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Suspending Zeolite Particles in Tanks

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Summary

The Savannah River Site (SRS) is in the process of removing waste (sludge and salt cake) from million gallon waste tanks. The current practice for removing waste from the tanks is adding water, agitating the tanks with long shaft vertical centrifugal pumps, and pumping the sludge/salt solution from the tank to downstream treatment processes. This practice has left sludge heels (~ 30,000 gallons) in the bottom of the tanks. SRS is evaluating shrouded axial impeller mixers for removing the sludge heels in the waste tanks.

The authors conducted a test program to determine mixer requirements for suspending sludge heels using the shrouded axial impeller mixers. The tests were performed with zeolite in scaled tanks which have diameters of 1.5, 6.0, and 18.75 feet. The mixer speeds required to suspend zeolite particles were measured at each scale. The data were analyzed with various scaling methods to compare their ability to describe the suspension of insoluble solids with the mixers and to apply the data to a full-scale waste tank. The impact of changes in particle properties and operating parameters was also evaluated.

The conclusions of the work are: Scaling of the suspension of fast settling zeolite particles was best described by the constant power per unit volume method. Increasing the zeolite particle concentration increased the required mixer power needed to suspend the particles. Decreasing the zeolite particle size from 0.7 mm – 0.3 mm decreased the required mixer power needed to suspend the particles. Increasing the number of mixers in the tank decreased the required mixer power needed to suspend the particles. A velocity of 1.6 ft/sec two inches above the tank bottom is needed to suspend zeolite particles.

Introduction

In the early 1980s, the Savannah River Site performed a demonstration to remove salt cake from a million gallon waste tank. The salt removal was performed in the following manner: Water was added to the waste tank, and mixed with two long shaft vertical centrifugal pumps. After the liquid in the tank became saturated with salt, the liquid was retrieved from the tank with a centrifugal transfer pump. After four cycles of salt cake dissolution and retrieval, approximately 30,000 gallons of waste solids remained in the tank. The solids are composed of sludge, zeolite, and insoluble salts. Based on the topography of the solids heel in the tank, it is suspected that the long shaft vertical centrifugal pumps did not have sufficient power to maintain the faster settling solids in suspension, or that the pump jets pushed the larger, settled solids out beyond the reach of the jets.

Efforts are now being made to identify and design alternative waste retrieval techniques for the waste. Shrouded axial impeller mixers manufactured by ITT Flygt Corporation are one of the suggested alternatives (Figure 1). The shrouded axial impeller mixers consist of an electrically powered propeller surrounded by a close-fitting shroud. The 50 hp mixer being considered for use at SRS has a propeller diameter of approximately 20 inches and runs at 860 rpm. The rapidly spinning propeller creates a turbulent fluid jet with a flow rate of 19,000 gpm and an average exit velocity of 20 ft./sec.

The authors are conducting a test program to evaluate the ability of these mixers to remove the heels from waste tanks. The test program consists of mixer tests being performed in a 1.5 ft. diameter tank, a 6.0 ft. diameter tank, and an 18.75 ft. diameter tank. The 1.5 ft. diameter tank was mixed with a single 0.4 hp mixer, the 6.0 ft. diameter tank was mixed with a single 4.0 hp mixer, and the 18.75 ft. diameter tank was mixed with three 4.0 hp mixers. Tests were performed with different size tanks so that scaling methods can be developed and used to determine whether the mixers can adequately suspend and retrieve the solids heel in a million gallon (85 ft. diameter) waste tank.

The purpose of the test program was to determine the best scaling method for describing the suspension of fast settling solids such as zeolite, and to determine the effects of particle properties (e.g., particle size and particle density) and operating parameters (e.g., particle concentration, liquid level, and number of mixers) on the suspension process.

Background

One scaling method evaluated was the constant shear stress method developed by Gladki.[1] This method involves determining the magnitude of the average wall shear stress (τ_o) required to maintain solids in suspension for a given tank geometry and type of solids. The magnitude of the wall shear stress is computed by dividing the mixer thrust by the tank wetted surface area (bottom and sides). According to this method, the average wall shear stress required is independent of scale provided the same materials are used and the tanks are geometrically scaled.

Power per unit volume is another method for mixing system scaleup. This method is described by equation [1].

$$\frac{(P/V)_2}{(P/V)_1} = \left[\frac{T_2}{T_1}\right]^a \qquad [1]$$

where P is the hydraulic horsepower, V is the tank volume, T is the tank dimension, and a is a constant. The value of a is a function of the mixing application.[2]

A number of researchers have investigated the requirements for suspending insoluble solids in tanks mixed with agitators. In these studies, they measured the agitator speed required to “just suspend” all of the particles (i.e., no particles remains stationary on the tank bottom for more than one second). Table 1 shows the correlations developed by these researchers.

Table 1. Agitator Speed Required to Suspend Insoluble Particles

Reference	Correlation
3	$N_{js} = \dfrac{3.5\left(\dfrac{r_s - r_f}{r_f}\right)^{1/2} g^{1/2} d_p^{\ 1/6} C_v^{\ 1/3} T}{C_D^{\ 1/6} Po^{1/3} D^{5/3}} = K\dfrac{d_p^{\ 1/6} C_v^{\ 1/3} T}{D^{5/3}}$
4	$N_{js} = \left(\dfrac{g(r_s - r_f)}{r_f}\right)^{1/2} \dfrac{1}{Po^{1/3}} \left(\dfrac{T}{D}\right) \dfrac{d_p^{\ 1/6}}{D^{2/3}} \dfrac{1}{Z} = K\dfrac{Td_p^{\ 1/6}}{ZD^{5/3}}$
5	$N_{js} = \dfrac{Su^{.1} d_p^{\ .2} \left(\dfrac{g(r_s - r_f)}{r_f}\right)^{.45} X^{.13}}{D^{.85}} = K\dfrac{d_p^{\ .2} X^{.13}}{D^{.85}}$
6	$N_{js} = \dfrac{Su^{.1} d_p^{\ .15} \left(\dfrac{g(r_s - r_f)}{r_f}\right)^{.4} X^{.12}}{D^{.76}} = K\dfrac{d_p^{\ .15} X^{.12}}{D^{.76}}$
7	$N_{js} = \dfrac{m^{.17} d_p^{\ .14} \left[g(r_s - r_f)\right]^{.42} T}{r_f^{\ .58} D^{1.89} Po^{.28}} = K\dfrac{d_p^{\ .14} T}{D^{1.89}}$

In Table 1, ρ_s is the particle density, ρ_f is the fluid density, g is the gravitational constant, d_p is the particle size, C_v is particle volume concentration, T is tank diameter, C_D is the drag coefficient, Po is the power number, D is the impeller diameter, Z is the liquid height, ν is the kinematic viscosity, μ is the fluid viscosity, X is the particle weight fraction, S is a constant, and K is a constant. Since the flow will be turbulent, the power number will be constant. The solid density, fluid density, viscosity, the gravitational constant, and the drag coefficient are assumed to be constant. The correlations in Table 1 can be simplified to functions of particle size, particle concentration, tank diameter, and impeller diameter.

Since thrust (F) and horsepower (P) are functions of mixer speed, the thrust and horsepower required to suspend insoluble solids can be calculated from equations [2] and [3].

$$F = K N^2 D^2 \qquad [2]$$

$$P = K N^3 D^5 \qquad [3]$$

In equations [2] and [3], K is a constant, N is the impeller speed, and D is the impeller diameter.

Table 2 shows the results.

Table 2. Shear Stress and Horsepower Required to Suspend Insoluble Particles

Reference	Thrust	Horsepower
3	$F_{js} = K \frac{d_p^{1/3} C_v^{2/3} T^2}{D^{10/3}}$	$P_{js} = K \frac{d_p^{1/2} C_v T^3}{D^5}$
4	$F_{js} = K \frac{T^2 d_p^{1/3}}{Z^2 D^{10/3}}$	$P_{js} = K \frac{T^3 d_p^{1/2}}{Z^3 D^5}$
5	$F_{js} = K \frac{d_p^{.4} X^{.26}}{D^{1.7}}$	$P_{js} = K \frac{d_p^{.6} X^{.39}}{D^{2.55}}$
6	$F_{js} = K \frac{d_p^{.3} X^{.24}}{D^{1.52}}$	$P_{js} = K \frac{d_p^{.45} X^{.36}}{D^{2.28}}$
7	$F_{js} = K \frac{d_p^{.28} T^2}{D^{3.78}}$	$P_{js} = K \frac{d_p^{.42} T^3}{D^{5.67}}$

Experiments

Tests were performed in three different sized tanks: a 1.5 ft. diameter tank, a 6.0 ft. diameter tank, and an 18.75 ft. diameter tank. The 1.5 ft. diameter tank was filled to liquid levels of 7 inches and 10 inches. The mixer contained a 3-bladed propeller with a diameter of 3 inches and a pitch of 2 inches. The blade angle was 12 degrees. The mixer had a variable speed drive and a maximum speed of 2500 rpm. The mixer did not contain a shroud. However, because the mixer thrust was measured directly, the lack of a jet ring does not affect the results. Figure 2 shows the tank layout for these tests.

The 6.0 ft. diameter tank was approximately a 4:1 geometric scale up of the 1.5 ft. diameter tank. The tank was filled to liquid levels of 28 inches and 41 inches. The mixer was a 4 hp Model 4640 Flygt mixer. The mixer contained a 3-bladed propeller with a diameter of 14 inches and a blade angle of 11 degrees. The mixer had a variable speed drive and a maximum speed of 860 rpm. Figure 3 shows the tank layout for these tests.

The 18.75 ft. diameter tank contained 3 Flygt model 4640 mixers. The mixers were placed in the 90°, 225°, and 270° positions approximately 1.5 feet from the tank wall. The 90° and 270° mixers were directed 30 degrees to the left of the tank center. The 225° mixer was pointed 10° to the left of the tank center. Figure 4 shows the tank layout for these tests.

The tests were performed in the following manner: The tank was filled with zeolite, and the zeolite spread evenly over the tank bottom. Water was added to the specified level. The mixers were turned on and the speed increased until all of the solids were suspended. In the 1.5 and 6.0 ft. diameter tanks, the solids were visually determined to be suspended when all particles were found to be in motion on the tank bottom (i.e., no particle was stationary on the tank bottom for more than 1 second). In the 18.75 ft. diameter tank, the solids suspension was determined by measuring the fluid density at various points in the tank with a coriolis flow meter (Krohne model #300P). The coriolis mass flow meter was connected to a pump and plastic tubing. Fluid was pumped through the flow meter at 5 gpm. The tubing inlet was placed a various spots in the tank to obtain a density profile within the tank. The vertical density profile was integrated to determine the fraction of zeolite in suspension.

The mixer thrust was measured in the 1.5 foot diameter tank and determined from the affinity laws for the 6 and 18.75 foot diameter tanks (see equation [2]). The mixer hydraulic horsepower was determined from the affinity laws in all of the tanks (see equation [3]).

Table 3 shows the test conditions.

Table 3. Mixer Test Conditions

Test#	Tank Diameter (ft)	Liquid Level (in)	Concentration (vol. %)	Particle Diameter (mm)
1	1.5	7	1.5	.7
2	1.5	10	1.1	.7
3	1.5	10	1.5	.7
4	1.5	7	6	.7
5	1.5	10	4.3	.7
6	1.5	10	6	.7
7	1.5	7	1.5	.3
8	1.5	10	1.1	.3
9	1.5	10	1.5	.3
10	1.5	7	6	.3
11	1.5	10	4.3	.3
12	1.5	10	6	.3
14	6	28	1.5	.7
15	6	40	1.1	.7
16	6	40	1.5	.7
19	18.75	39	1.5	.7

During the tests, the point on the tank bottom at which the last particle was suspended was recorded. Following the test, the velocity at the point was measured to determine the velocity required to suspend the zeolite particles. In the 1.5 ft tank, the velocity was measured with a hot film probe (TSI). In the 6.0 and 18.75 ft tanks, the velocity was measured with a Marsh-McBirney probe.

Results

Table 4 shows the test results. The table shows the tank diameter, the number of mixers, the required shear stress (τ_o, mixer thrust divided by wetted surface area) to suspend all of the particles, and the required mixer power per unit tank volume (P/V) to suspend all of the particles.

Table 4. Test Results

Test #	Tank Diameter (ft)	Number of Mixers	τ_o (Pa)	P/V (W/m^3)
1	1.5	1	16.5	530
2	1.5	1	16.3	510
3	1.5	1	16.1	501
4	1.5	1	21.1	736
4a	1.5	2	21.1	545
5	1.5	2	20.0	490
6	1.5	2	21.5	530
7	1.5	1	11.0	285
8	1.5	1	11.8	311
9	1.5	1	10.8	276
10	1.5	1	14.7	431
11	1.5	1	13.8	392
12	1.5	1	14.9	438
14	6	1	86	760
15	6	1	62	510
16	6	1	89	890
19	18.75	3	> 55	> 280

Table 5 shows the effect of liquid level on the required mixer thrust and power. The results from the 1.5 and 6.0 foot diameter tanks showed minimal change in required shear stress or power per unit volume when the liquid level was increased. The power per unit volume required to suspend the zeolite is expected to decrease with increasing tank volume.[8] The absence of a measurable effect could be due to the small change in liquid level or to the effect being smaller than the experimental uncertainty.

Table 5. Effect of Liquid Level on Required Mixer Power

Diameter (ft)	Conc. (vol%)	Particle Diam. (mm)	Level (in)	τ_o (Pa)	P/V (W/m^3)	Level (in)	τ_o (Pa)	P/V (W/m^3)
1.5	1.5	.7	7	16.5	530	10	16.1	501
1.5	6.0	.7	7	21.1	545	10	21.5	530
1.5	1.5	.3	7	11.0	285	10	10.8	276
1.5	6.0	.3	7	13.8	392	10	15.9	492
6.0	1.5	.7	28	86	760	40	89	890

Table 6 shows the effect of particle concentration on the required mixer thrust and power. Increasing the zeolite concentration from 1.5 vol. % to 6.0 vol. % increased the required shear stress by approximately 25% and the required power per unit volume by approximately 45%. Previous research[3,5,6] has shown the required mixer speed is related to particle concentration by equation [4]

$$N_{js} \propto c^a \quad [4]$$

where N_{js} is the speed required to just suspend all of the particles, c is the particle concentration, and a is a constant. For suspending particles with agitators, Zwietering and Chapman reported values of a equal to 0.12 – 0.13.[5,6] If a is equal to 0.12, increasing the solids concentration from 1.5 vol. % to 6.0 vol. % would increase the minimum required mixer thrust by 40% and the required hydraulic horsepower by 65%. The measured increases in required shear stress and horsepower are less than predicted by the correlations for agitators, but are of the same order of magnitude.

Table 6. Effect of Particle Concentration on Required Mixer Power

Diameter (ft)	Liquid Level (in)	τ_o (1.5 vol. %) (Pa)	τ_o (6 vol. %) (Pa)	P/V (1.5 vol. %) (W/m^3)	P/V (6 vol. %) (W/m^3)
1.5	7	16.5	21.1	530	736
1.5	7	11.0	14.7	285	431
1.5	10	11.8	13.8	311	392
1.5	10	10.8	14.9	276	438

Table 7 shows the effect of particle size on the required mixer thrust and power. Decreasing the particle size from 0.7 mm to 0.3 mm, decreased the required shear stress by approximately 30% and the required power per unit volume by approximately 35%. This result is expected. Previous research[3-7] has shown the required mixer speed is related to particle concentration by equation [5]

$$N_{js} \propto d_p^{\,b} \qquad [5]$$

where N_{js} is the speed required to just suspend all of the particles, d_p is the particle diameter, and b is a constant. Typical values of b for suspending particles with agitators are 0.14 – 0.20. If b is equal to 0.14 – 0.20, decreasing the particle size from 0.7 mm to 0.3 mm would decrease the minimum required mixer thrust by 20 - 30% and the required hydraulic horsepower by 30 - 40%. The agreement between the test results and correlations developed for particle suspension with agitators is good.

Table 7. Effect of Particle Size on Required Mixer Power

Diameter (ft)	Liquid Level (in)	Conc. (vol. %)	τ_o (.7mm) (Pa)	τ_o (.3mm) (Pa)	P/V (.7mm) (W/m^3)	P/V (.3mm) (W/m^3)
1.5	7	1.5	16.5	11.0	530	285
1.5	10	1.5	16.3	11.8	512	311
1.5	10	1.5	16.1	10.8	501	276
1.5	7	6	21.1	14.7	736	431

Table 8 shows the effect of the number of mixers on the required mixer thrust and power. Increasing the number of mixers in the 1.5 foot diameter tank from one to two decreased the required power per unit volume by 25%, but had no effect on the required shear stress. Multiple mixers in a tank would provide a more even distribution of energy, and therefore, a lower average energy in the tank would be needed to suspend all of the particles. More testing is needed to better quantify the effect of changing the number of mixers.

Table 8. Effect of Number of Mixers on Required Mixer Power

# of Mixers	Diameter (ft)	Liquid Level (in)	Conc. (vol. %)	τ_o (Pa)	P/V (W/m^3)
1	1.5	7	6	21.1	736
2	1.5	7	6	21.1	545

Table 9 shows the effect of tank diameter on the mixer shear stress required to suspend zeolite. Increasing the tank diameter caused an increase in the required shear stress to suspend zeolite. The increase in required shear stress between the 1.5 ft tank and the 6.0 ft tank is approximately a factor of 5, which suggests scaling based on tank volume rather than wetted surface area. These results disagree with the constant shear stress model, and suggest it does not apply to suspension of fast settling solids such as zeolite. Even though the zeolite in the 18.75 ft tank was not completely suspended, the average shear stress was much larger than in the 1.5 ft tank supporting the conclusion that the constant shear stress model does not describe scaling of fast settling zeolite particles.

Table 9. Effect of Tank Size on Required Mixer Shear Stress

Test #s	1.5 ft Tank Required τ_o (Pa)	6.0 ft Tank Required τ_o (Pa)	18.75 ft Tank Required τ_o (Pa)
1, 14, 19	16.5	86	> 55
2, 15	16.3	62	
3, 16	16.1	89	

Table 10 shows the effect of tank diameter on the mixer power required to suspend zeolite. Increasing the tank diameter had a small effect on the power per unit volume required to suspend the zeolite. The differences in required power per unit volume measured are most likely due to experimental uncertainty. This result disagrees with much of the technical literature.[9] However, Herringe showed the exponent in $P/V = T^n$ is a function of particle size.[10] When the particle size was 0.5 – 0.7 mm, he found the exponent to be 1. This data agrees with that work. Even though the zeolite in the 18.75 ft tank was not completely suspended, the power per unit volume was less than in the 1.5 ft and 6.0 ft tanks which is consistent with constant power per unit volume describing the scaling of fast settling zeolite particles.

Table 10. Effect of Tank Size on Required Mixer Power

Test #s	1.5 ft Tank Required P/V (W/m^3)	6.0 ft Tank Required P/V (W/m^3)	18.75 ft Tank Required P/V (W/m^3)
1, 14, 19	530	760	> 280
2, 15	512	510	
3, 16	501	890	

Following the zeolite suspension tests, the authors measured the velocity on the tank bottom at the location where the last zeolite particle was suspended. In the 1.5 foot tank, the velocity was measured 0.4 inches above the tank bottom and found to be 0.8 – 1.3 ft/sec.. In the 6.0 foot tank, the velocity was measured 2 inches above the tank bottom found to be 1.0 – 1.6 ft/sec. These results suggest a fluid velocity of 1.6 ft/sec two inches above the tank bottom is needed to suspend the 0.7 mm zeolite particles used in these tests.

Conclusions

The conclusions of the work are:

- Scaling of the suspension of fast settling particles (i.e., zeolite) was best described by the constant power per unit volume method.
- Increasing the zeolite particle concentration increased the required mixer power needed to suspend the particles.
- Decreasing the zeolite particle size from 0.7 mm – 0.3 mm decreased the required mixer power needed to suspend the particles.
- Increasing the number of mixers in the tank decreased the required mixer power needed to suspend the particles.
- A velocity of 1.6 ft/sec two inches above the tank bottom is needed to suspend 0.7 mm zeolite particles.

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Figure 1. Shrouded Axial Impeller Mixer (ITT Flygt)

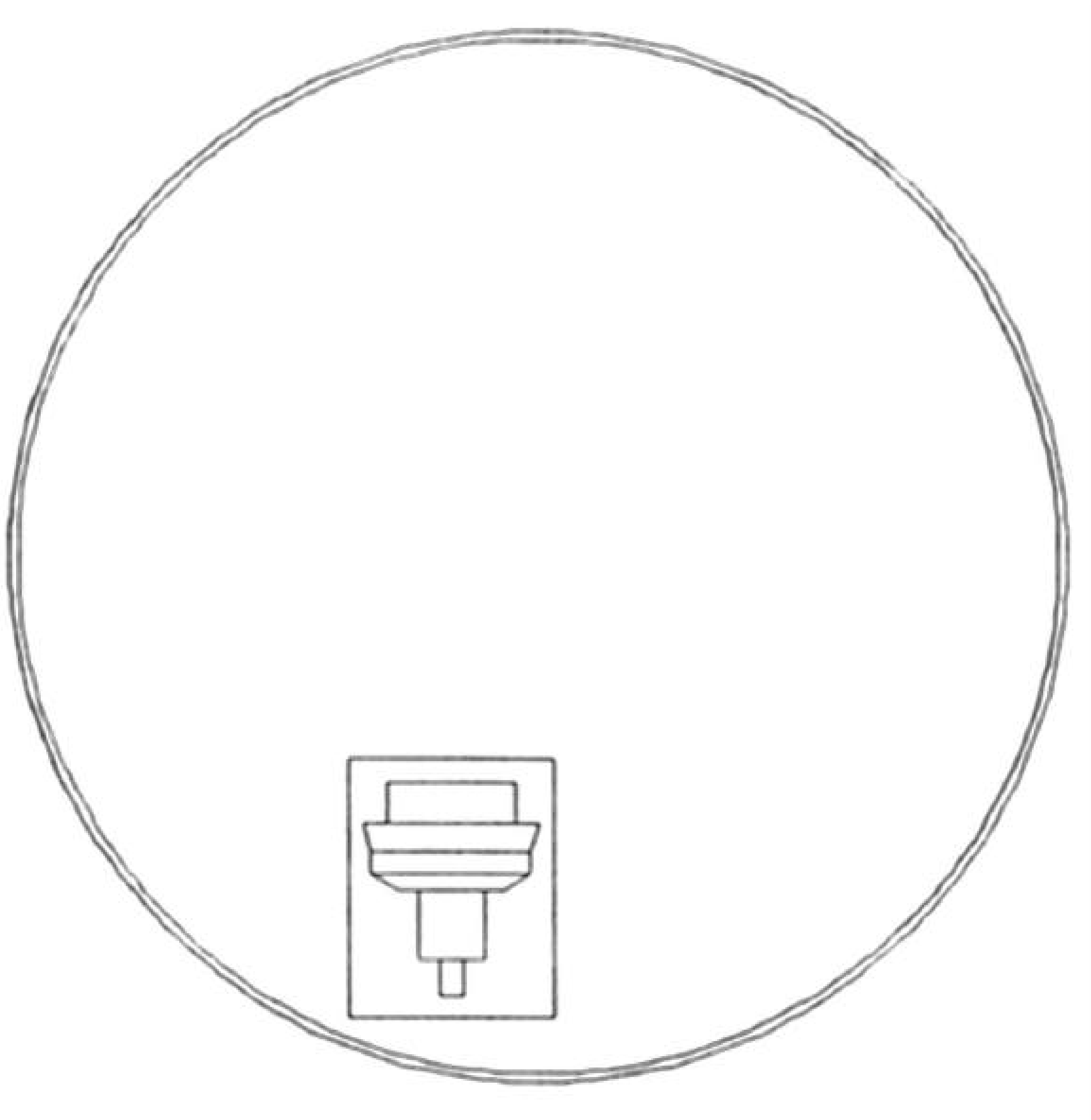

Figure 2. Layout for Mixer Tests in 1.5 Foot Diameter Tank

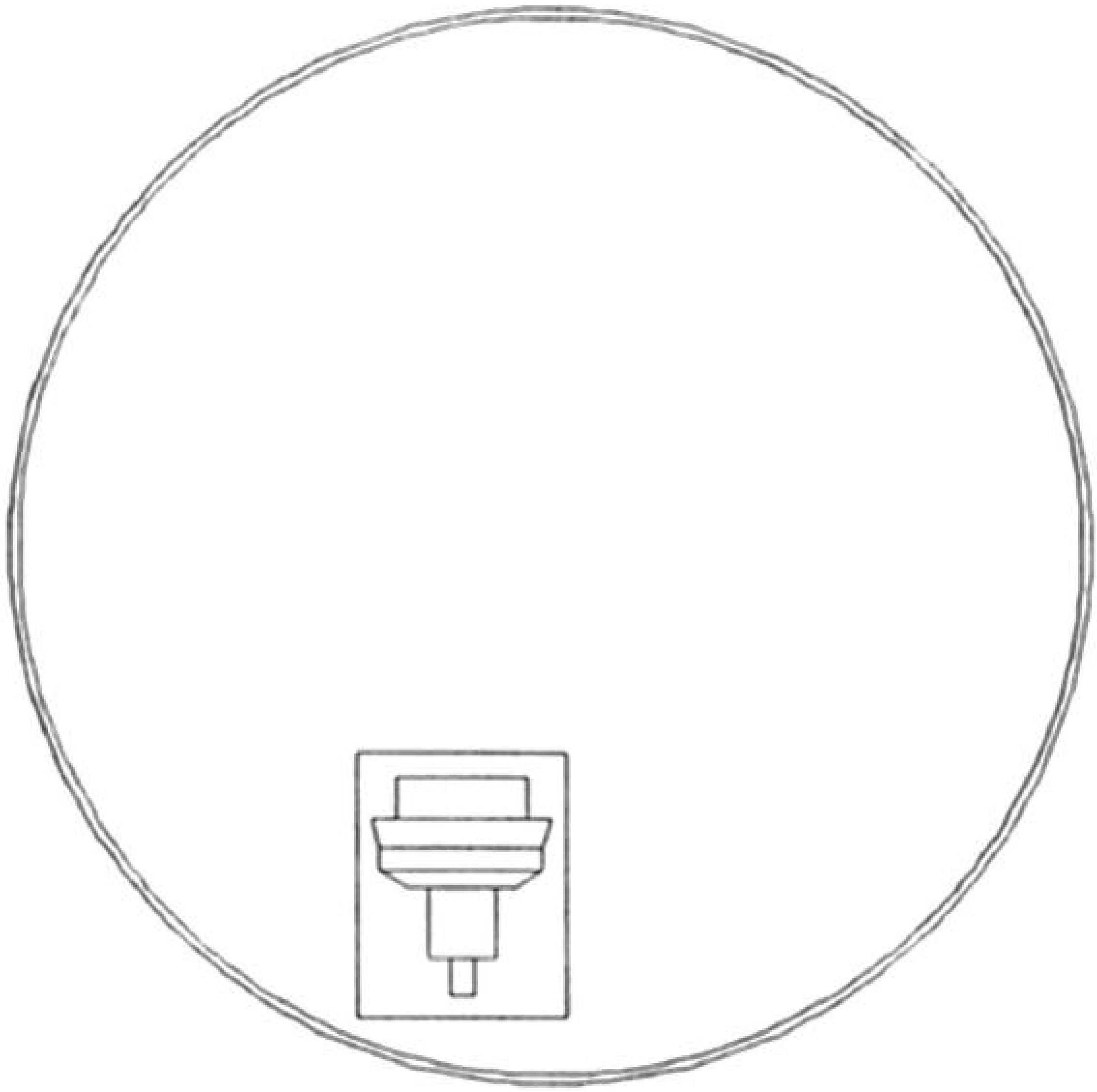

Figure 3. Layout for Mixer Test in 6.0 foot Diameter Tank

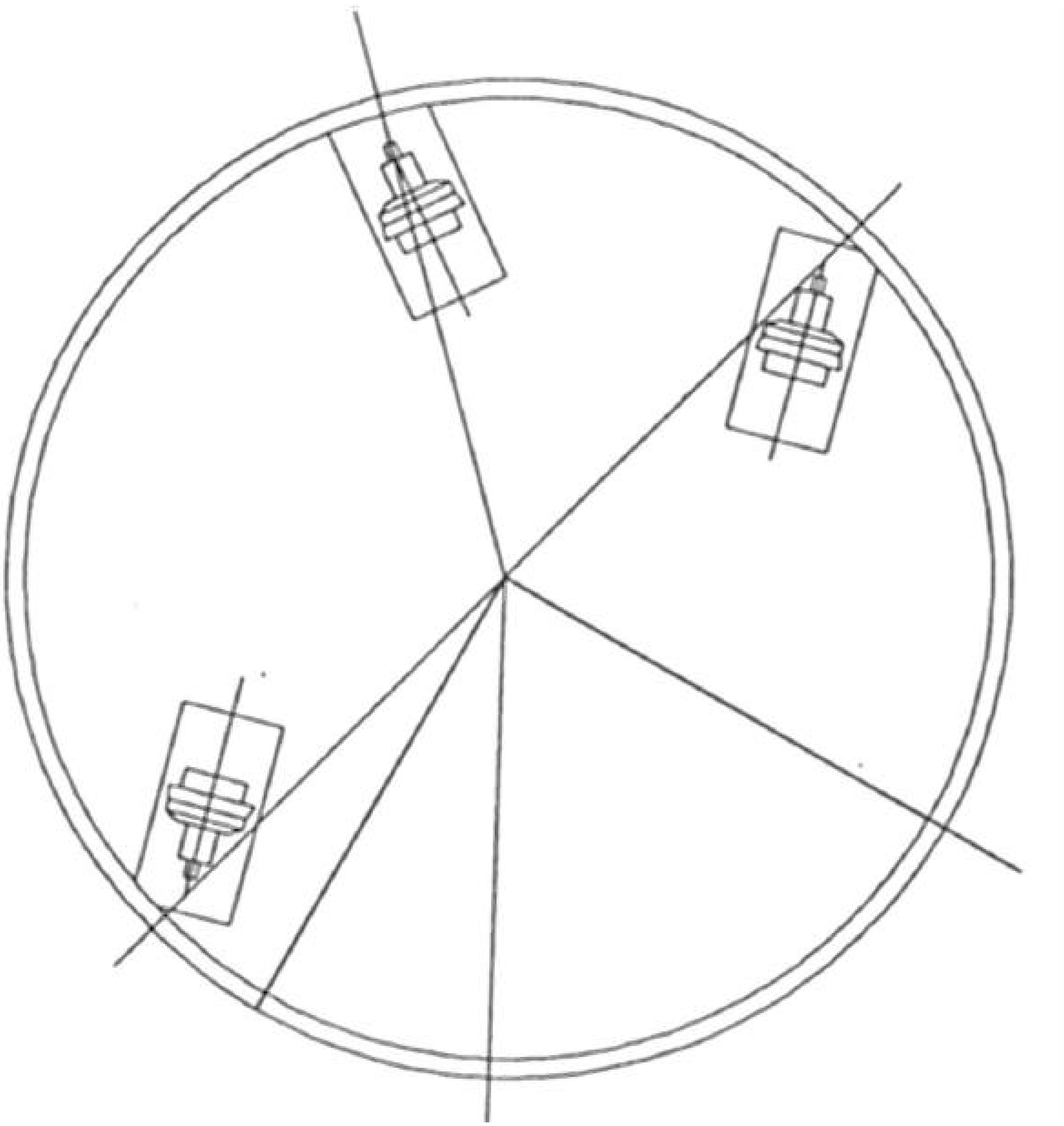

Figure 4. Layout for Mixer Test in 18.75 Foot Diameter Tank