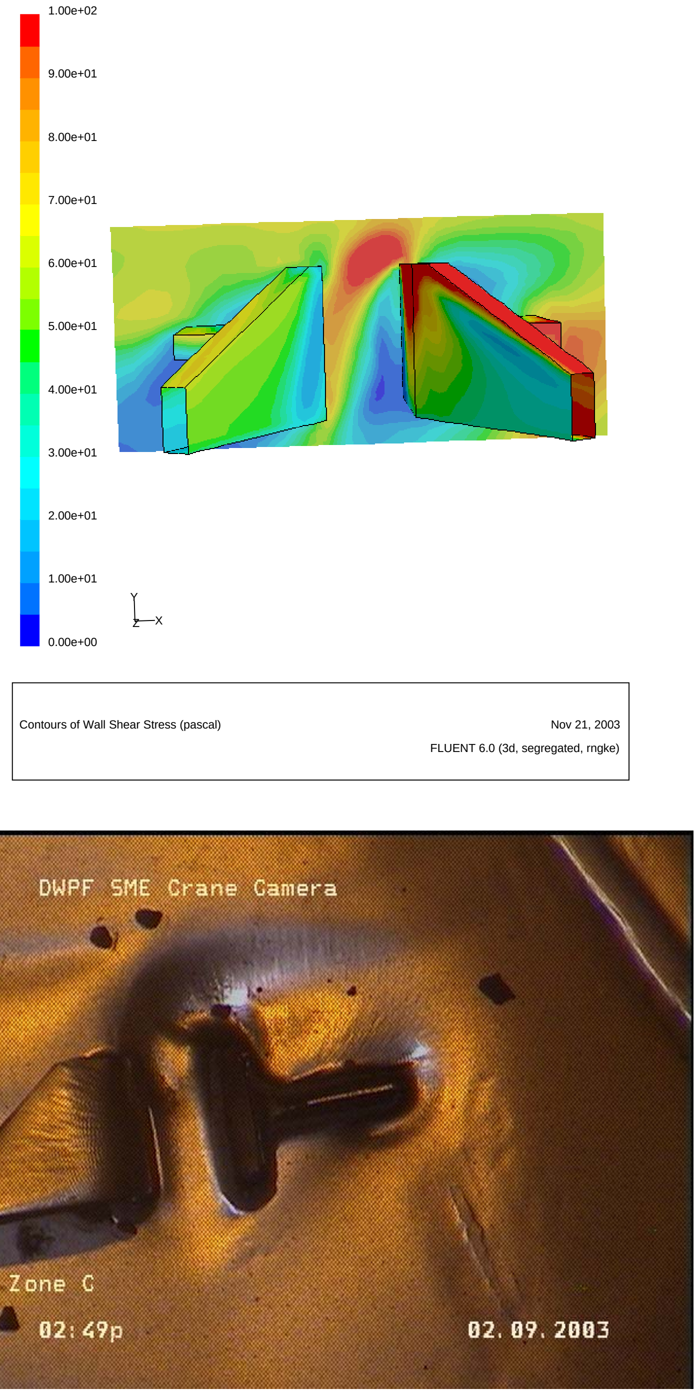
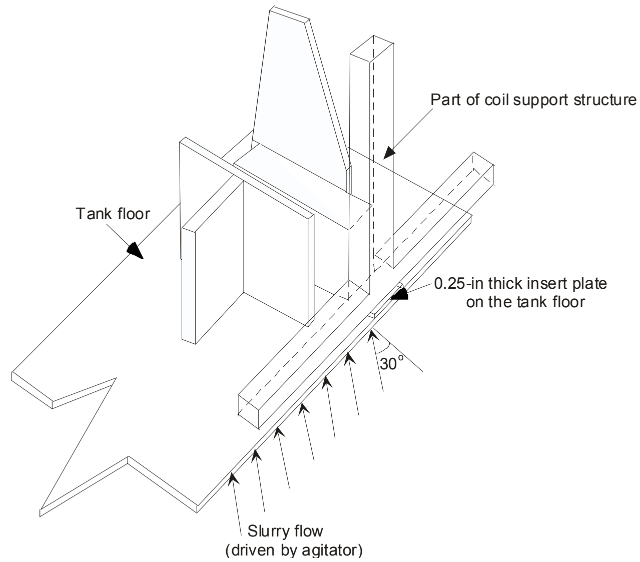


Figure 5. Comparison of the predicted high wall shear indicated on the right lead-in plate (above) to the worn-away lead-in plate shown in the visual inspection photo (below) (the model predictions based on 130 rpm (1.8 m/sec) and 30^o flow incidence)



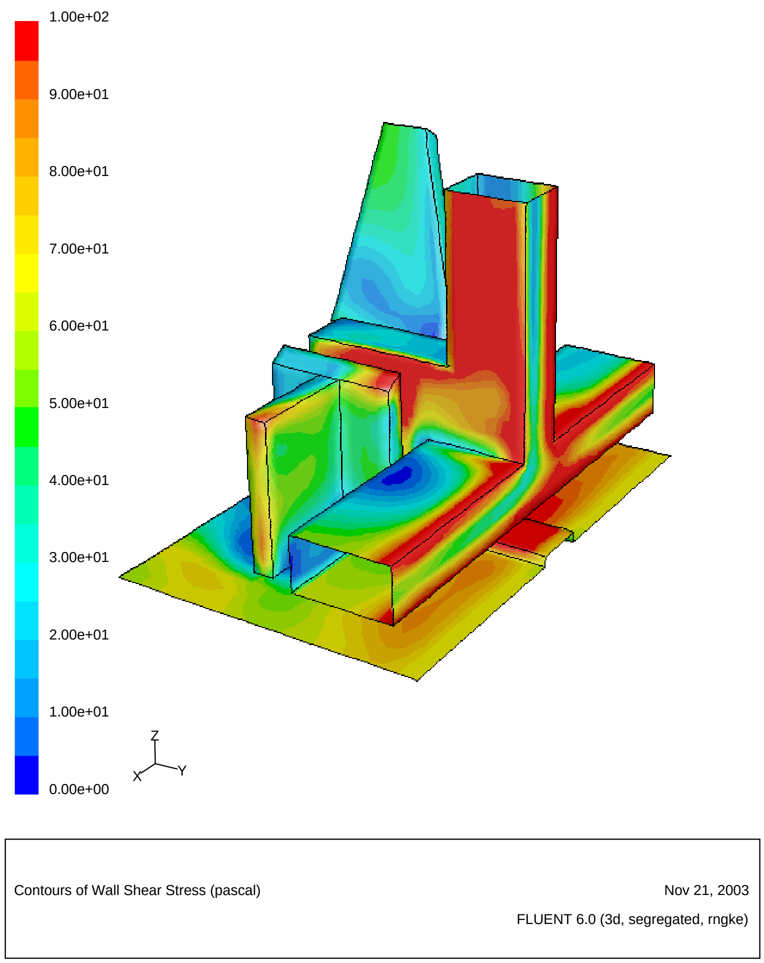


Figure 6. Wall shear distributions for 130 rpm (1.5 m/sec) with 30° flow incidence based on the model of the modified SME tank vessel

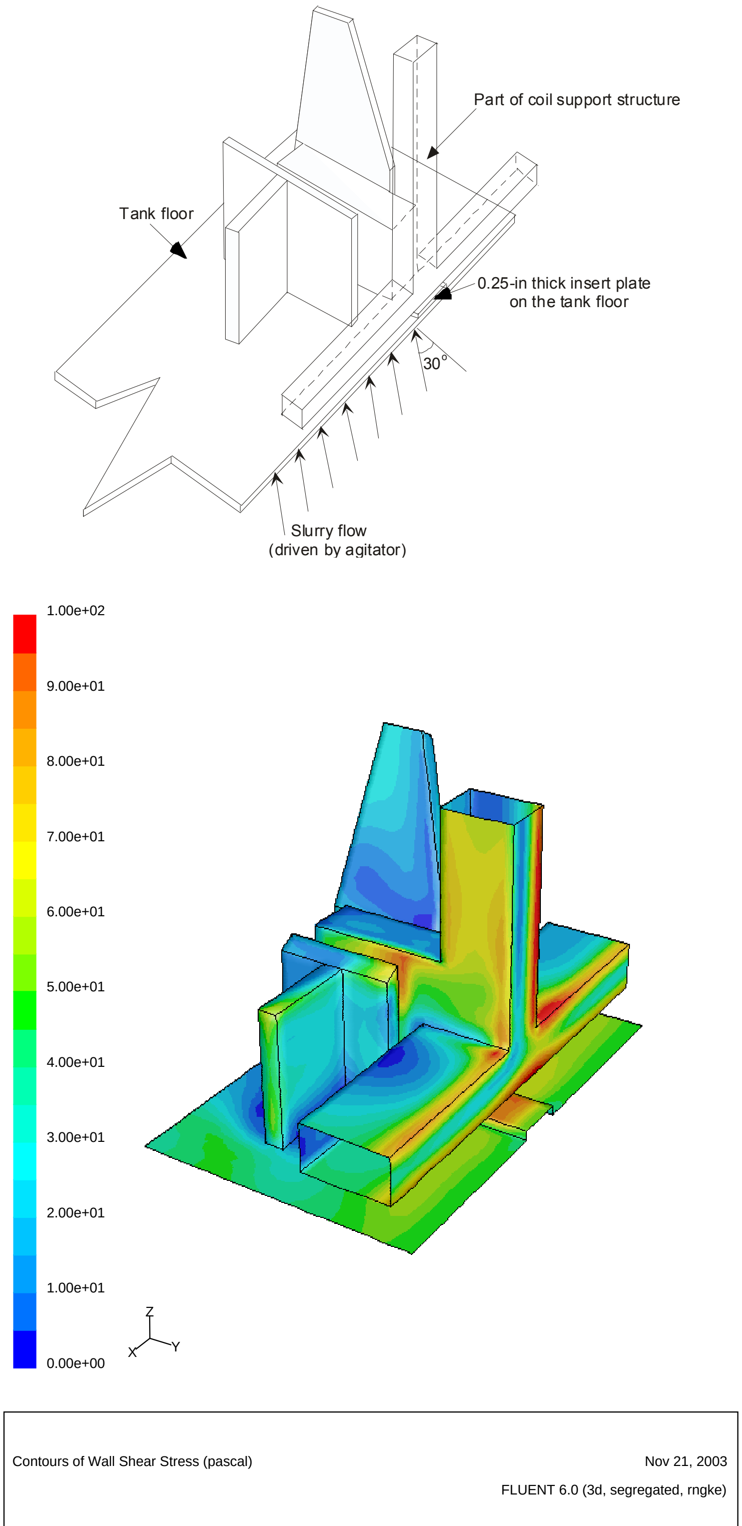
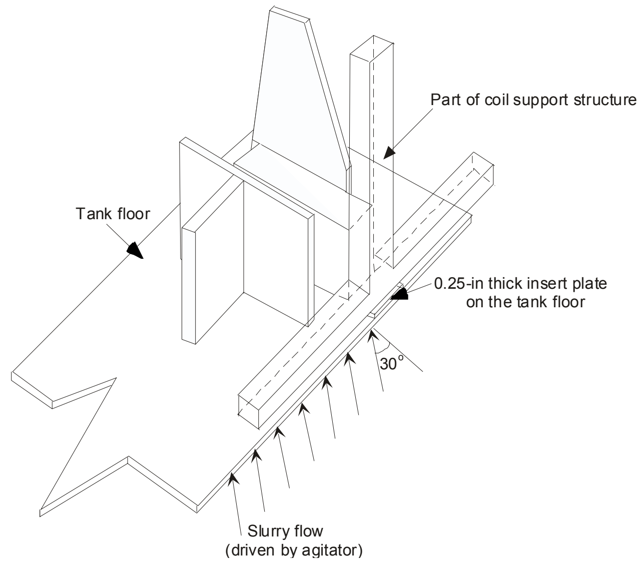


Figure 7. Wall shear distributions for 103 rpm (1.3 m/sec) with 30° flow incidence based on the model of the modified SME tank vessel



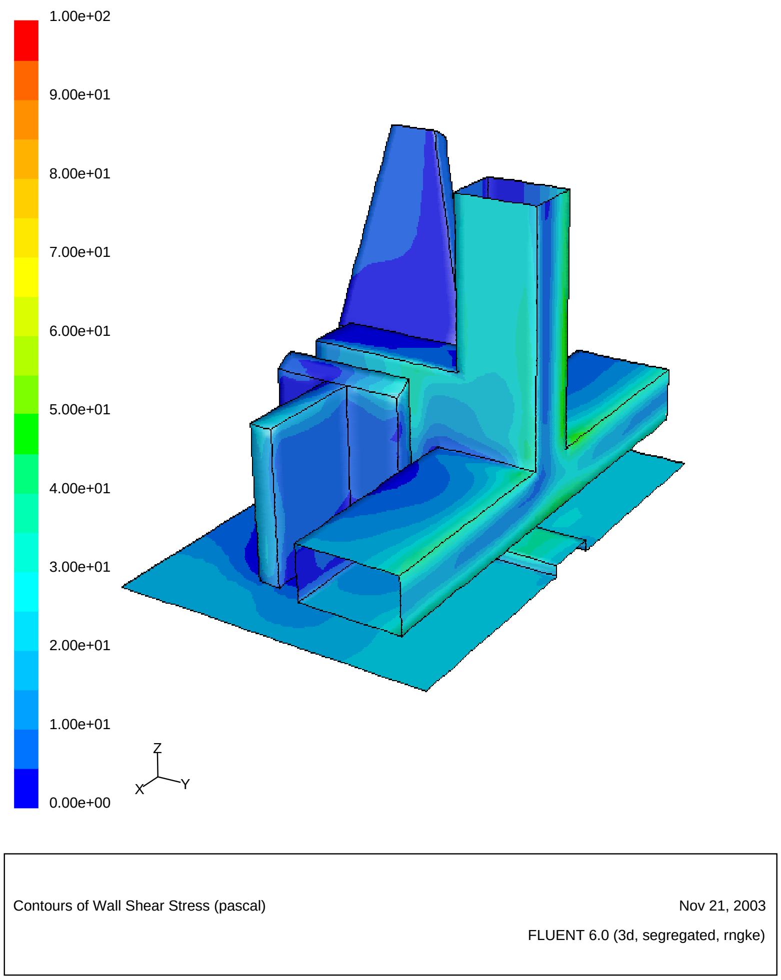
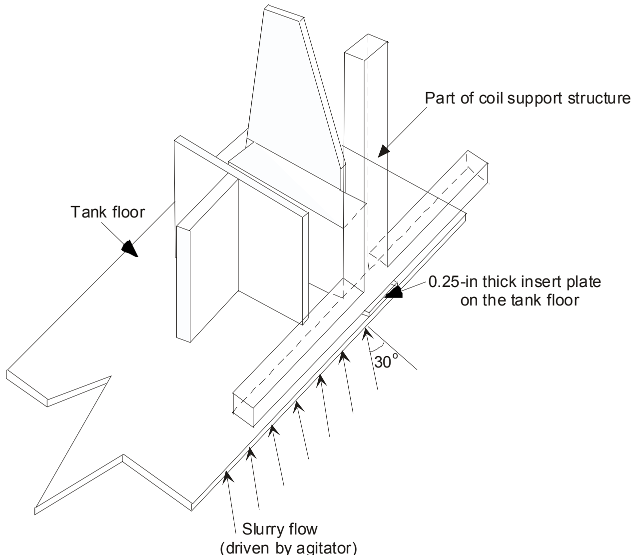


Figure 8. Wall shear distributions for 65 rpm (0.65 m/sec) with 30° flow incidence based on the model of the modified SME tank vessel



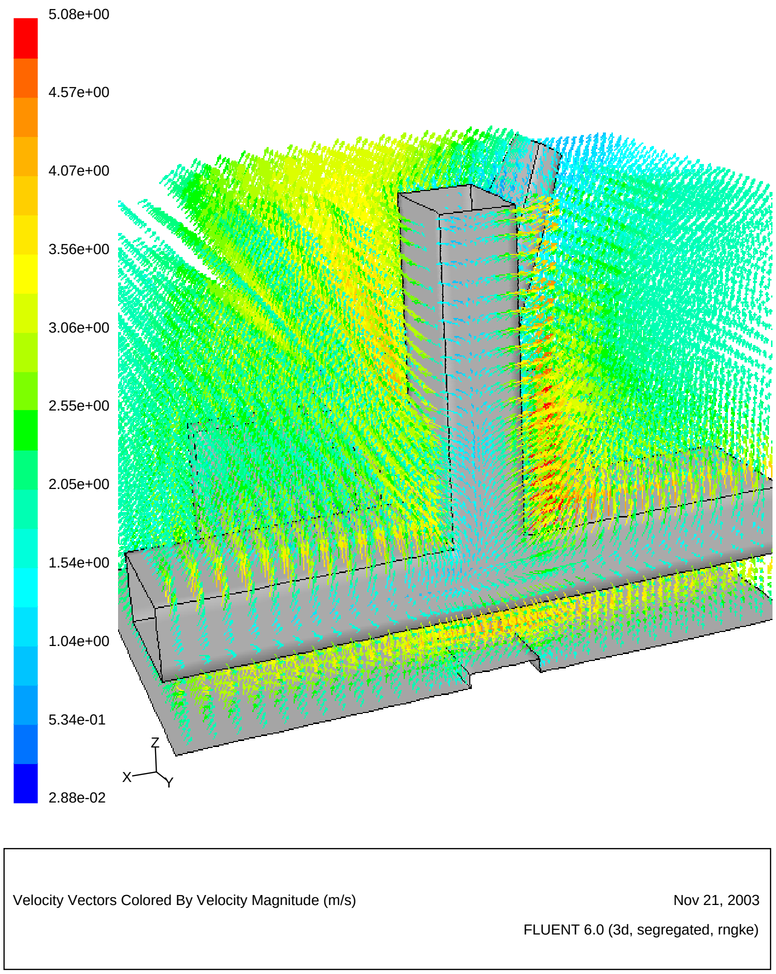


Figure 9. Flow patterns around the SME guide pin for 30^{o} incident angle and 130 rpm (1.8 m/sec)

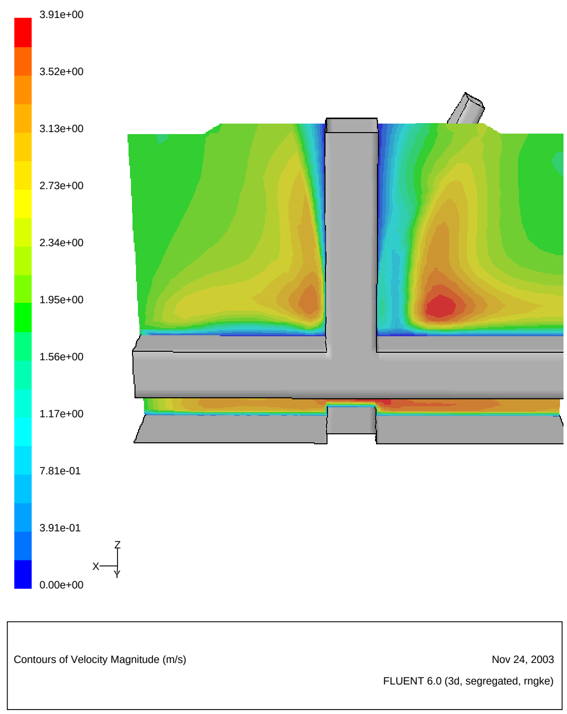


Figure 10. Velocity contour at the upstream of coil support structure for 130 rpm SME agitator speed (1.8 m/sec) and 30^o incidence as shown in Fig. 1.

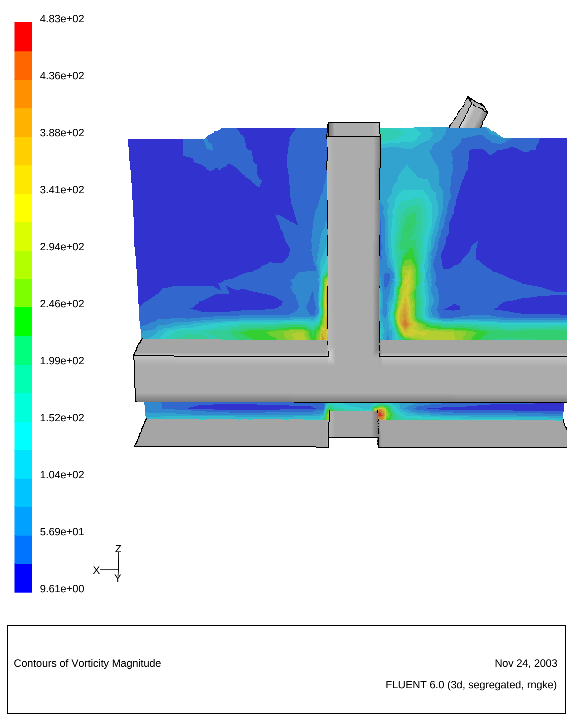
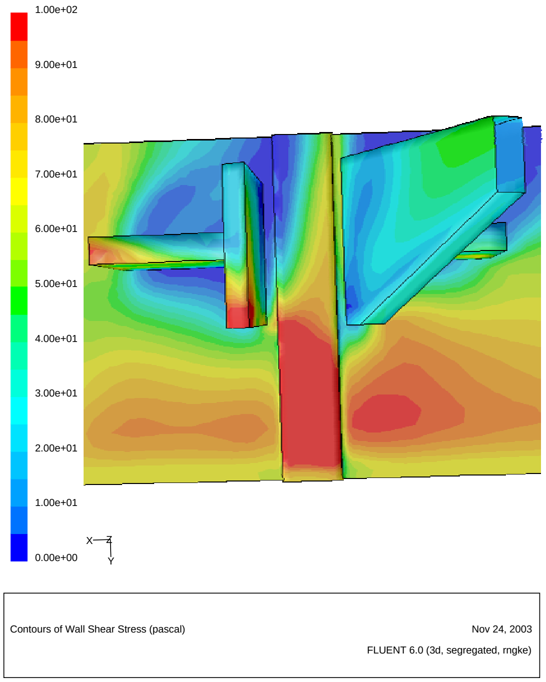
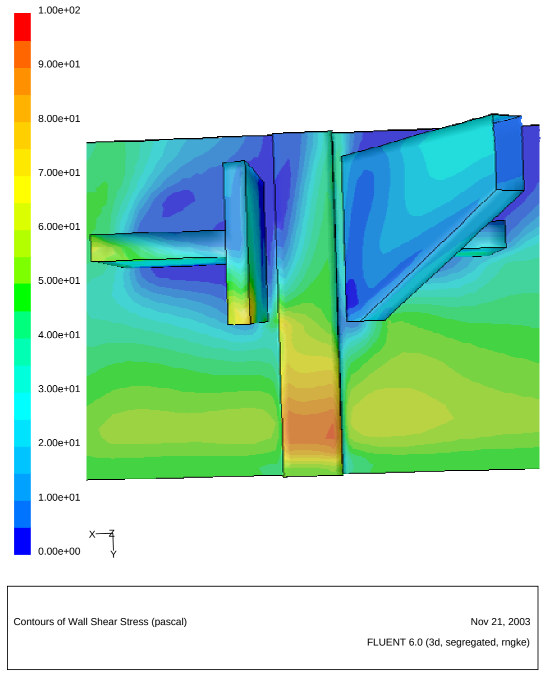


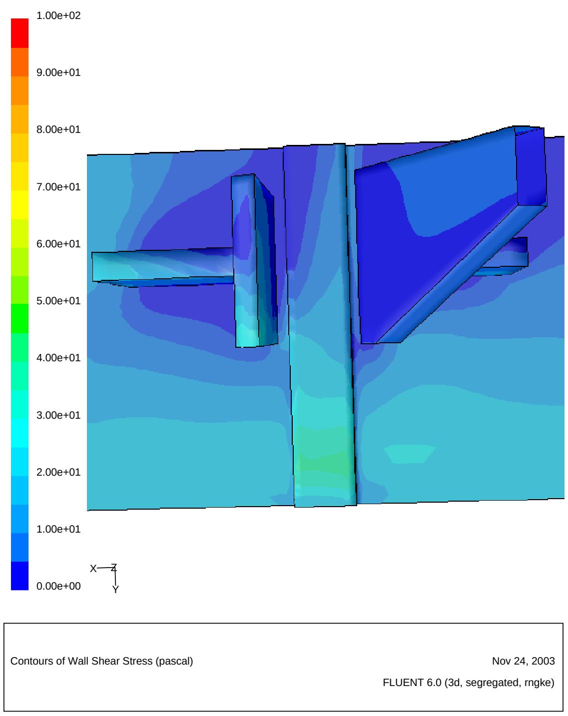
Figure 11. Vorticity contour at the upstream of coil support structure for 130 rpm SME agitator speed (1.8 m/sec) and 30^o incidence as shown in Fig. 1.



(130 rpm)



(103 rpm)



(65 rpm)

Figure 12. Comparison of abrasive wall shears for SME tank floor among three different agitation speeds with 30^o incidence angle of slurry flow into the guide pin (The coil support is removed from the figures to show the shear pattern on the tank floor)

5. Summary and Conclusions

The method used to evaluate the potential for erosion in the SME is consistent with the method to evaluate the erosion potential in the MFT [1]. The computational results of the erosion study were estimated qualitatively in terms of flow patterns and erosion characteristics since the modeling predictions could not be benchmarked against the actual test data in a quantitative way. This report utilizes computational fluid dynamics (CFD) methods to qualitatively estimate the erosion phenomena expected to the bottom of the SME (with the insert coil support installed). The modeling domain is defined in Fig. 2 and the operating conditions shown in Table 1.

The results show:

1. The locations with the highest erosion are at the leading edge of the guide (Region 3 in Table 3), external surface of the insert plate, the tank floor next to the insert plate of the coil guide support, and the upstream lead-in plate.

2. The modeling predictions for the high erosion sites of the coil guide are similar to the observed sites of the recent inspections of the SME vessel done by DWPF Engineering.

3. Potential damage sites due to the abrasive wall erosion are at the upstream regions and the downstream side of insert plate of the coil guide support as shown in Table 3.

4. When the SME agitator operates between 65 rpm and 103 rpm, the upstream coil guide lead-in plate will be damaged by erosion, but maximum wall shear for the tank floor below the coil support tab is about 63 Pa, which is well below the 169 Pa shear that resulted in serious erosion of the leading edge component as observed in the recent inspections of the SME vessel.

These findings are consistent with the observed damage to the coil guide of the SME vessel. The results show that the potential for erosion of the SME floor becomes much smaller when the impeller speed is reduced from 130 rpm to 103 rpm. Only minor wear is predicted to the region of the tank floor in the area of the insert plate of the coil guide. When the SME is operated below 103 rpm, inspection of the SME floor in the vicinity of the coil guide is not required.

6. References

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