**CFD Simulation of Anaerobic Digester Mixing**

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## Summary of Simulation

Active volume values were calculated from CFD decay curves based on the methods of Monteith and Stephenson (1981) and Wolf and Resnick (1963). The calculations resulted in negligibly small dead volume values; hence, the configuration examined has Active Volumes of effectively 100%.[1,2]

Wolf and Resnick (1963) predicted that sludge outlet concentrations should decay as $C_{SO} = C_{initial} \exp(-t/[T_{HRT}(1 - D)])$, where $T_{HRT}$ is Hydraulic Retention Time and D is any fractional dead volume. Thus, $D = 1 + (t/T_{HRT})/[\ln C_{SO} - \ln C_{Initial}]$ which can be evaluated at typical times after wash-out has reached a steady decay rate. Values calculated from the wash-out curves produced during the full scale, 1/10 th and 1/20 th scale simulations ranged from -.003, -.013, and -0.13 which suggests 100% active mixing volume for the tank. (Full scale tracer tests also have produced negative dead volume results, suggesting method is sensitive to measuring accuracy.

## Discussion

Environmental engineers generally agree that the key to good anaerobic digester operation is mixing. **Mixing** disperses the substrate, produces better biomass contact and uniform thermal distribution, and reduces scum buildup in the digester. If **mixing** is inadequate, the efficiency of digestion and the stability of the product sludge may be jeopardized.

Several “rules-of-thumb” are common among digester designers to size anaerobic digestion systems, these include:
- *Digester Volume Turnover Time* (DVTT) = (Tank volume/Pump Capacity),
- *Hydraulic Retention Time* (HRT) = (Tank volume/Sludge input rate),
- *Unit Power* (UP) = (Pump horsepower/Tank volume/1000), and
- *RMS Velocity Gradient* (VGT) = (Pump power/Tank volume/Sludge viscosity)$^{1/2}$.

DVT and HRT are measures of anticipated mixing efficiency of the digester, whereas UP and VGT quantify pump capacity and normalize mixing intensity based on the flow properties of the sludge, respectively. Desirable magnitudes of DVTT, HRT, UP and VGT are typically about 0.5-1 hr, 15-20 days, 0.2-0.3 Hp/1000 ft$^3$, and 50-85 s$^{-1}$, respectively.

Once a system is designed, some confirmation of mixing effectiveness is often sought. In the past this has been determined by full-scale tracer methods which can be quite time-consuming and require internal placement of instrumentation and expensive test apparatus.

Today modern Computational Fluid Dynamics (CFD) software permits the confirmation of mixing efficiencies for different digester configurations before construction which eliminates the need for expensive post-construction field tests. Furthermore, this

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[1]Monteith, H.D. and Stephenson, J.P. (1981), Mixing efficiencies in full-scale anaerobic digesters by tracer methods, Journal of WPCF, Vol. 53, No. 1, 78-84.

[2]Wolf, D. And Resnick, W., (1963), Residence Time Distribution in Real Systems, I & EC Fundamentals, Vol. 2, No. 4, 287-293.

approach eliminates the painful realization a system is inefficient after installation. CFD visualization and analysis also provide an opportunity to examine alternative inlet, outlet and pump configurations. Visualization of fluid velocity vectors, streamlines and particle trajectories can help the user understand the mixing processes, and it can identify possible problems in advance.

Analysis and Results

An anaerobic digester tank with the following dimensions was evaluated using CFD software:

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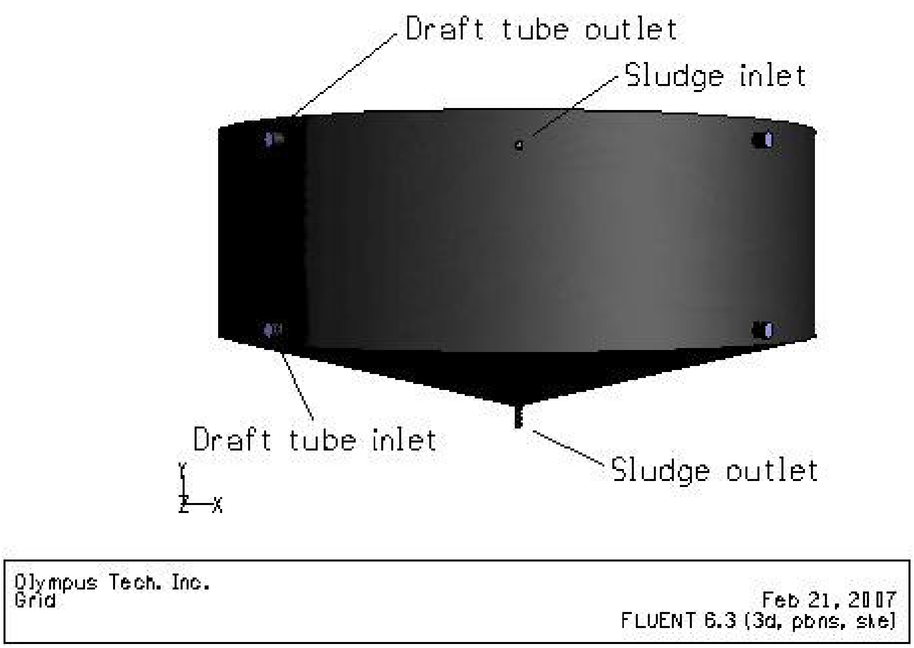
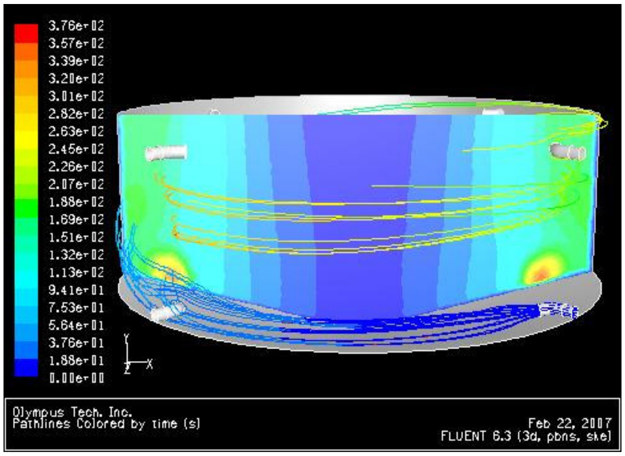
|---|---|
| Tank Diameter = 100 ft | Side-water Depth = 33.2 ft |
| Cone (floor) Depth = 12.5 ft | Number of external mixers = 4 |
| Mixer flow rate = 10,200 gpm/mixer | Sludge inlet flow rate = 100 gpm |

The CFD software used was the commercial code FLUENT 6.3: a general, finite-volume method solver. The grid system consisted of an unstructured array using ~685,000 tetrahedral elements. The solver used a 3D, implicit, pressure based steady solver for the velocity and turbulence fields, and a time dependent mode for predicting sludge concentrations. SIMPLE pressure-velocity coupling and second-order upwind discretization of flow properties were chosen. A standard kappa-epsilon turbulence model with standard wall functions was specified. The inlet sludge was assumed diluted to about 4% concentration such that the density of the solid-water suspension and its viscosity approximate the same respective values as characteristics of water.

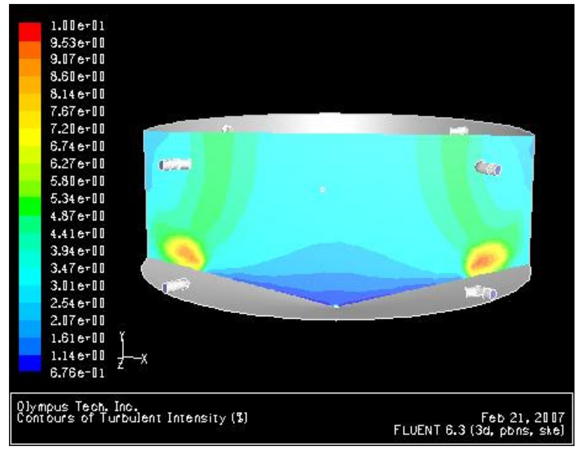



Initially the velocity and turbulence flow field within the tank were calculated including the influence of inlet, outlet and 4 external draft-tube mixers. The resultant mean motion of the flow included a vortex-like motion about the tank center which spiraled slowly down to the sludge outlet at the bottom of the cone floor. The draft tubes also induced vertical motions upward along the outer walls and downward along the tank center. Turbulence was maximum around the draft-tube inlet jets, but mixing was fairly uniform across the tank. Mean streamlines of the particle paths involved rising and falling concentric spirals which eventually exit at the outlet. But actual instantaneous particle pathlines were deflected from mean streamlines such that sludge particles quickly mixed throughout the outer region of the tank, and eventually they populated the entire tank volume.



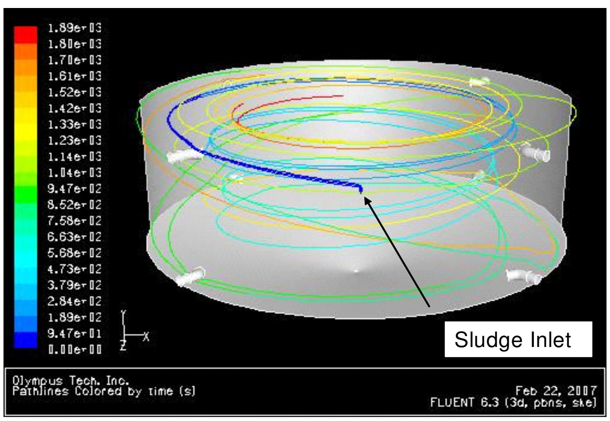

Mean velocity contours and pathlines

Colors on cross-section depict magnitudes of mean velocity. Note two circular zones produced by mixer inlets and presence of higher circumferential speeds near tank walls. Mean velocities at tank centerline are, of course, essentially zero. Pathlines emitted from mixer outlet on right follow average fluid motions around tank, line colors indicate time since entry.



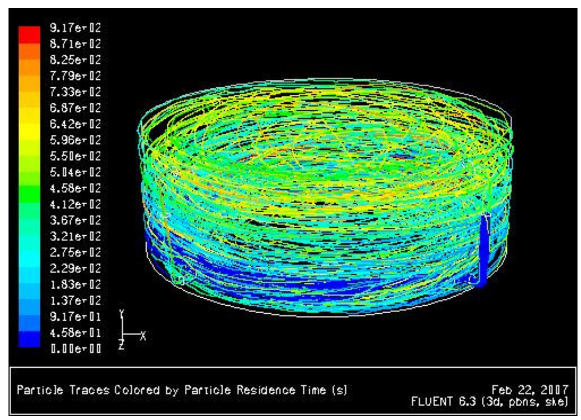

Turbulence intensity (mixing)

Colors on cross-section depict magnitude of mixing expressed in terms of root-mean-square average of velocity deviations from the mean values displayed in the figure to left. Note that most intense mixing occurs around the mixer inlet zones and in regions of radial shear associated with flow rotation. In most of the tank mixing is maintained at optimum levels between 4 and 5 %




Average pathlines of inlet sludge

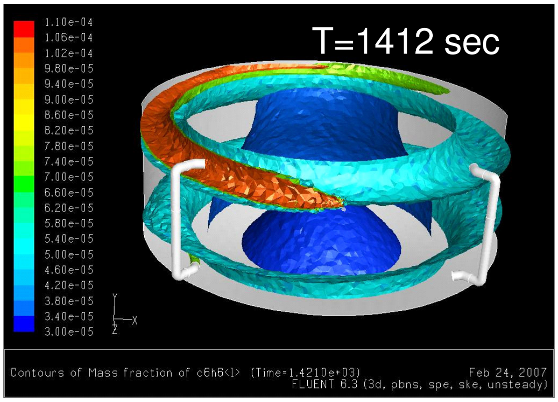
Spirals of colored pathlines initiate from the sludge inlet. They spiral upward and downward about the tank following the local mean fluid velocities. Line colors represent the time since particle insertion; hence, blue colors suggest short residence time in the tank, and red particles have resided longest. The tip of the red line depicts particles that have spent nearly 1900 sec (~31 min) within the tank.

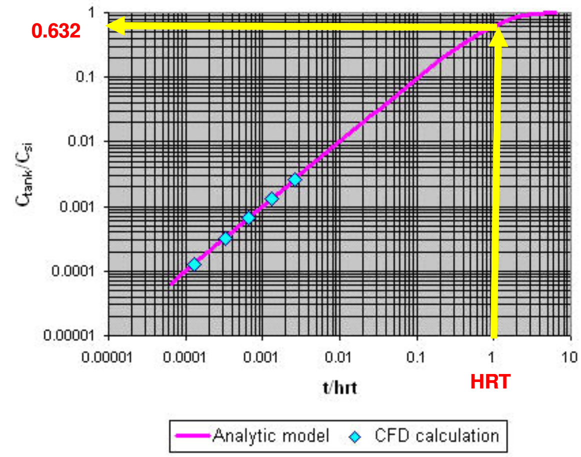



Pathlines of sludge recirculated through external mixer

These erratic spiral lines depict the random motion of particles that have been deflected from the mean pathline motion by local turbulence repeatedly thoughout their time in the tank since passing through the external mixer on right. Line colors represent the time since particles last passed through the first mixer pump. Particles were traced here for a total of 15 minutes, during which they may have passed through several mixer turbines.

Once the velocity and turbulence fields were defined it was possible to introduce a step increase in tracer concentration at the sludge inlet and observe the build up of average concentrations within the entire tank. Plotting sludge exhaust concentration versus time permits the calculation of actual hydraulic retention time (HRT).




Step inlet concentrations after ~24 min

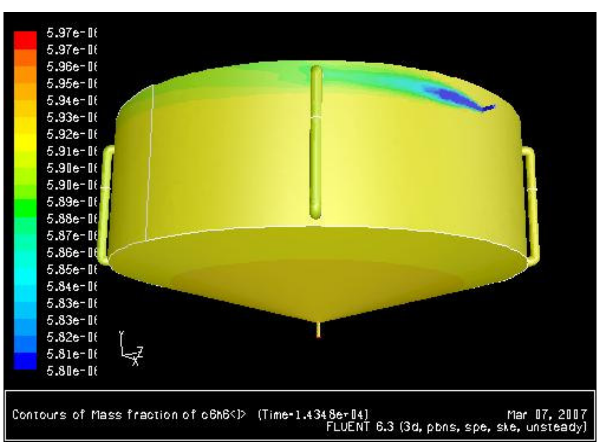
Fluid from a 5% step increase of sludge concentration at the inlet mixes progressively throughout the tank in spiral swirls. Concentration isosurfaces are depicted by different colors. Concentrations in the tank regions between the individual surfaces are bounded by values depicted by surface colors. This figures depicts mixing accomplished after 1412 sec (~24 min), but eventually at about 10 HRT the entire tank concentration will approach 5%.

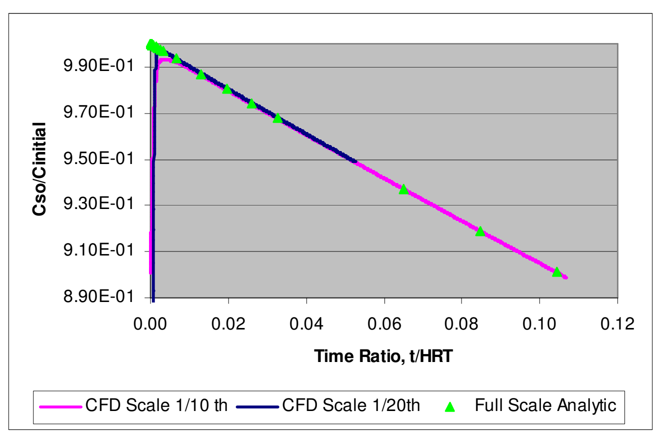
$$\frac{\overline{C}_{tank}}{C_{SI}} = (1.0-\exp(-\frac{Q_{SI}t}{V_{tank}})) = (1.0-\exp(-\frac{t}{T_{HRT}}))$$

If one plots the ratio of mean tank concentration to step inlet concentration versus time since step inception on a log-log graph it is found that concentrations rise exponentially. By fitting the curve noted above to the CFD data one can determine the effective Hydraulic Retention Time (HRT) of the tank configuration.

The calculated HRT was 17.9 days, whereas the nominal HRT based on proposed tank volume and external draft tube capacity was 15.2 days. The difference in these numbers reflects the reality of actual tank configuration versus idealized behavior.

Alternatively, one can introduce a slug of tracer spilled into the tank and observe how it mixes throughout the tank. The time for the outlet concentration to reach 99% of maximum is the Mixing Diffusion Time (MDT). This was calculated for three situations, a full scale tank, a 1/10th scale tank and a 1/20th scale tank. The calculated values can be related through similarity (scaling) theory and were 19.2, 29.4 and 26.5 min, respectively. Furthermore, one can observe the decay of outlet concentrations after the outlet maximum occurs. For the 1/10th and 120th scale models the calculated values were 18.0 and 17.9 days, respectively.




1/10 th scale tank at t/HRT = 0.11

Wash-out curves for slug tracer case

Surface concentrations on the tank boundary are represented by color. The fresh fluid entering at the sludge inlet contains no new tracer; hence it shows zero concentrations. Highest concentrations occur in the tank cone region as the slug of tracer exhausts from the tank at the outlet.

Plots of the ratio of sludge outlet concentrations to initial slug tracer concentration from 1/10 th and 1/20 th scale model simulations are superimposed on the ideal analytic expectation for a full size tank. The fact all curves superimpose based on length-scale-ratio confirms validity of modeling theory.