Improving WWTP Design and Operations Through 3D CFD Modeling

(Application of CFD to Wastewater Process Engineering)

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Carollo Engineers

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“If we know what is happening within the vessel, then we are able to predict the behavior of the vessel as a reactor. Though fine in principle, the attendant complexities make it impractical to use this approach.” – Octave Levenspiel *Chemical Reaction Engineering* (1972)

Computational fluid dynamics (CFD) changes this picture. Using CFD, we can compute three-dimensional velocity fields and follow interactions of reactants and products through a tank. We can use this information to optimize tank geometry.

CFD can calculate the velocity fields in process tanks and channels.

Hydraulic Model

- Continuity (mass conservation)

$$\frac{\partial \rho}{\partial t} + \frac{\rho \partial U_i}{\partial X_j} = 0$$

CFD can calculate the velocity fields in process tanks and channels.

Hydraulic Model

- Continuity (mass conservation)
- Momentum transport

$$\frac{\partial \rho}{\partial t} + \frac{\rho \partial U_i}{\partial X_j} = 0$$

$$\rho \frac{\partial U_i}{\partial t} = -\rho U_j \frac{\partial U_i}{\partial X_j} - \frac{\partial P}{\partial X_i} + \frac{\partial}{\partial X_j}(\nu_t \frac{\partial U_i}{\partial X_j}) + F_i$$

CFD can calculate the velocity fields in process tanks and channels.

Hydraulic Model
- Continuity (mass conservation)
- Momentum transport
- k-epsilon turbulence model

$$\frac{\partial \rho}{\partial t} + \frac{\rho \partial U_i}{\partial X_j} = 0$$

$$\rho \frac{\partial U_i}{\partial t} = -\rho U_j \frac{\partial U_i}{\partial X_j} - \frac{\partial P}{\partial X_i} + \frac{\partial}{\partial X_j}(\nu_t \frac{\partial U_i}{\partial X_j}) + F_i$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon}$$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial X_i}(\rho k U_i) = \frac{\partial}{\partial X_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial X_j}\right] + P_k + P_b - \rho\varepsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial X_i}(\rho \varepsilon U_i) = \frac{\partial}{\partial X_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial X_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon$$

CFD can calculate the velocity fields in process tanks and channels.

Hydraulic Model

- Continuity (mass conservation)
- Momentum transport
- k-epsilon turbulence model
- Control volume solution scheme

$$\frac{\partial \rho}{\partial t} + \frac{\rho \partial U_i}{\partial X_j} = 0$$

$$\rho \frac{\partial U_i}{\partial t} = -\rho U_j \frac{\partial U_i}{\partial X_j} - \frac{\partial P}{\partial X_i} + \frac{\partial}{\partial X_j}\left(\nu_t \frac{\partial U_i}{\partial X_j}\right) + F_i$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon}$$

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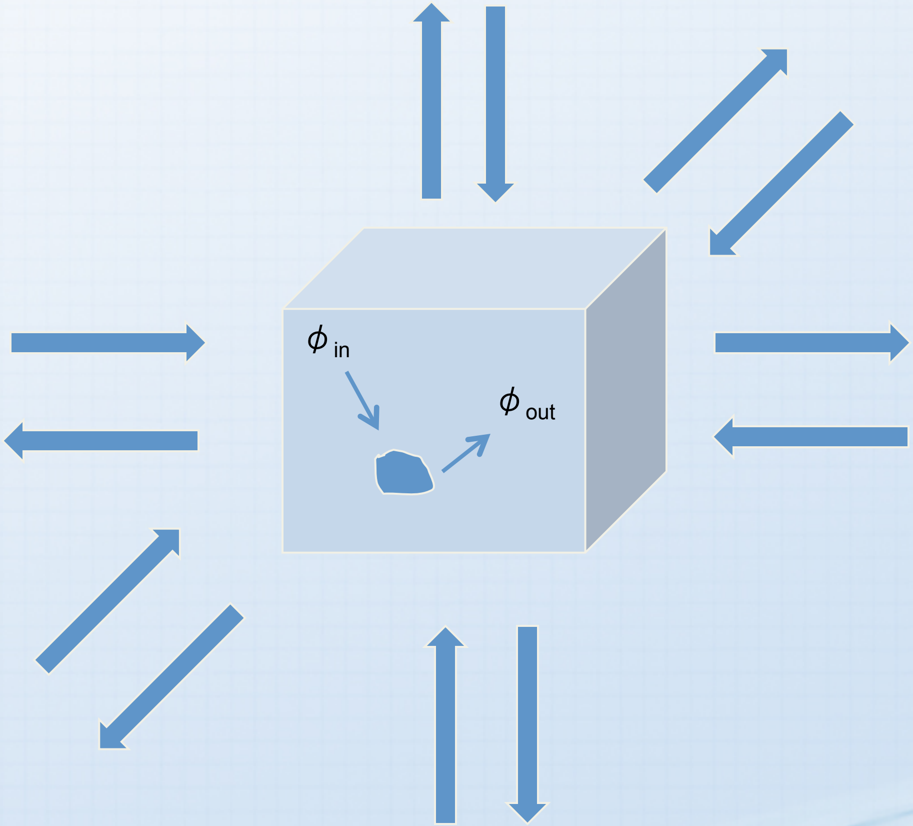
But CFD can also be used as to track solids flow and reactions in the tank.



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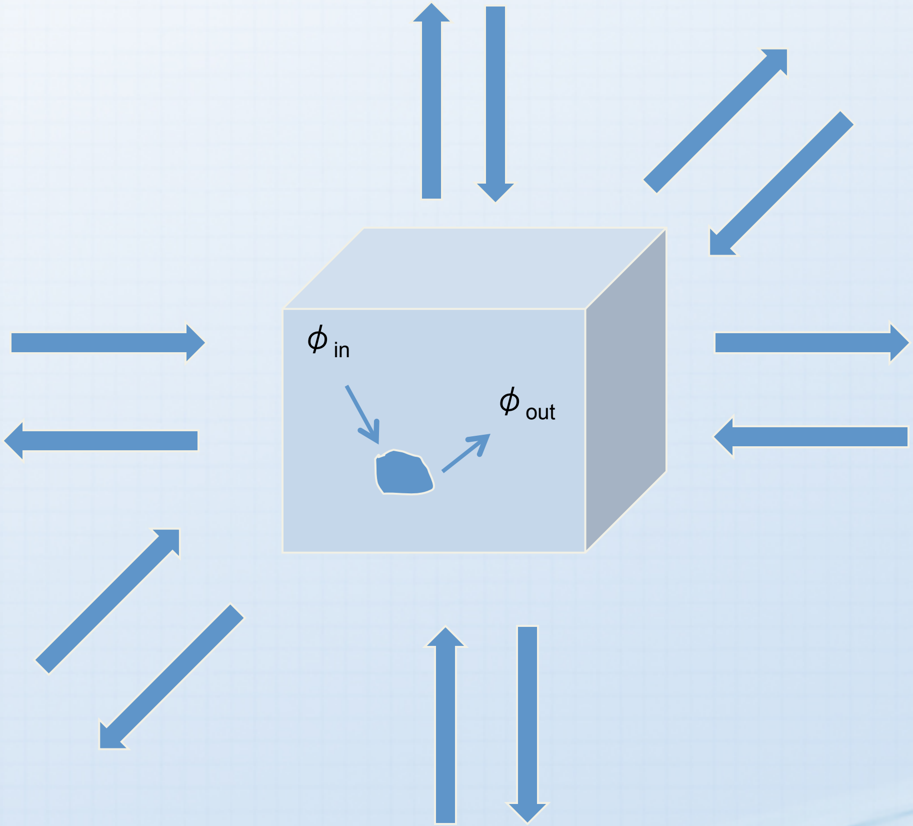
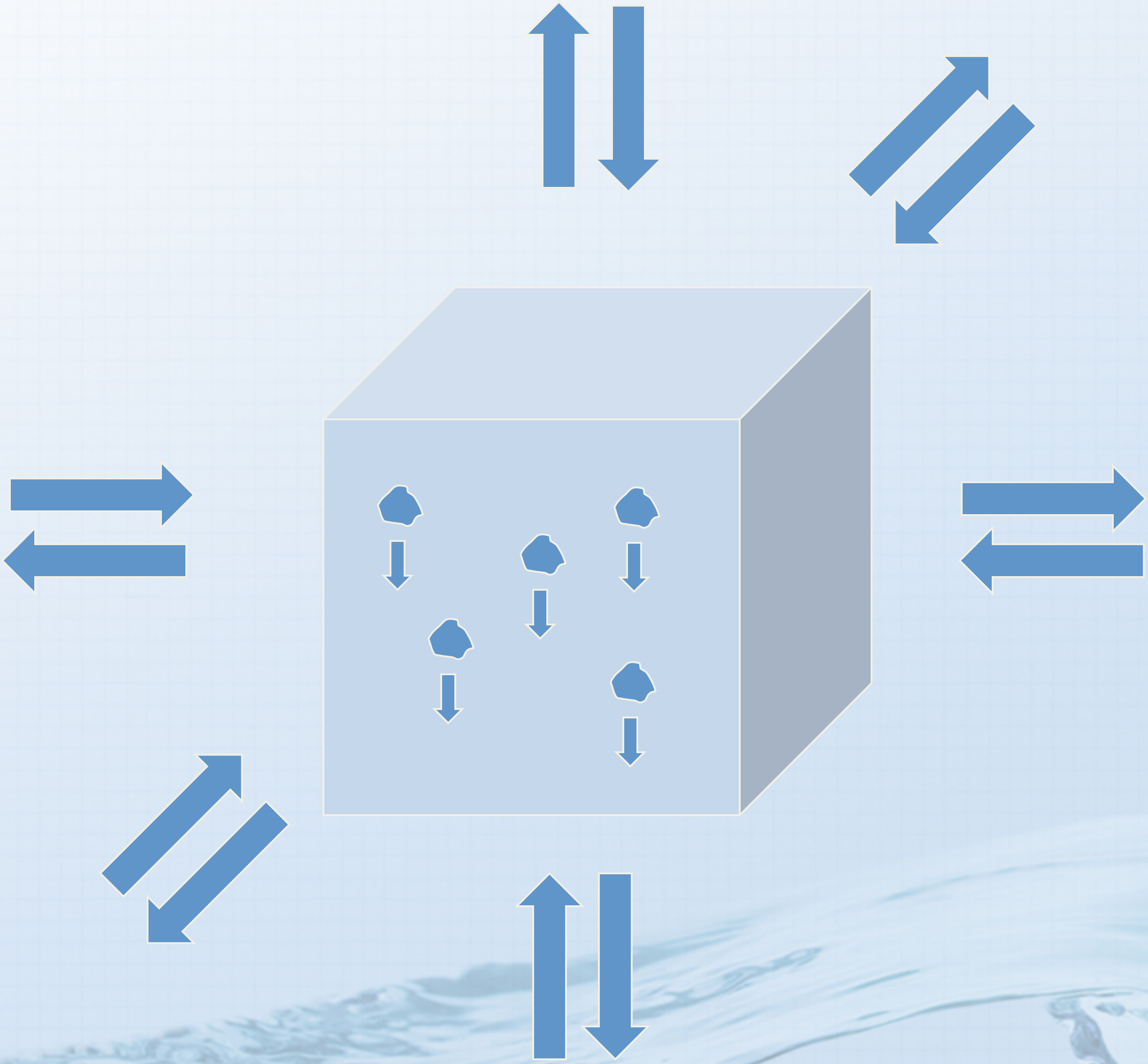


A typical transport model

$$\frac{\partial \phi}{\partial t} = \frac{-U_i \partial \phi}{\partial X_i} + \frac{\partial}{\partial X_i}\left(\frac{\nu_t}{\sigma_s}\frac{\partial \phi}{\partial X_i}\right) + S_i$$

3D Solids Transport Model

Individual Control Volume



3D transport models can be implemented by user defined functions (UDF) in Fluent or other commercial software.

- Solids transport UDF
  - Solids Transport

$$\frac{\partial C}{\partial t} = \frac{-U_i \partial C}{\partial X_i} + \frac{\partial}{\partial X_i}\left(\frac{\nu_t}{\sigma_s}\frac{\partial C}{\partial X_i}\right) + V_s \frac{\partial C}{\partial z}$$

3D transport models can be implemented by user defined functions (UDF) in Fluent or other commercial software.

- Solids transport UDF
  - Solids Transport
  - Vesilind settling

$$\frac{\partial C}{\partial t} = \frac{-U_i \partial C}{\partial X_i} + \frac{\partial}{\partial X_i}\left(\frac{\nu_t}{\sigma_s}\frac{\partial C}{\partial X_i}\right) + V_s\frac{\partial C}{\partial z}$$

$$V_s = V_o * \exp(-k * C)$$

3D transport models can be implemented by user defined functions (UDF) in Fluent or other commercial software.

Solids transport UDF

- Solids Transport
- Vesilind settling
- Density couple

$$\frac{\partial C}{\partial t} = \frac{-U_i \partial C}{\partial X_i} + \frac{\partial}{\partial X_i}\left(\frac{\nu_t}{\sigma_s}\frac{\partial C}{\partial X_i}\right) + V_s \frac{\partial C}{\partial z}$$

$$V_s = V_o * \exp(-k * C)$$

$$\rho = \rho_w / (1 - C * (1 - \rho / \rho_w))$$

3D transport models can also be implemented for reactions in the fluid.

Biokinetic Models

- IWA Activated Sludge Models (ASM)
- Advanced oxidation models
- Disinfection models

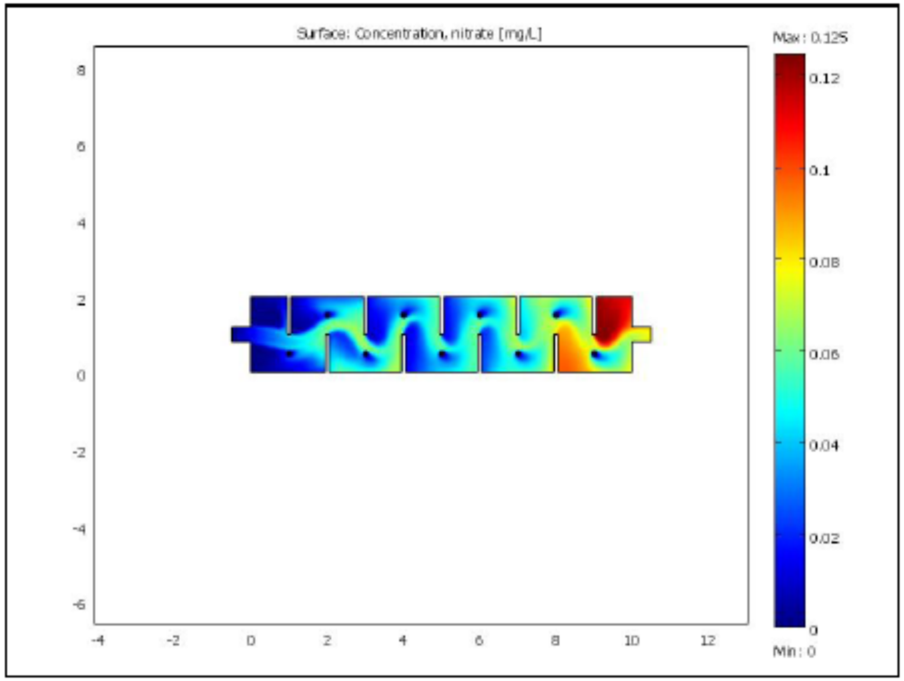
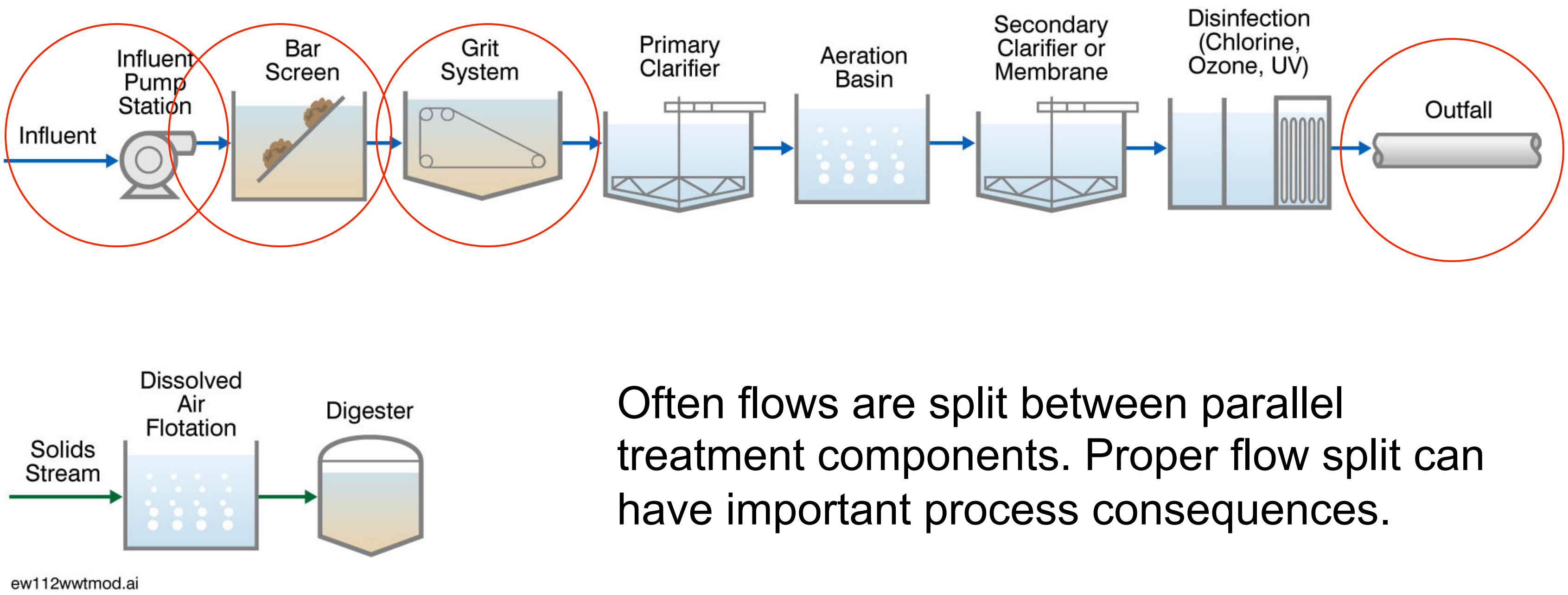


Figure 5c. Nitrate

Sobremisana, Ducoste, de los Reyes III (2011)

CFD is well established for analysis of hydraulic components.



Often flows are split between parallel treatment components. Proper flow split can have important process consequences.

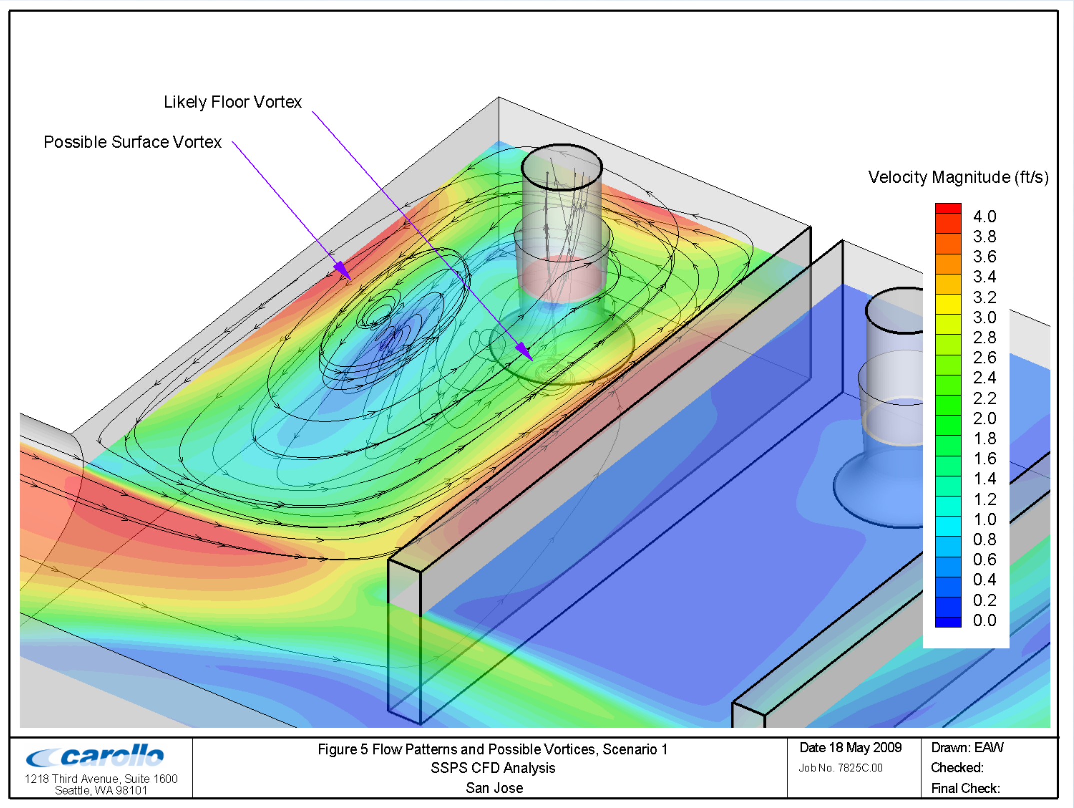
Pump Stations – Optimize Intake Hydraulics

Adverse Hydraulics:

- Vortices
- Pre-rotation
- Turbulence
- Velocity Distribution

Lead to:

- Decreased capacity
- Cavitation
- Excessive wear



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Seattle, WA 98101

Figure 5 Flow Patterns and Possible Vortices, Scenario 1
SSPS CFD Analysis
San Jose

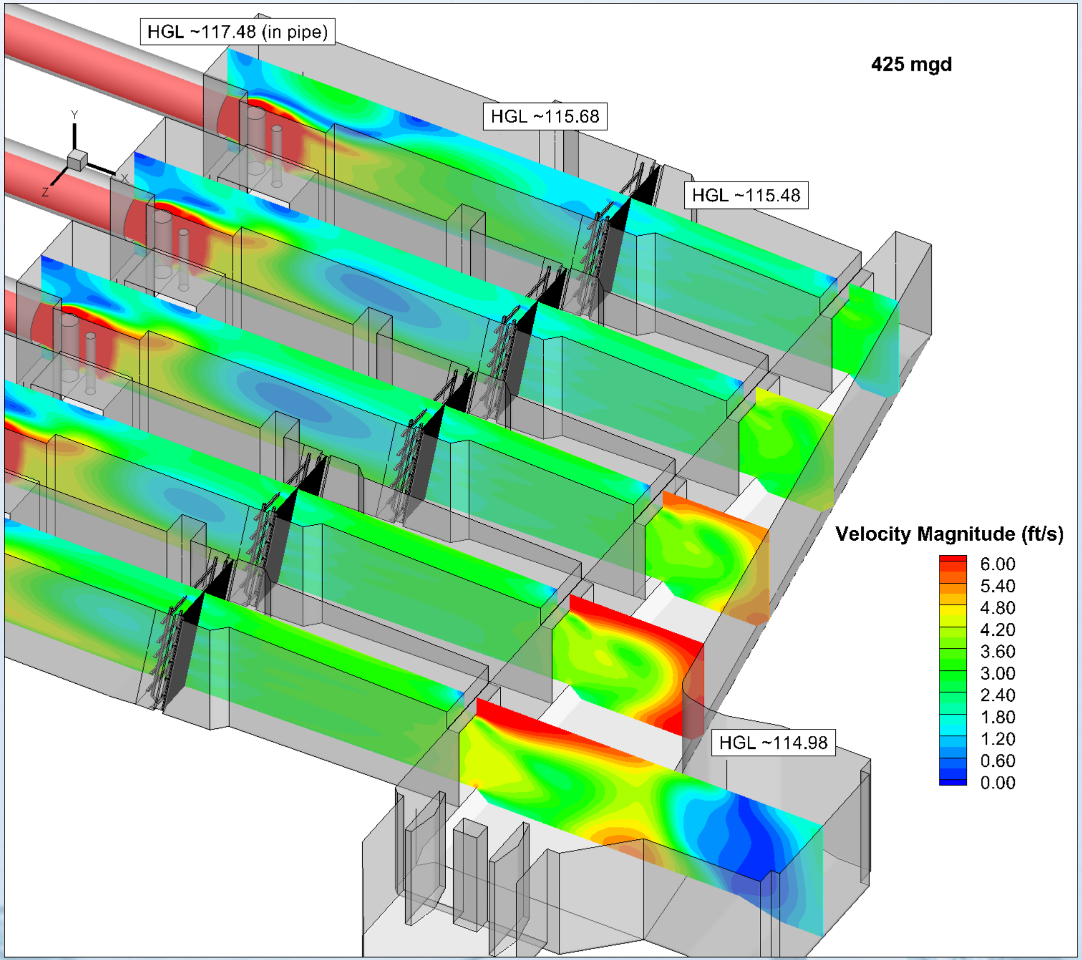
Date 18 May 2009
Job No. 7825C.00

Drawn: EAW
Checked:
Final Check:

Screening / Headworks

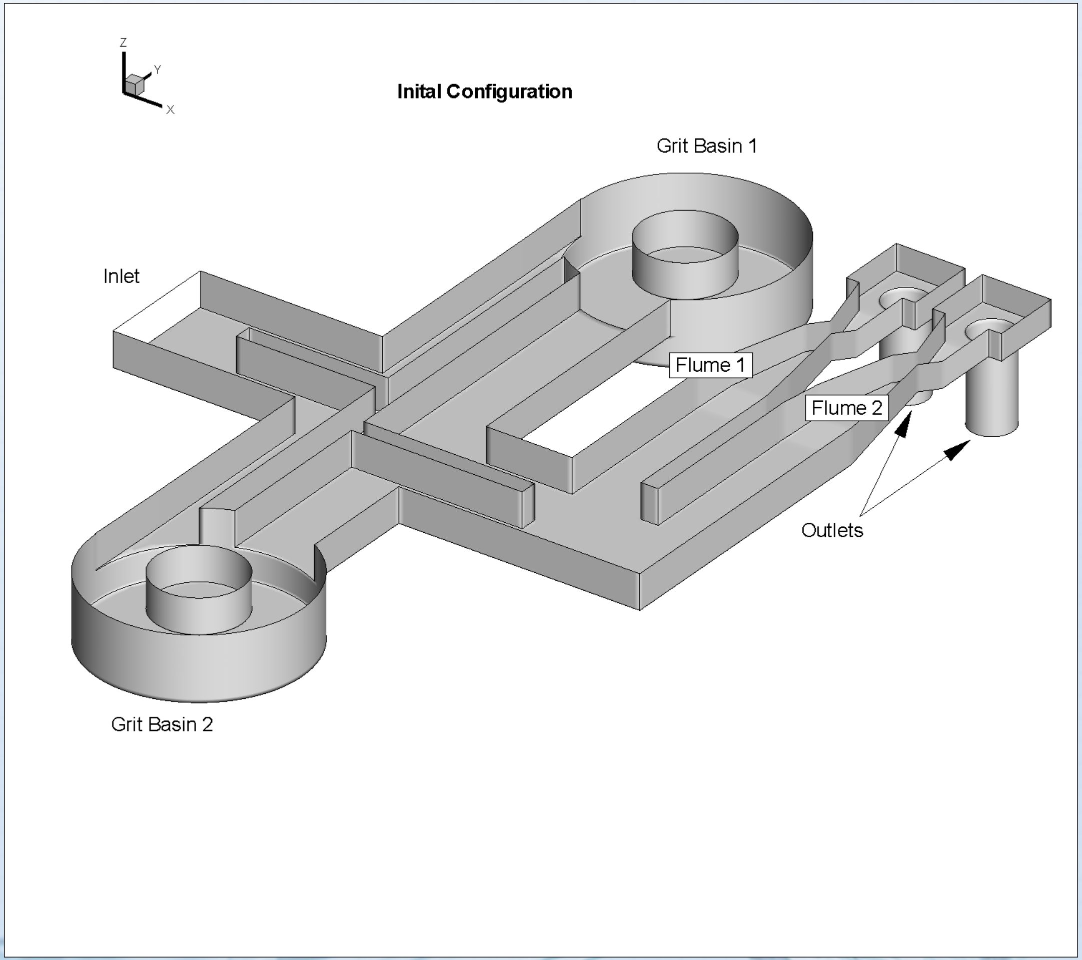
CFD can optimize design

- Screen channel flow balance
- Screen flow distribution
- Infer grit deposition from velocity profiles



Grit Management

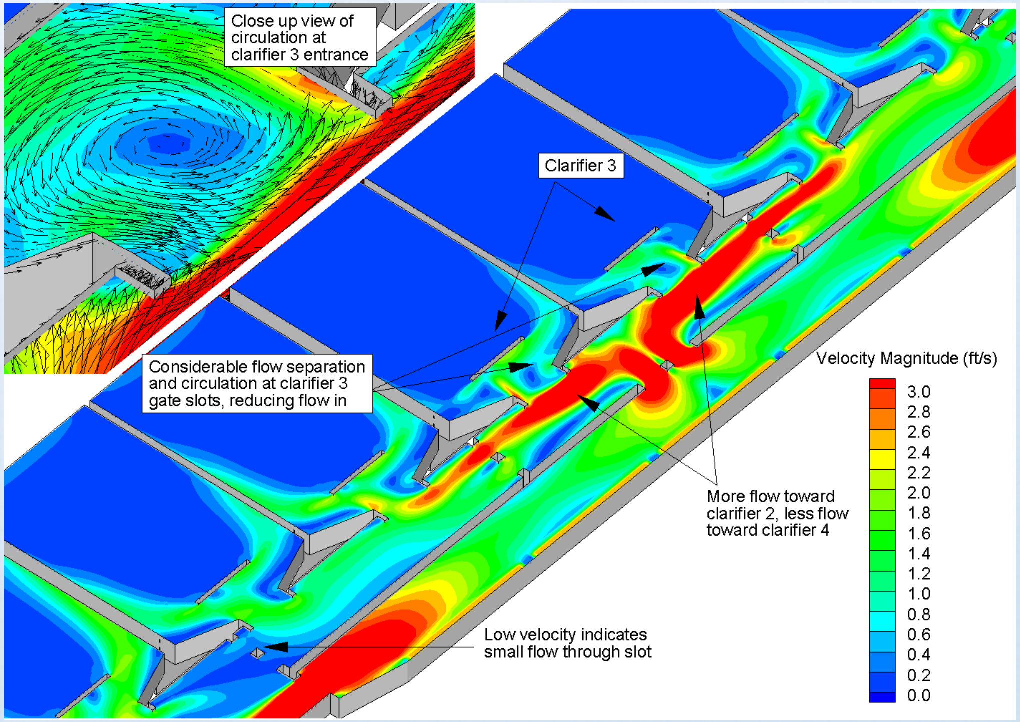
- Vortex grit system efficiency is a function of approach and exit velocity
- Aerated grit tanks require proper sizing and baffling to prevent short circuiting
- Grit deposition can be inferred from velocity profiles and neutral density particle tracking



Flow Splitting

Flow Splitting is critical to optimize the capacity of parallel treatment components

CFD analysis can be rigid lid or free surface



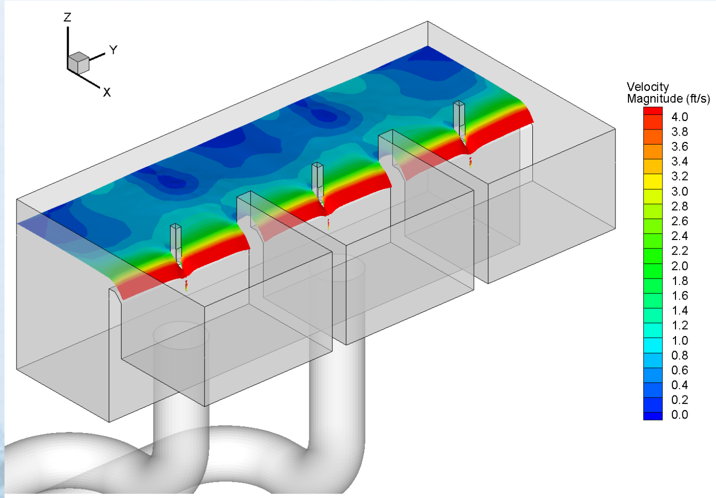
Close up view of circulation at clarifier 3 entrance

Clarifier 3

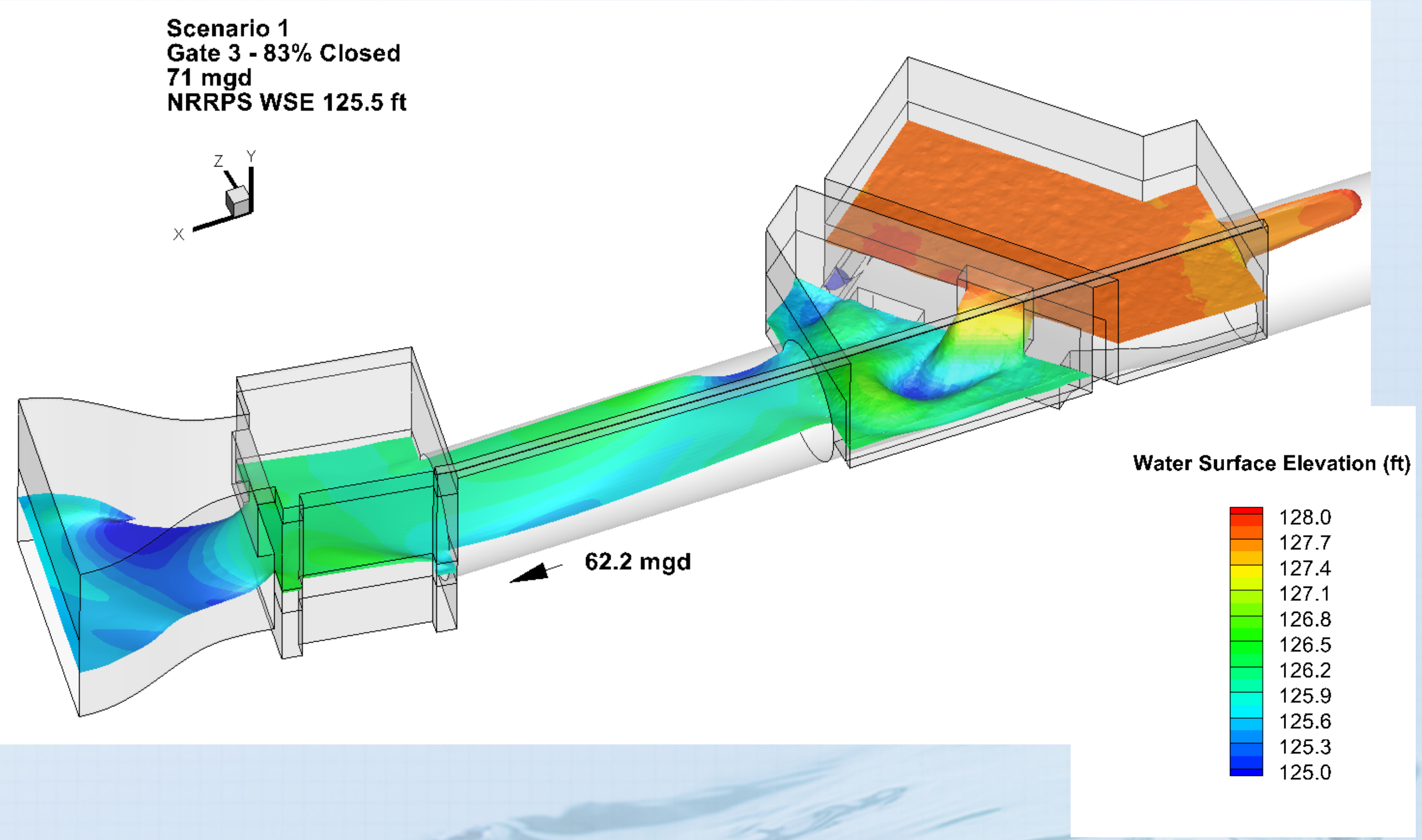
Considerable flow separation and circulation at clarifier 3 gate slots, reducing flow in

More flow toward clarifier 2, less flow toward clarifier 4

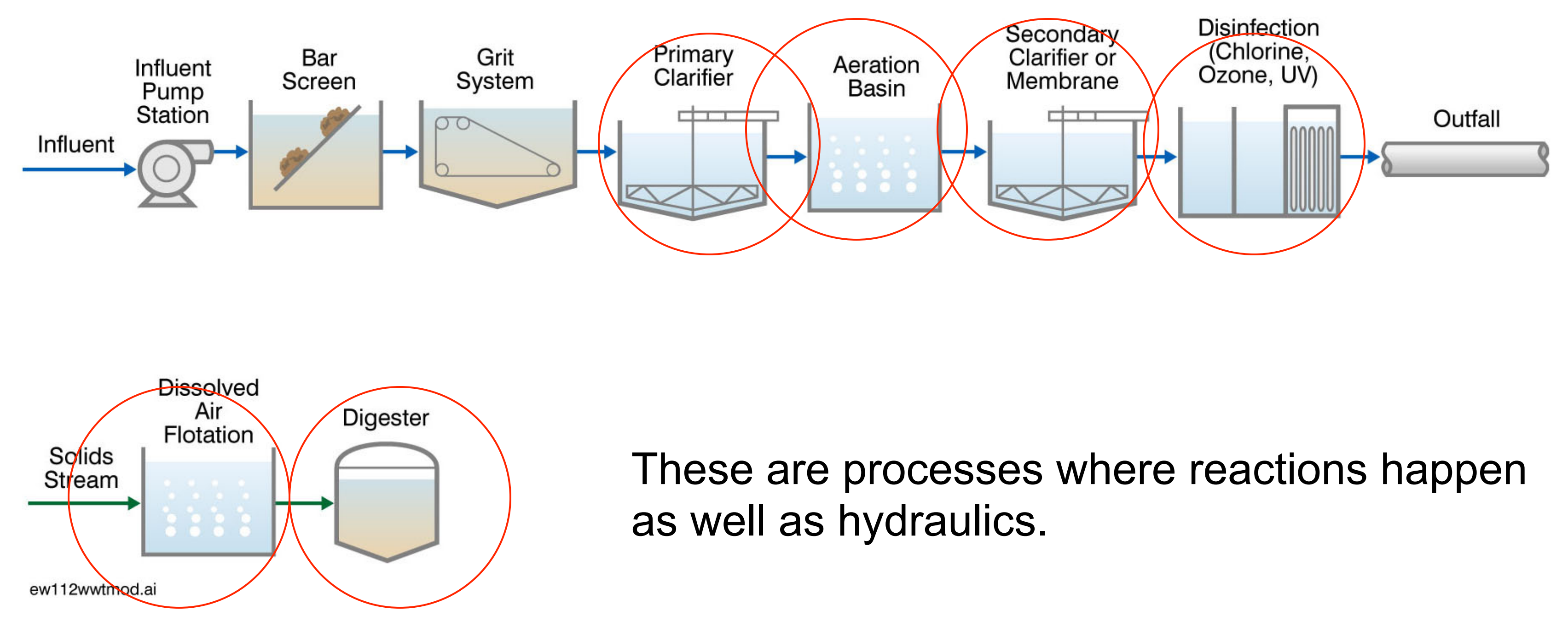
Low velocity indicates small flow through slot



Head losses through complex systems with non-uniform approach conditions can be investigated.



But CFD can also be used for analysis of transport processes.

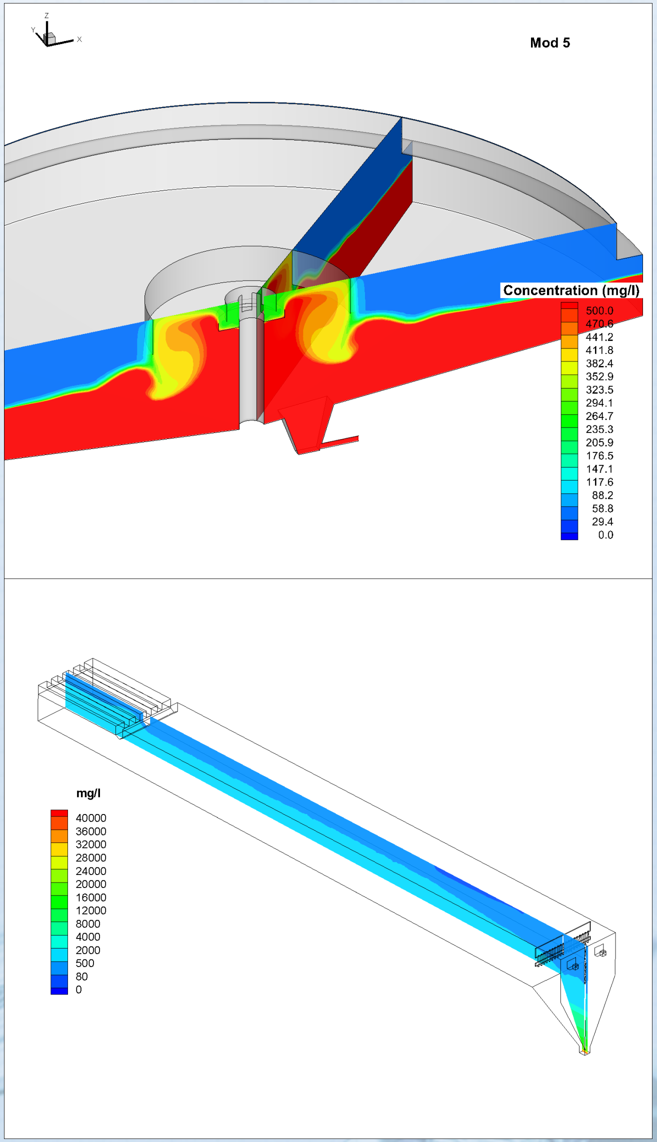


These are processes where reactions happen as well as hydraulics.

Primary Clarification

CFD can be used to investigate geometric influences on solids removal.

CFD can be used to investigate sludge consolidation problems.

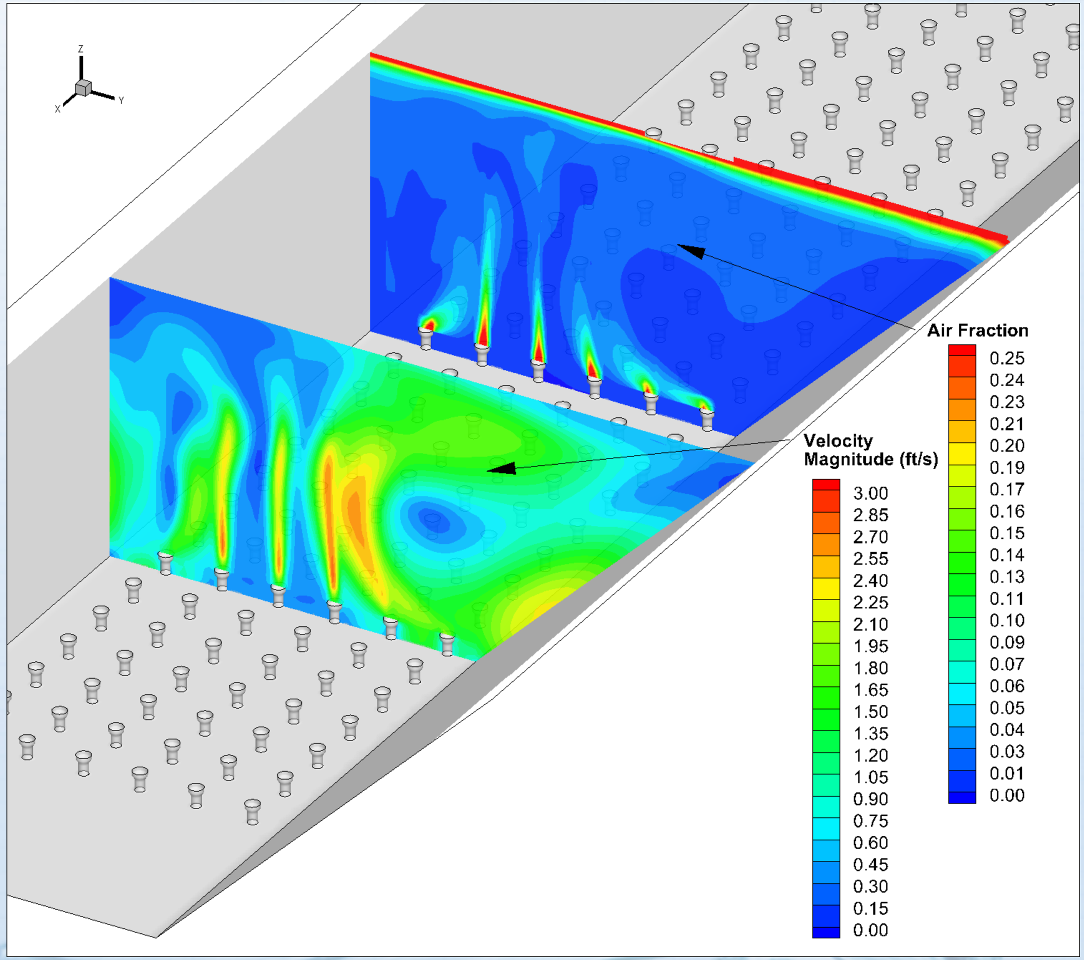


Aeration Tanks

Multiphase modeling can be used to investigate water-air flows.

Dissolved air transfer models can be incorporated.

Solids transport and biokinetic models can be incorporated.



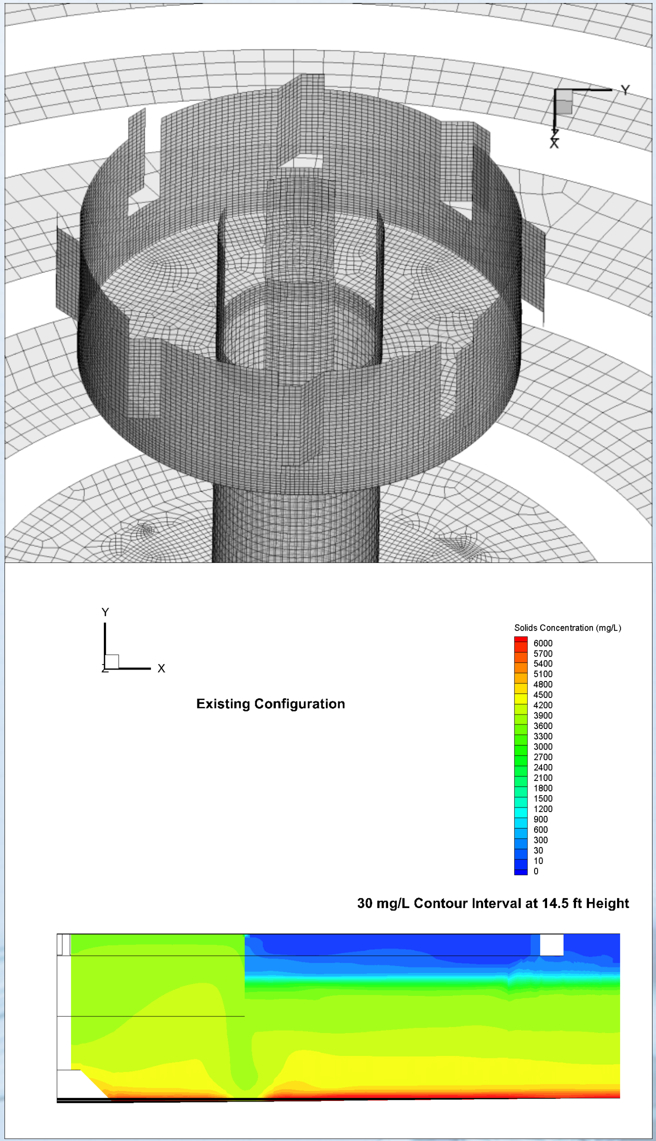
Secondary Sedimentation

Clarifiers require effective inlet energy dissipation.

Baffles can aid in sedimentation.

Density currents dominate flow field, therefore a custom transport model is required.

CFD analysis of activated sludge sedimentation is very well established.

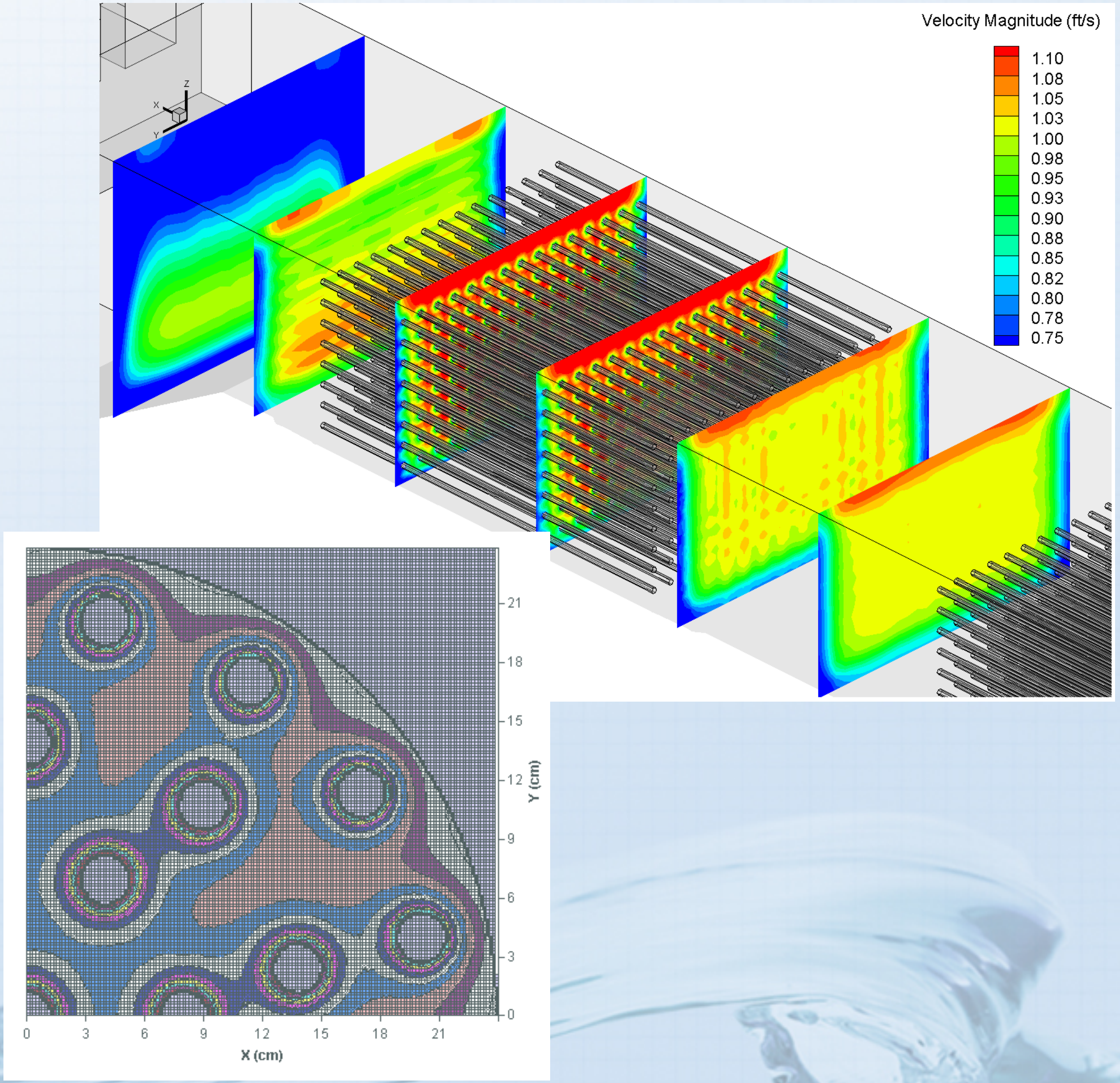


Disinfection - UV

Hydraulics are critical:

- Flow split between trains
- Flow distribution
- Head losses

Dose models can be incorporated when developing new designs.



Mixing Systems

Mixing Used When:

- Combining Fluid Streams
- Chemical Additions
- Minimizing Stagnation

Typical Mixing Systems

- Natural Diffusion
- Passive Baffles
- Aeration
- Mechanical
- Pumped Jets

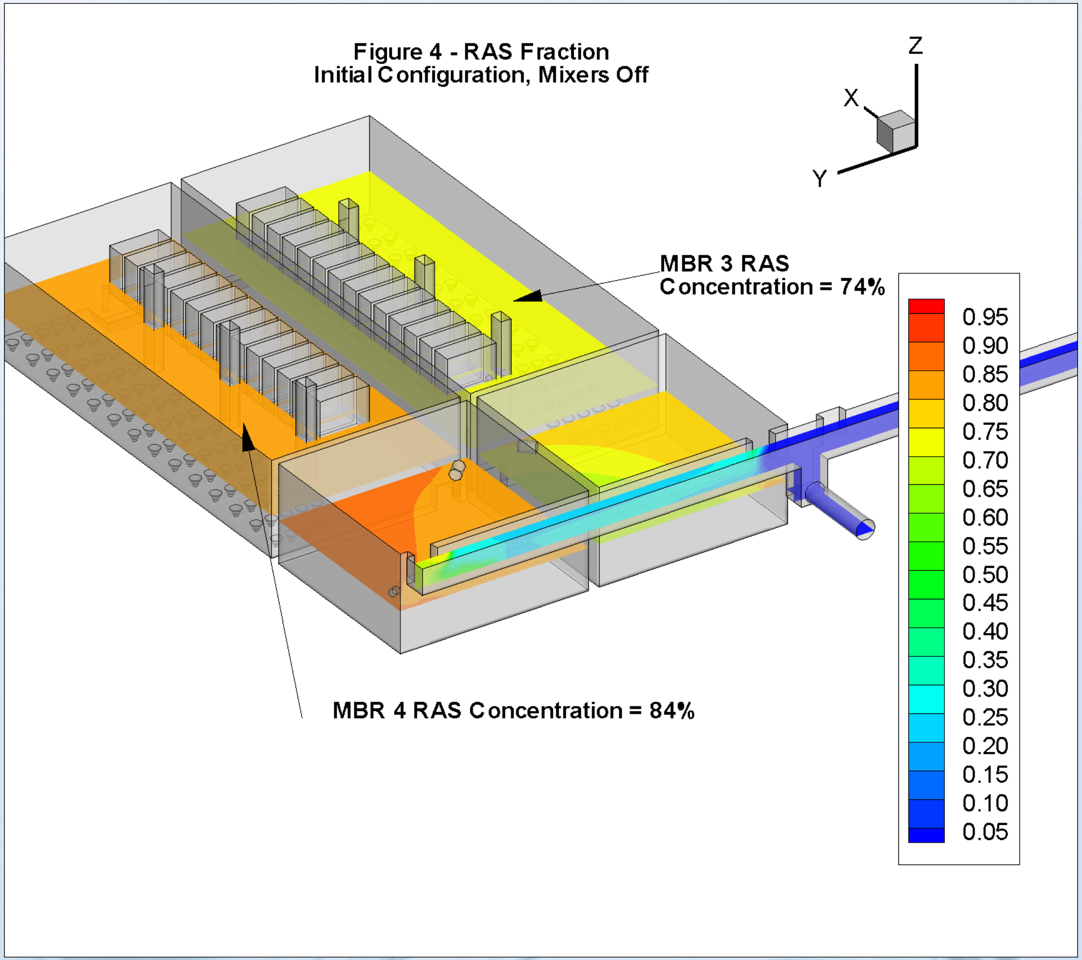


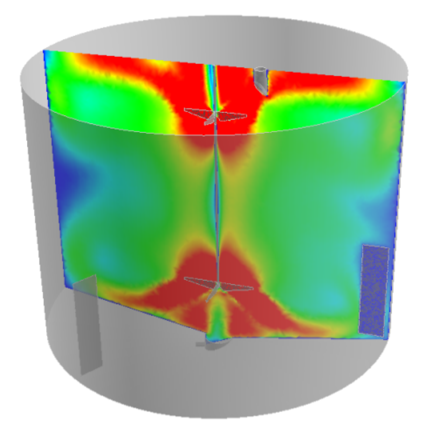
Figure 4 - RAS Fraction
Initial Configuration, Mixers Off

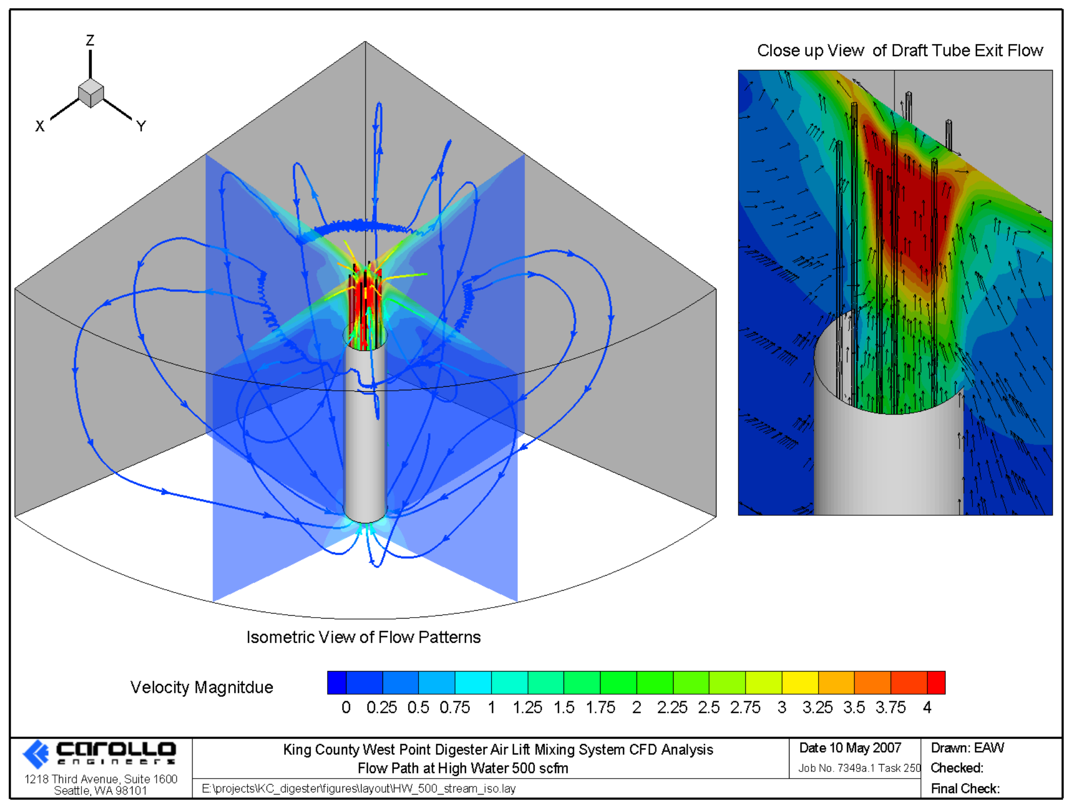
MBR 3 RAS Concentration = 74%

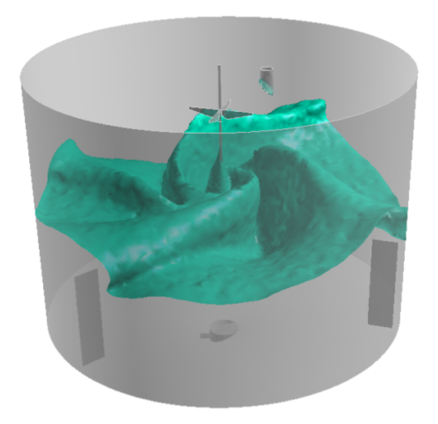
MBR 4 RAS Concentration = 84%

Digesters

- Good mixing is critical to performance
  - Improved kinetics → more gas production
  - Reduces foaming
  - Efficient mixing saves power







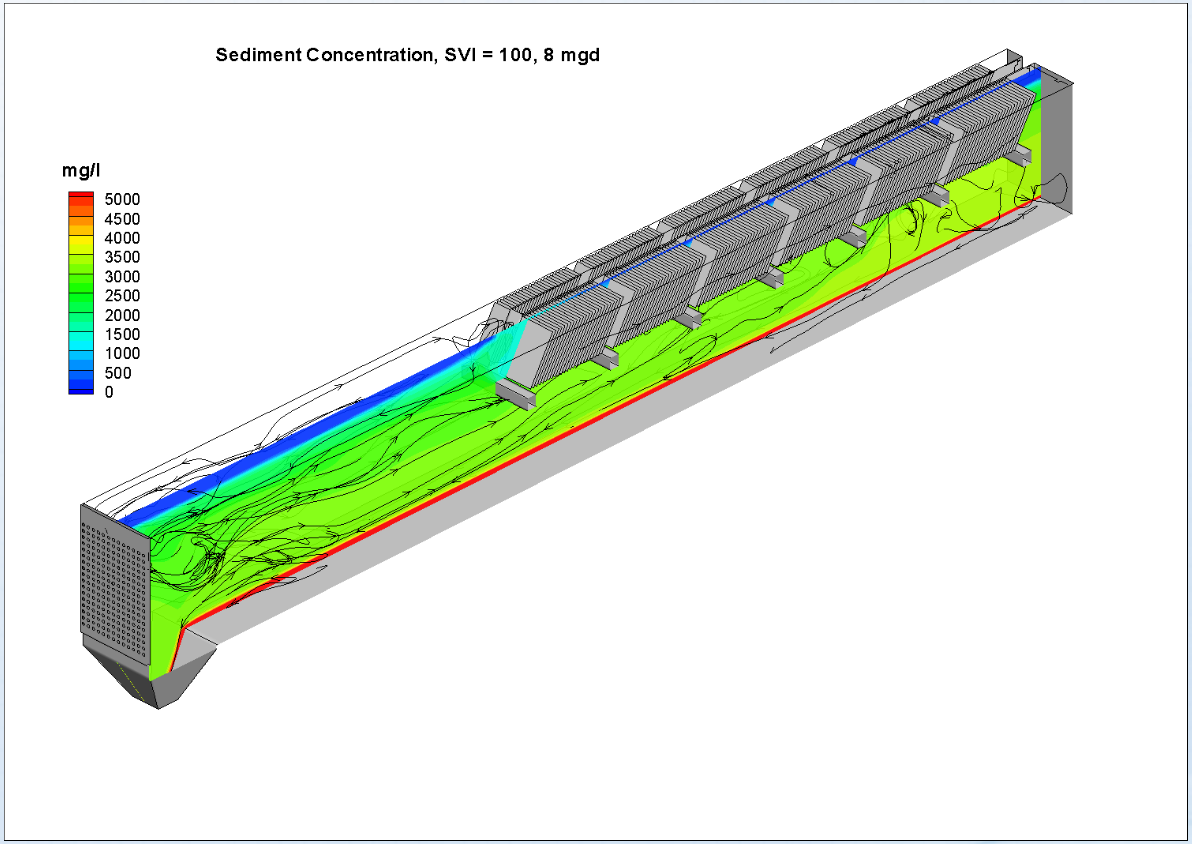
Case Studies Using Transport Modeling

Activated sludge lamella clarifiers

Use of UDF model to evaluate sedimentation inlets

Use of UDF models to evaluate activated sludge mixing

Sedimentation Case Study:
Activated Sludge Lamellas*

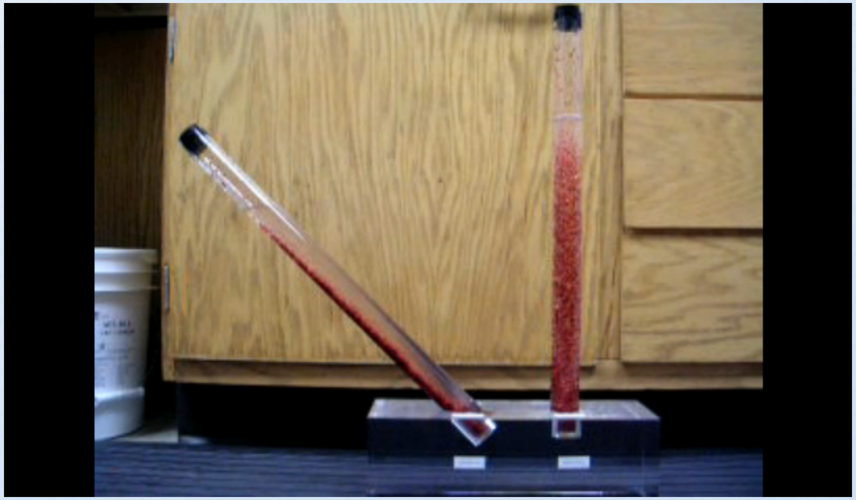


*Samstag, Wicklein, Lee (2012)

The Boycott Effect has been used as the basis for the PNK theory.

Boycott (1920) observed a difference in apparent batch settling rate of blood in slanted tubes.

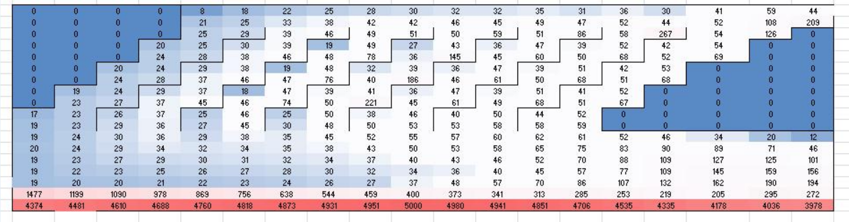
PNK theory: Settling is enhanced by the ratio of the projected area of inclined plates or tubes.



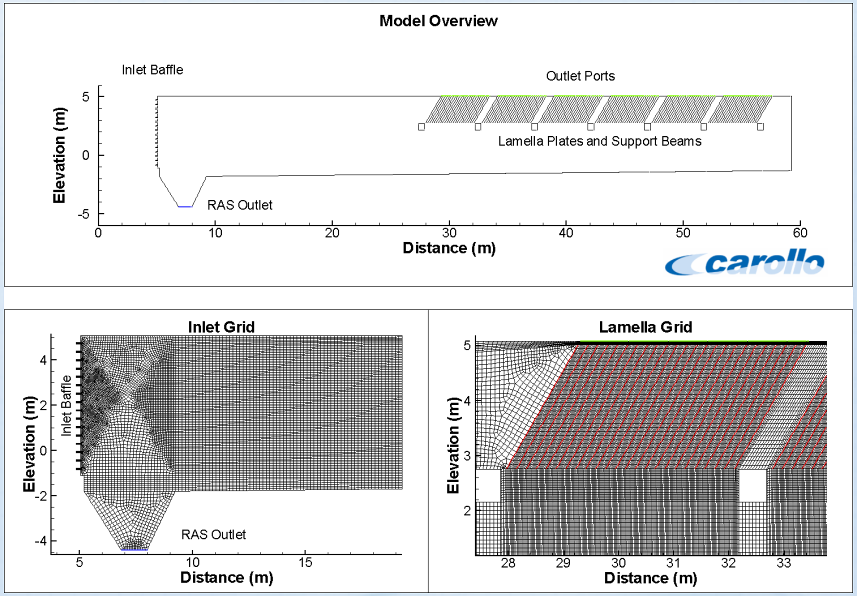
Does this apply to flow-through activated sludge lamella clarifiers?

Coarse Grid Custom Model

2D and 3D Commercial Models

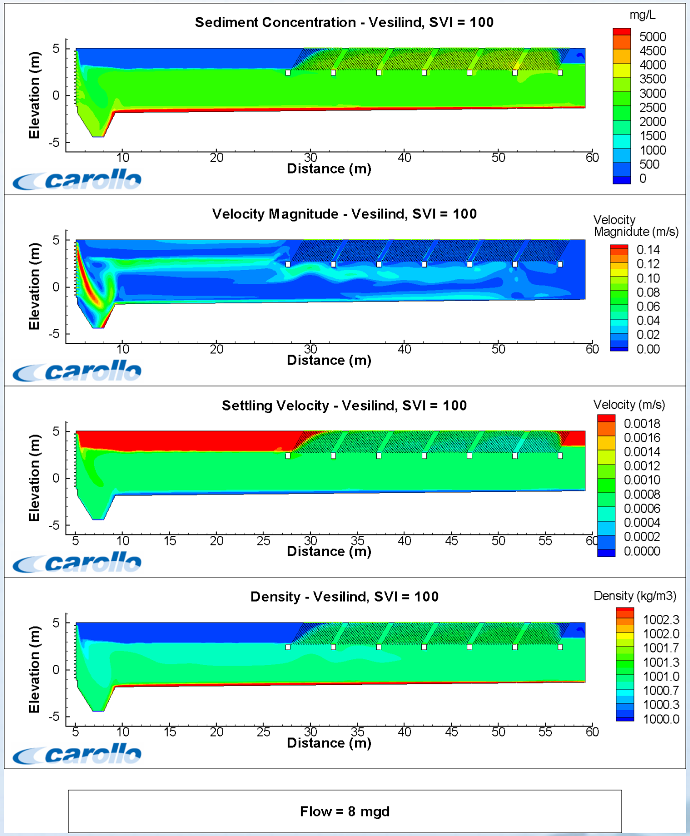


0	0	0	0	8	18	22	25	28	30	32	32	35	31	36	30	41	59	44
0	0	0	0	21	25	33	38	42	42	46	45	49	47	52	44	52	108	209
0	0	0	0	25	29	39	46	49	51	50	59	51	86	58	267	54	126	0
0	0	0	20	25	30	39	19	49	27	43	36	47	39	52	42	54	0	0
0	0	0	24	28	38	46	48	78	36	145	45	60	50	68	52	69	0	0
0	0	20	24	29	38	19	48	32	39	36	47	39	51	42	53	0	0	0
0	0	24	28	37	46	47	76	40	186	46	61	50	68	51	68	0	0	0
0	19	24	29	37	18	47	39	41	36	47	39	51	41	52	0	0	0	0
0	23	27	37	45	46	74	50	221	45	61	49	68	51	67	0	0	0	0
17	23	26	37	25	46	25	50	38	46	40	50	44	52	0	0	0	0	0
19	23	29	36	27	45	30	48	50	53	53	58	58	59	0	0	0	0	0
19	24	30	36	29	38	35	45	52	55	57	60	62	61	52	46	34	20	12
20	24	29	34	32	34	35	38	43	50	53	58	65	75	83	90	89	71	46
19	23	27	29	30	31	32	34	37	40	43	46	52	70	88	109	127	125	101
19	22	23	25	26	27	28	30	32	34	36	40	45	57	77	109	145	159	156
19	20	20	21	22	23	24	26	27	37	48	57	70	86	107	132	162	190	194
1477	1199	1090	978	869	756	638	544	459	400	373	341	313	285	253	219	205	295	272
4374	4481	4610	4688	4760	4818	4873	4931	4951	5000	4980	4941	4851	4706	4535	4335	4178	4036	3978



Results: No difference between tanks with and without lamella plates!

With lamella plates


Sediment Concentration - Vesilind, SVI = 100

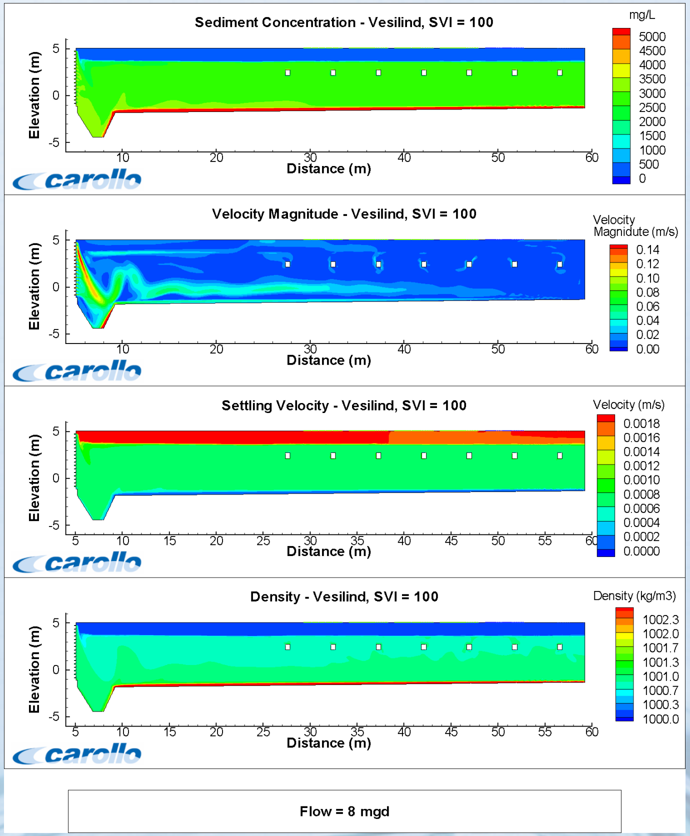
Velocity Magnitude - Vesilind, SVI = 100

Settling Velocity - Vesilind, SVI = 100

Density - Vesilind, SVI = 100

Flow = 8 mgd

Without lamella plates


Sediment Concentration - Vesilind, SVI = 100

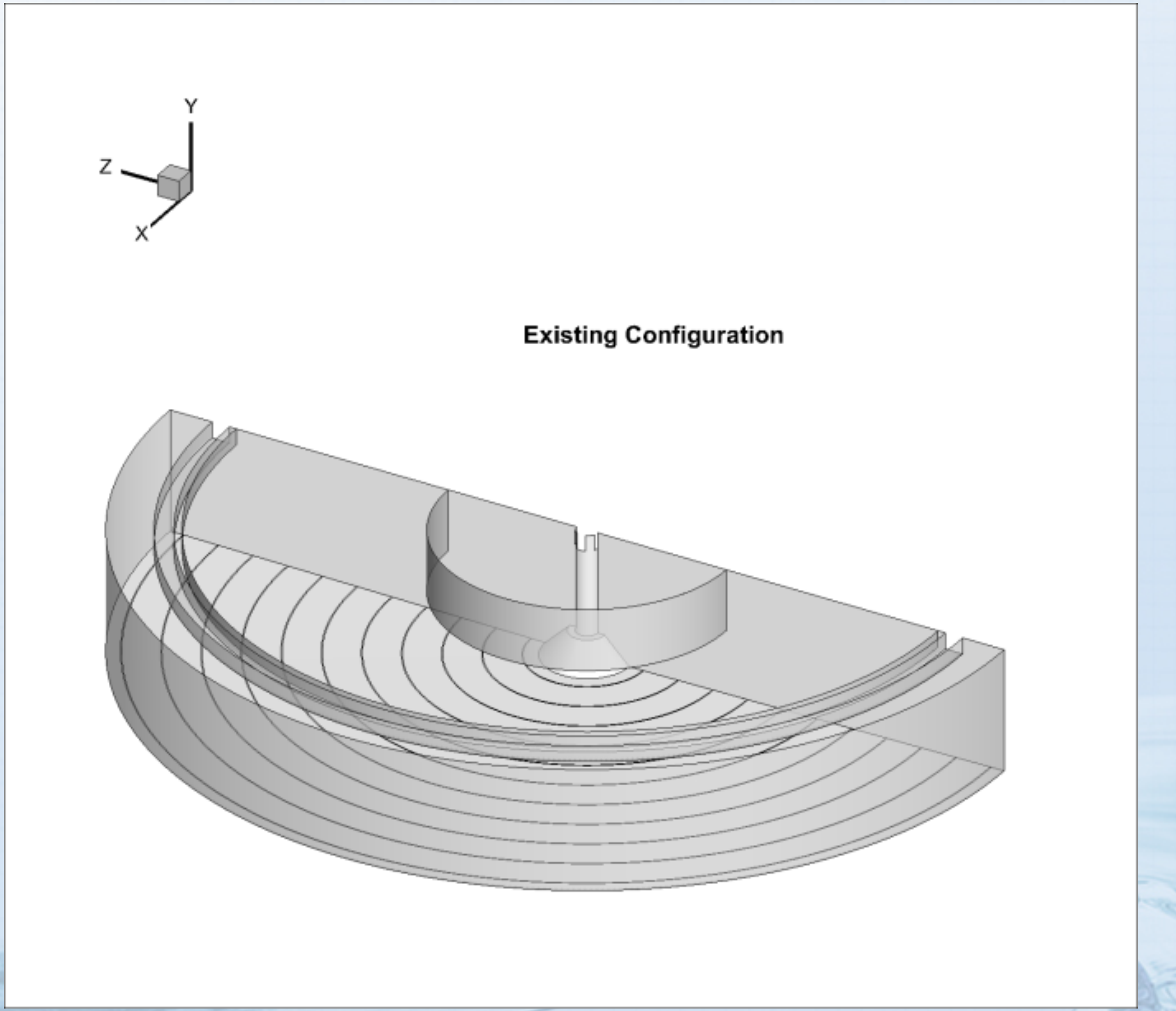
Velocity Magnitude - Vesilind, SVI = 100

Settling Velocity - Vesilind, SVI = 100

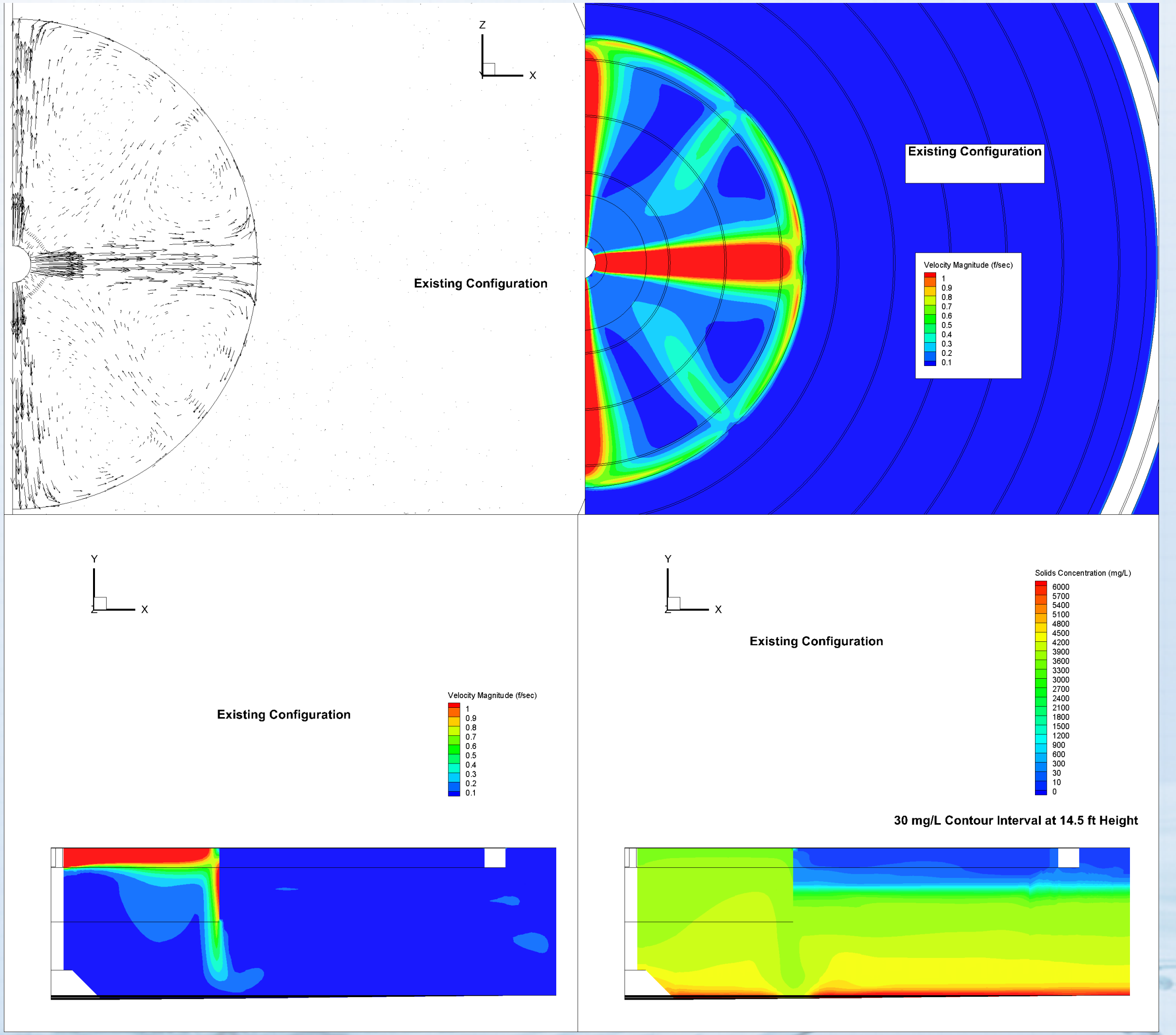
Density - Vesilind, SVI = 100

Flow = 8 mgd

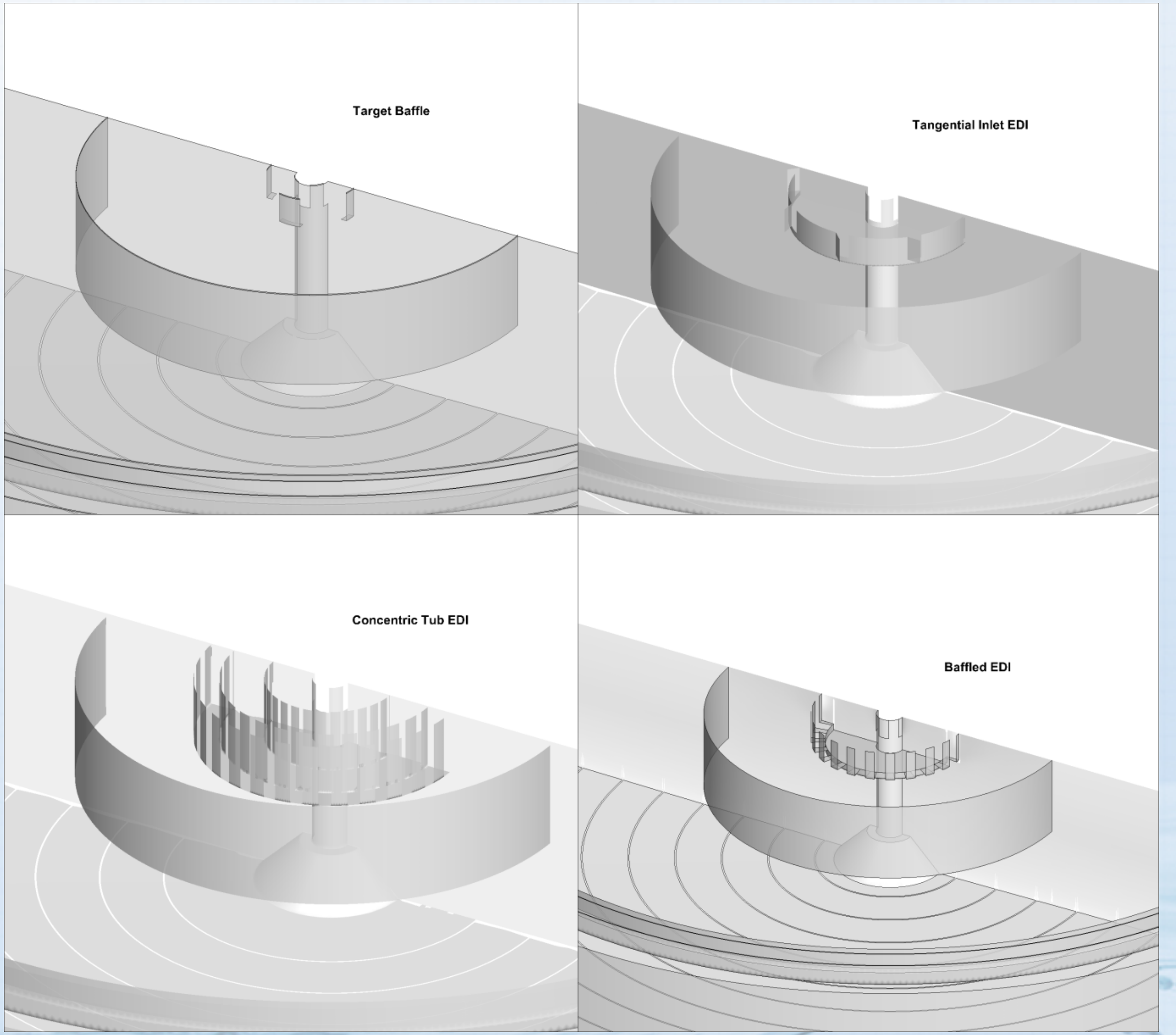
Sedimentation Case Study: Clarifier Inlet Comparison
Existing Configuration



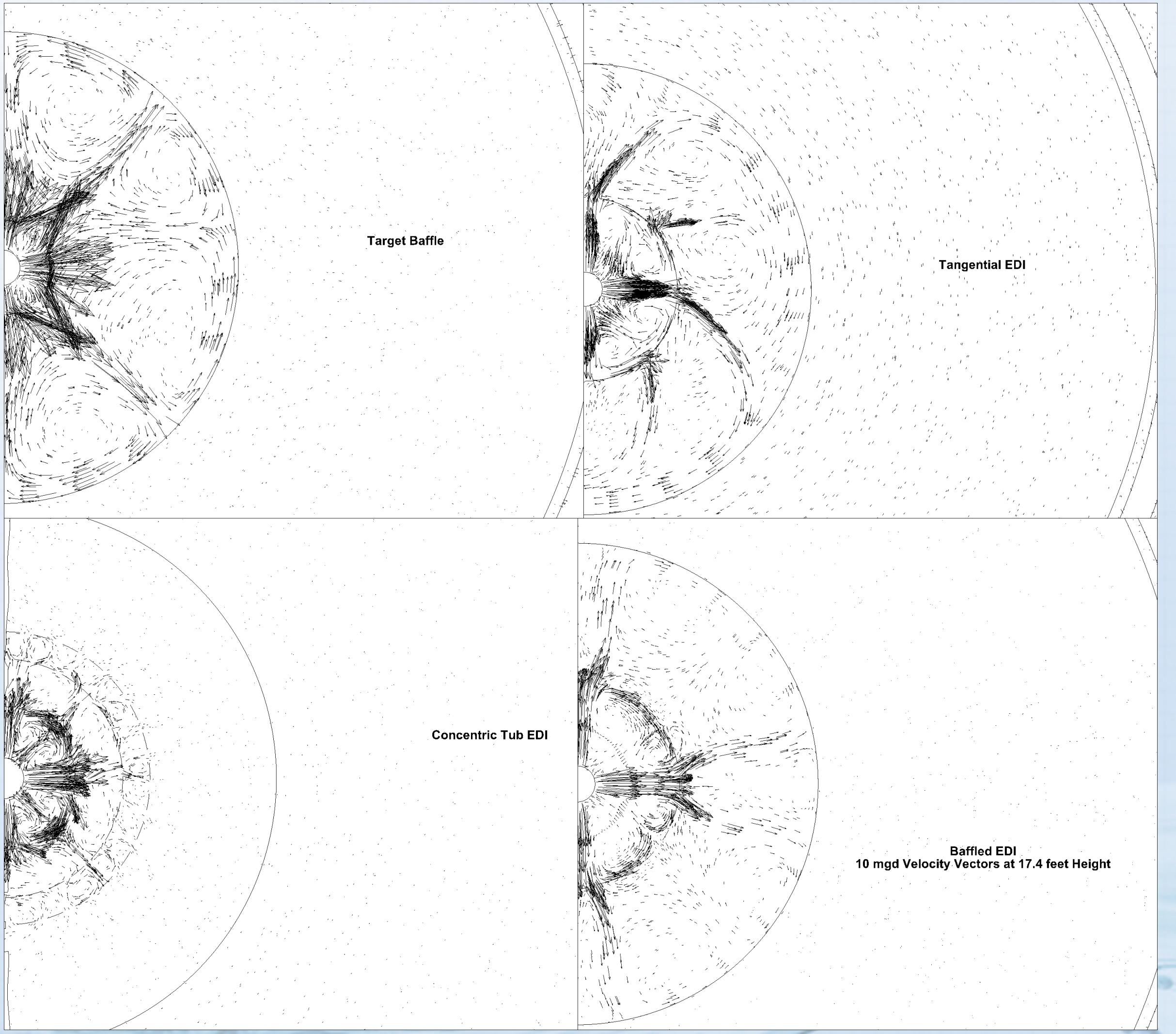
Clarifier Inlet Comparison
Existing Configuration



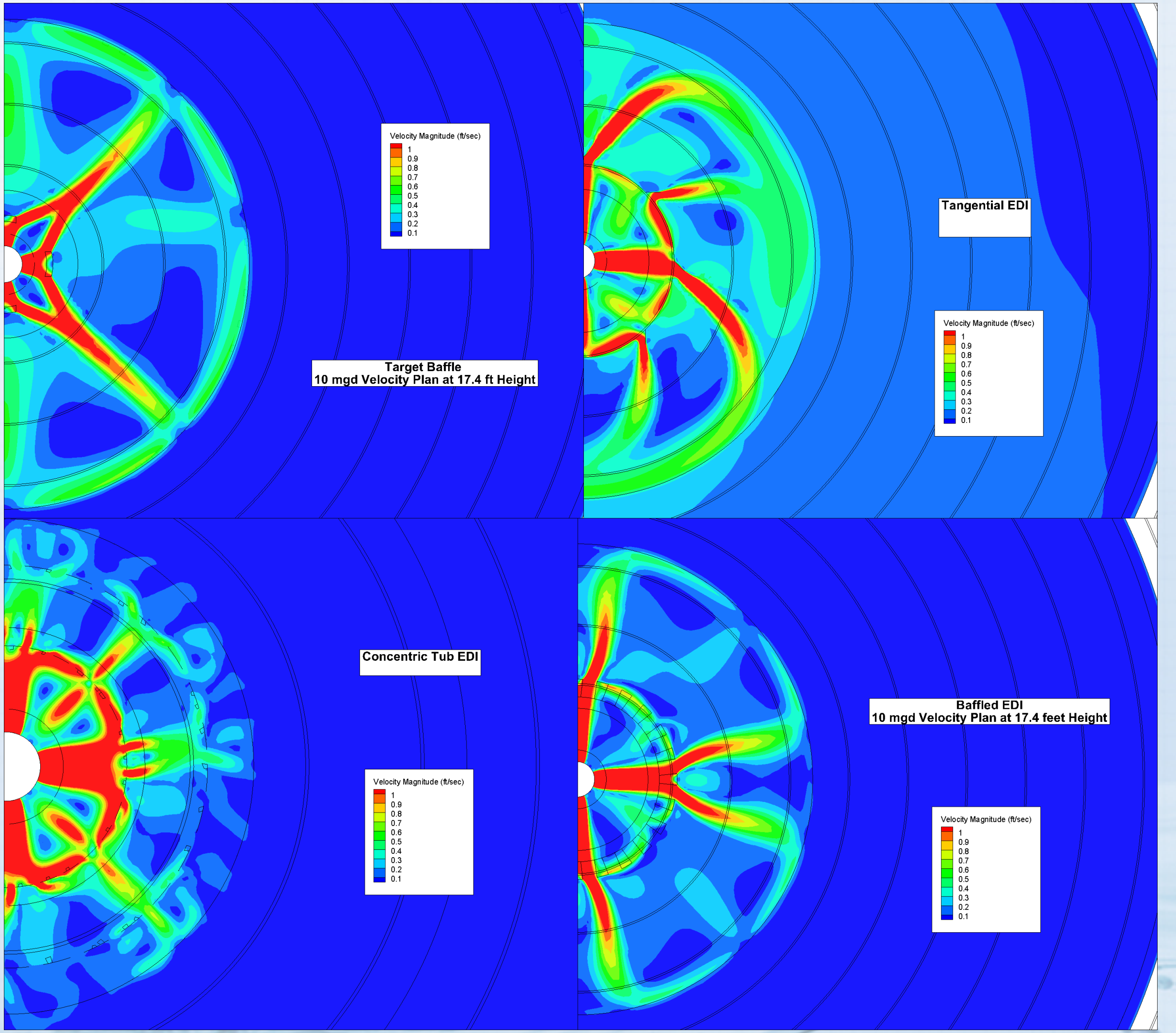
Alternative Inlet Configurations



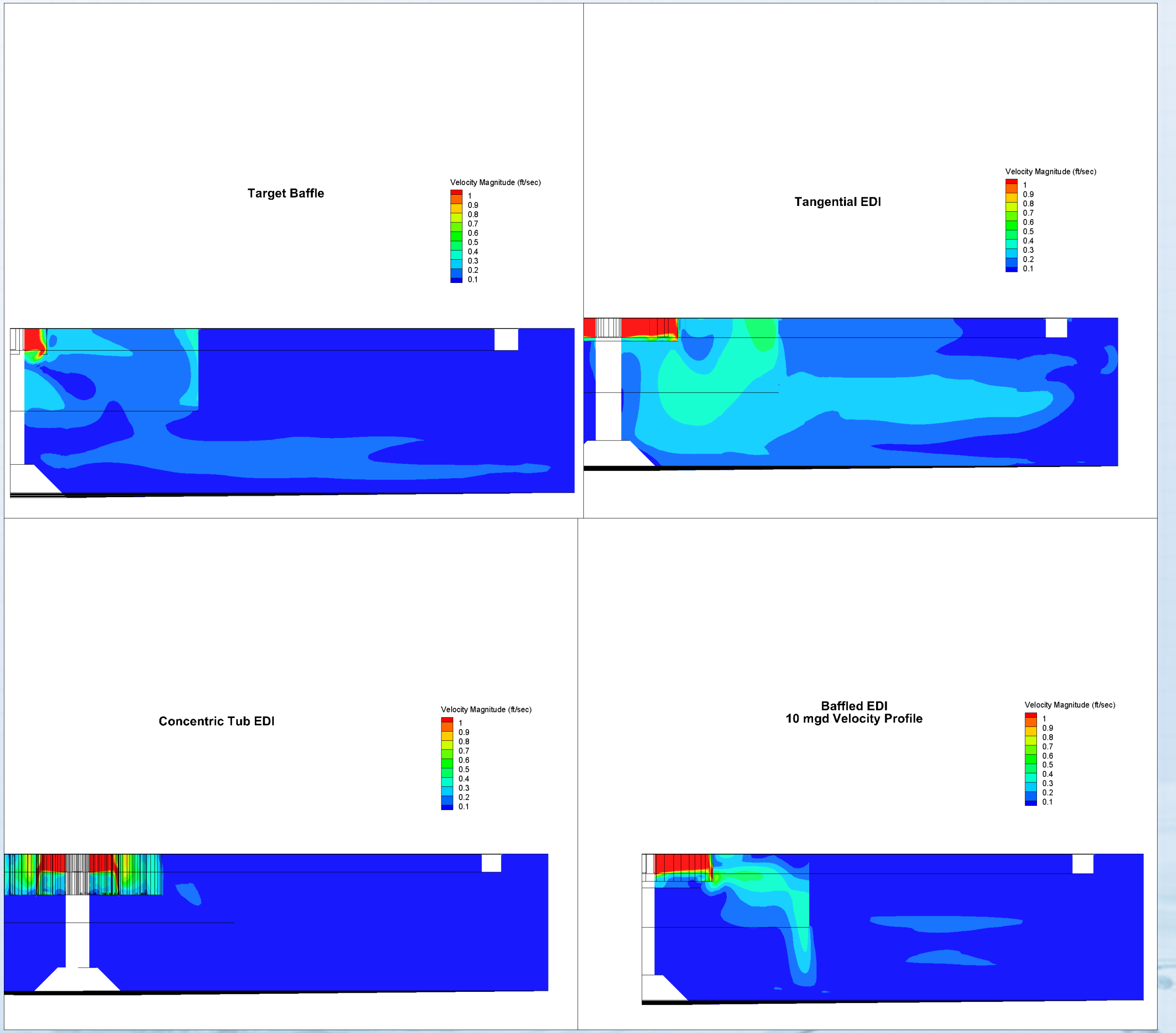
Alternative Velocity Vector Plans



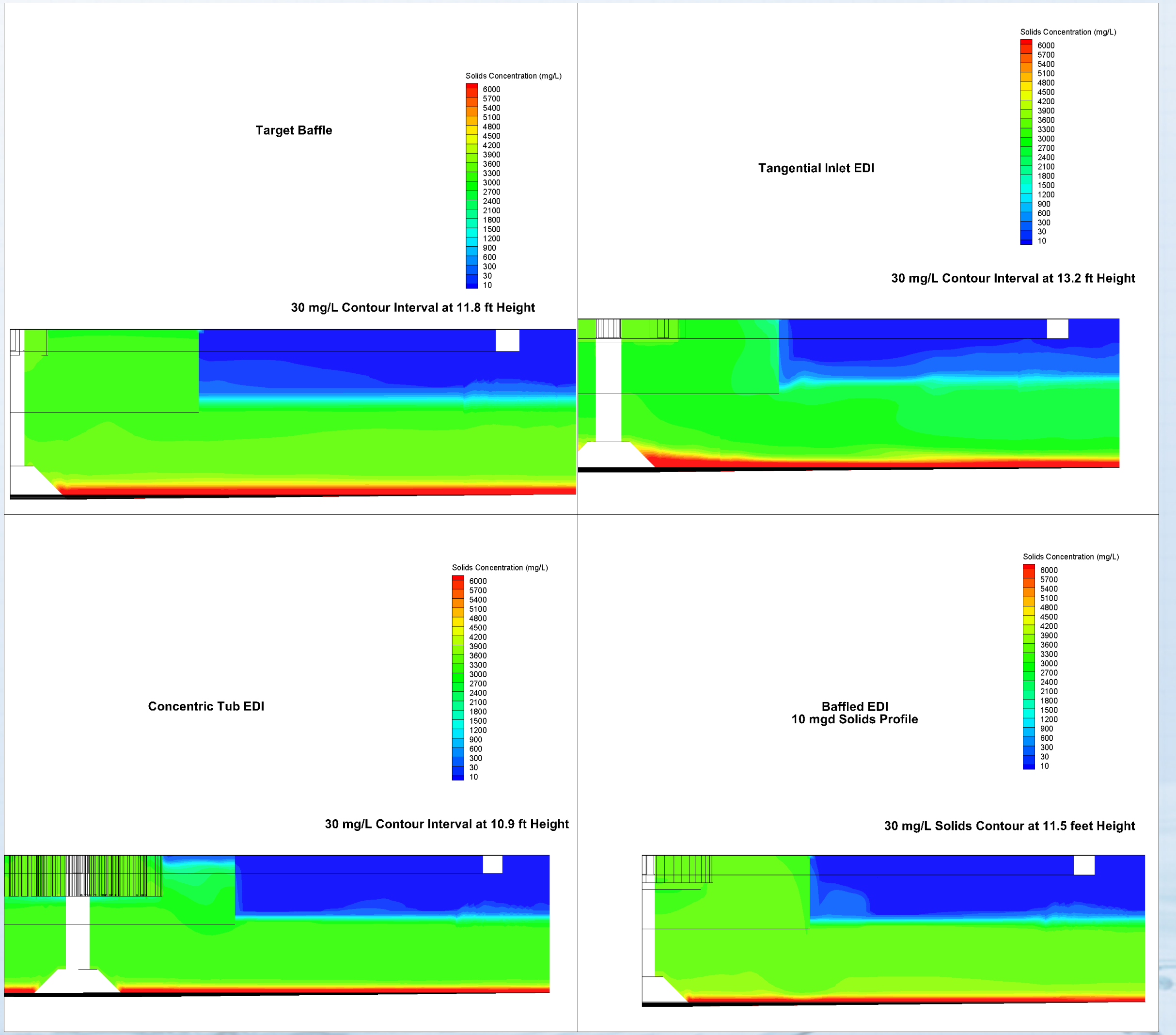
Alternative Velocity Plans



Alternative Velocity Profiles



Comparison Solids Profiles



Mixing Case Study:

Jet mixing and aeration in a sequencing batch reactor (SBR)*

415,350 mixed tetrahedral cells

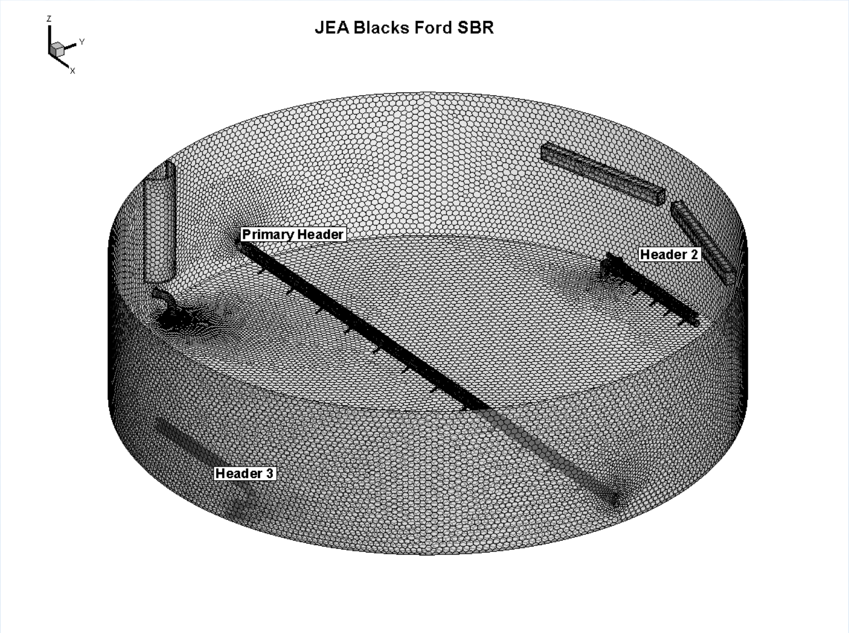
2,108,308 nodes

Inlet flow into jet nozzles

Outlet flow to pump suction

Air added as second phase

Solids transport, settling, and density impact modeled by UDF

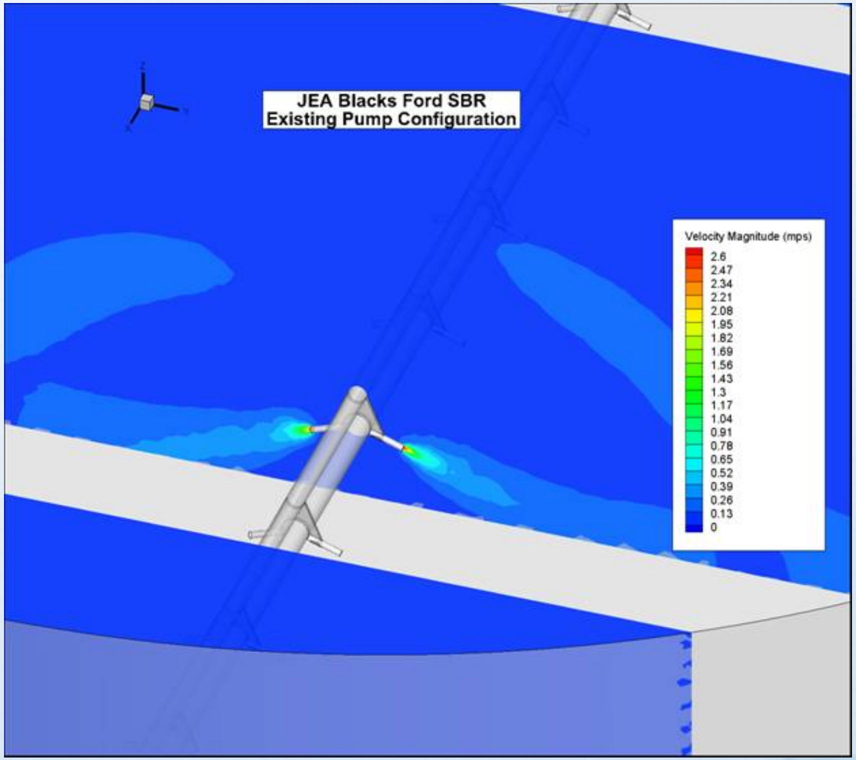


Mesh projected onto model surfaces.

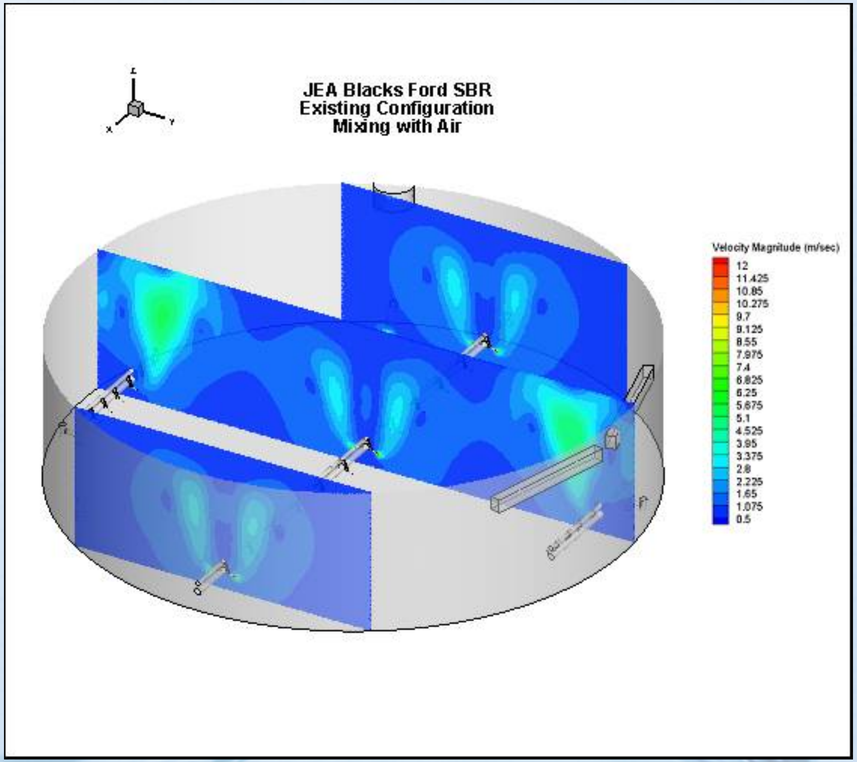
*Samstag, Wicklein, et al. (2012)

Velocity profiles for pumped mixing and aeration

Simulated Pumped Mixing Profile

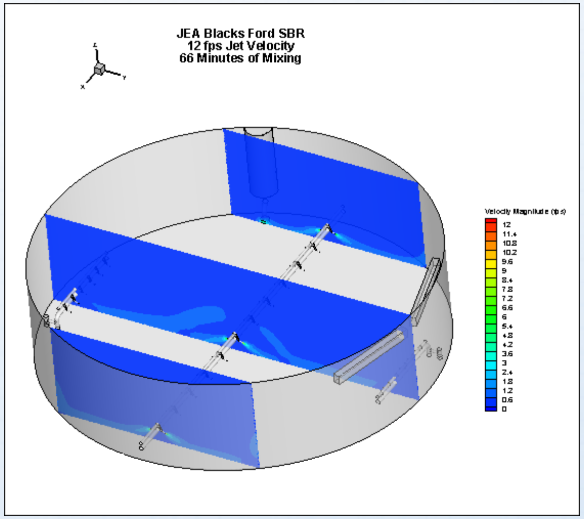


Simulated Aeration Profile

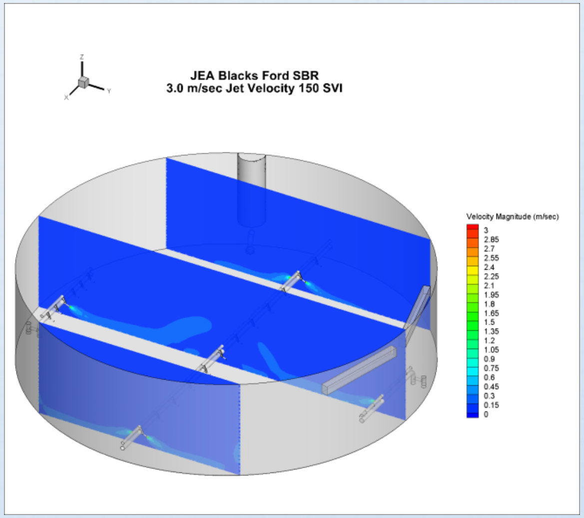


Comparison of pumped mix velocity profiles for increasing jet velocities

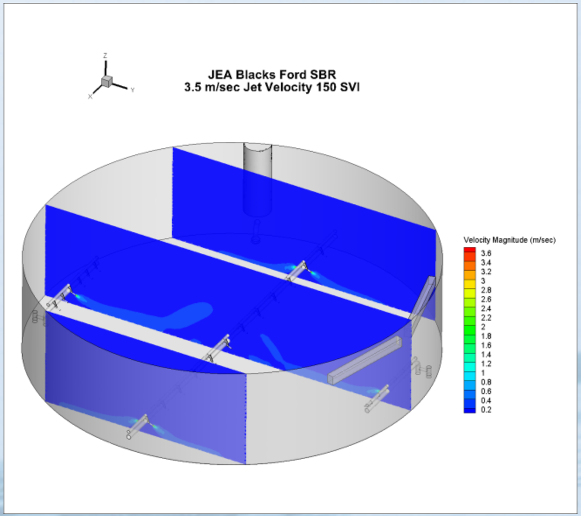
Existing (2.5 m/ sec Jet)



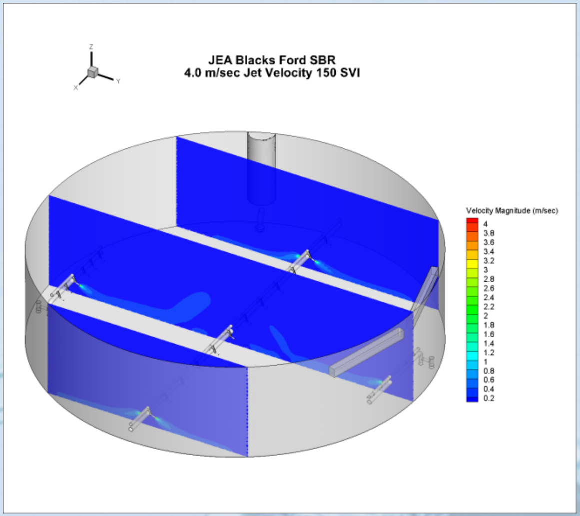
3.0 m/ sec Jet



3.5 m/ sec Jet

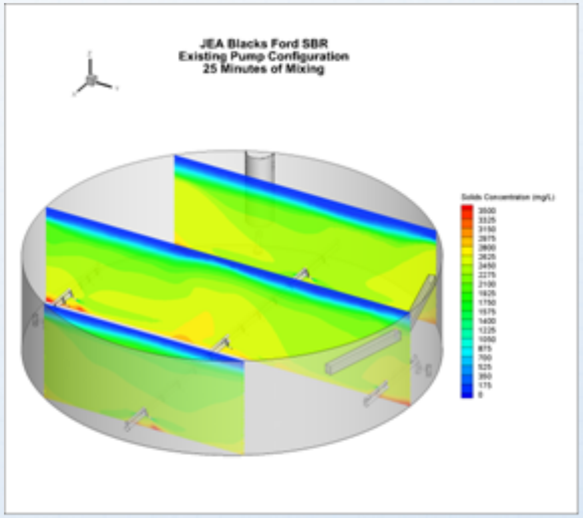


4.0 m/ sec Jet

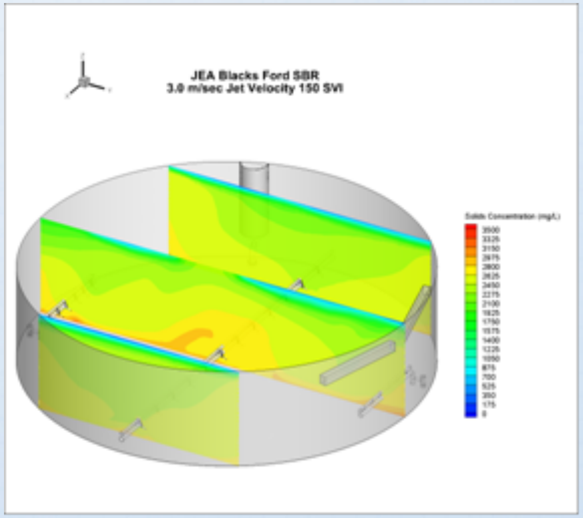


Comparison of solids profiles for increasing jet velocities

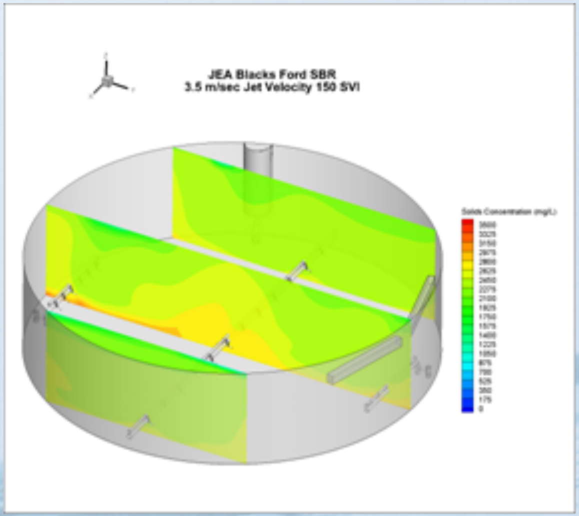
Existing (2.5 m/ sec Jet)



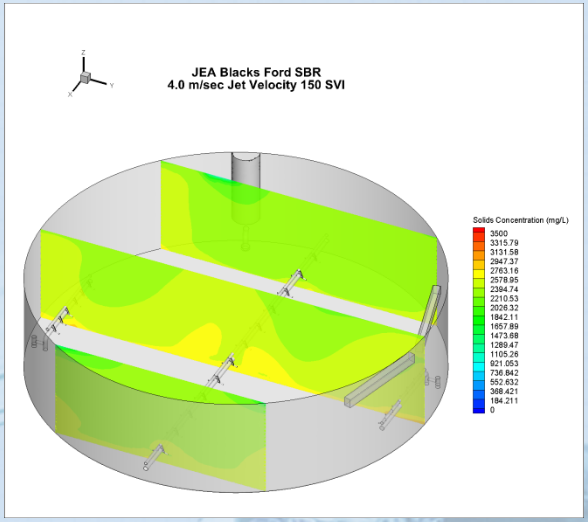
3.0 m/ sec Jet



3.5 m/ sec Jet



4.0 m/ sec Jet



Min / Max Deviations from Average

	Average TSS Concentration (mg/L)			
Layer	2.5 m/sec	3.0 m/sec	3.5 m/sec	4.0 m/sec
Top	1,208	1,404	2,102	2,155
2	2,385	2,331	2,280	2,285
3	2,519	2,374	2,322	2,308
4	2,538	2,422	2,448	2,387
5	2,554	2,518	2,526	2,443
6	2,604	2,620	2,511	2,456
Bottom	3,008	2,806	2,559	2,500
Average	2,402	2,353	2,392	2,362
Max Deviation From Average (%)	50%	40%	12%	9%

Comparison of Power Levels at Different Jet Velocities

Jet Velocity	Mix Criterion	Power Level (hp/MG)	Power Level (W/m^3)
2.5 m/sec jet velocity	50% Max Deviation	39	7.7
3.0 m/sec jet velocity	40% Max Deviation	66	13.0
3.5 m/sec jet velocity	12% Max Deviation	105	20.7
4.0 m/sec jet velocity	< 10% Max Deviation	156	30.8

To meet a 10 percent deviation criterion would require four times more power than currently installed.

Comparison of Power Levels to Other Mixing Devices

Mixer	Reference	Mix Criterion	Power Level (hp/MG)	Power Level (W/m^3)
4.0 m/sec jet	This study	< 10% Max Deviation	156	30.8
Large Propeller in Racetrack	Carollo Field Visit	Little MLSS separation	5	~1
Surface Mixing Impeller	Carollo Witnessed Test	0.6 m/sec (2 fps) bottom velocity	39	7.6
Hydrofoil mixer	Otun et al. (2009)	< 30% Max Deviation	39	7.6
Hyperboloid mixer	Otun et al. (2009)	< 11% Max Deviation	20	4.0

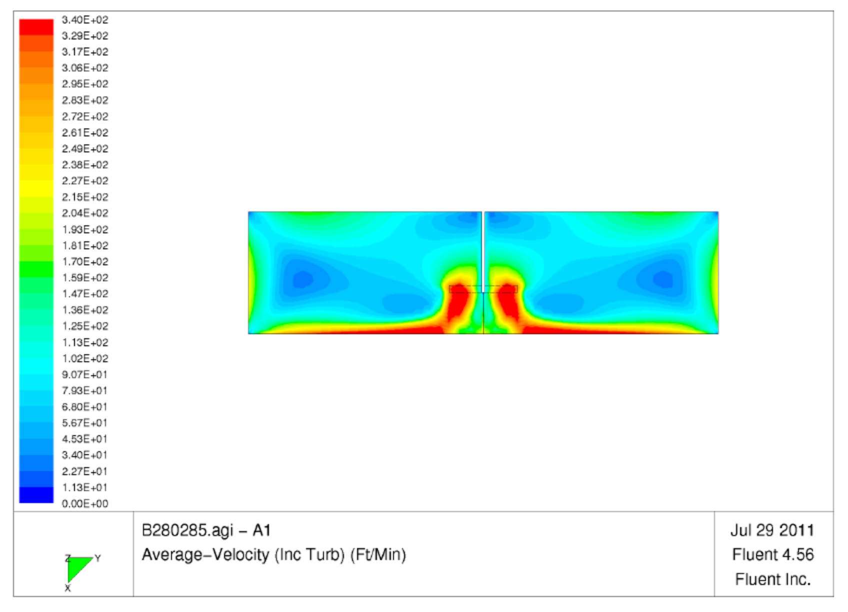
Frequent CFD practice for mixing is to assume neutral density.

The influence of solids on the velocity pattern is ignored.

A velocity profile is then calculated assuming clear water.

It is then assumed that a given minimum velocity (2.5 ft/min) will be sufficient to provide mixing.

But it is SOLIDS that we are trying to mix. They aren't typically modeled.



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Average–Velocity (Inc Turb) (Ft/Min)

Jul 29 2011
Fluent 4.56
Fluent Inc.

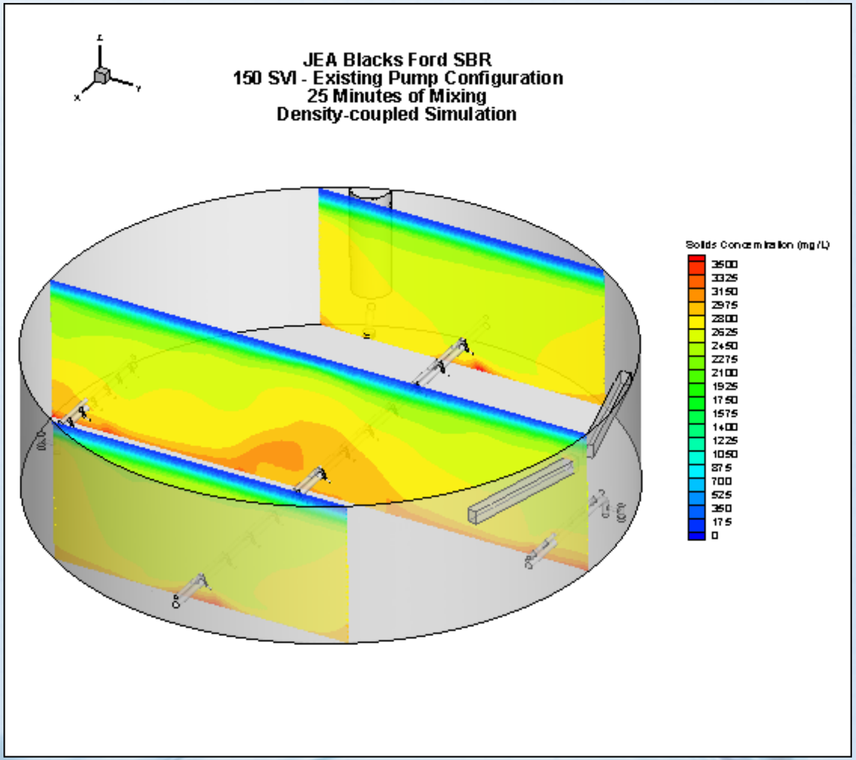
Comparison of density-coupled and neutral density simulations

Density-coupled

Solids transport model calculates the local solids concentration based on flow regime.

The influence of the local solids concentration on the local density is then iteratively calculated.

This approach was verified by the field solids profile test data.



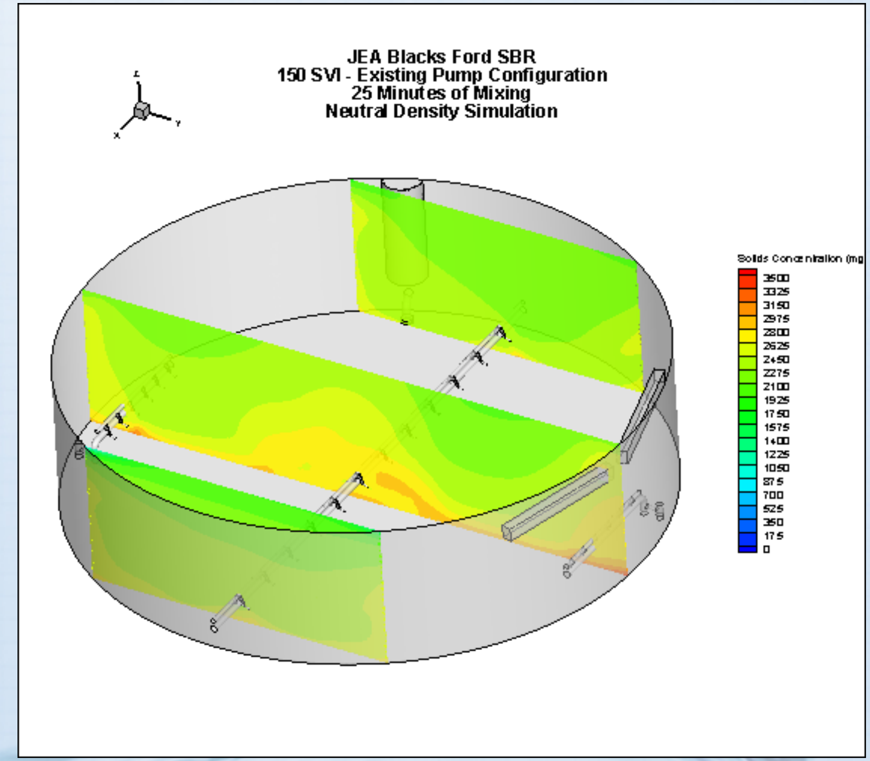
Comparison of density-coupled and neutral density simulations

Neutral Density

Solids transport model calculates the local solids concentration based on flow regime.

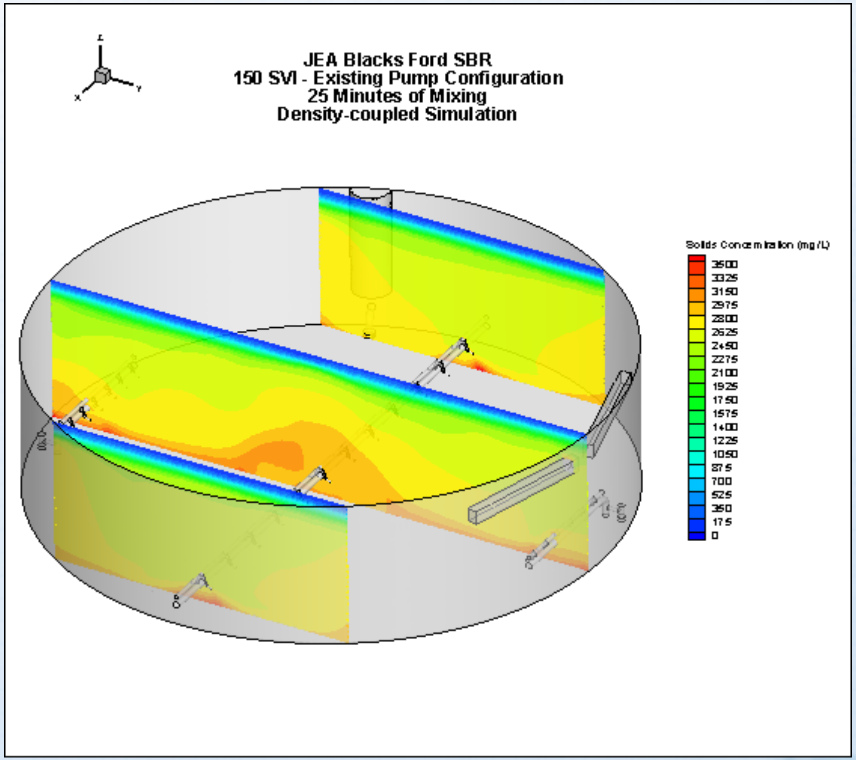
Influence of the local solids concentration on the local density was turned off.

This approach over-predicted measured solids mixing.

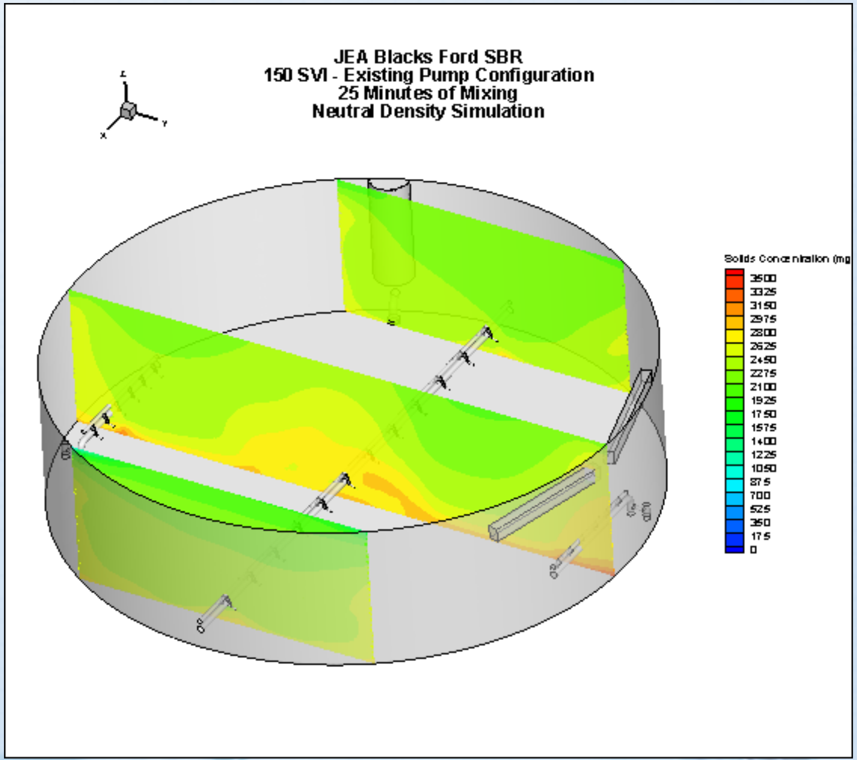


Comparison of density-coupled and neutral density simulations

Density-coupled



Neutral density



Neutral density simulation dramatically over-predicts the degree of mixing.

CFD and Process Engineering
Conclusions

CFD is well established and important for analysis of hydraulic components.

There is growing appreciation that CFD can be a powerful tool for analysis of the impact of geometry and hydrodynamics on process performance.

Results from studies of lamella settlers, radial flow clarifier inlets, and activated sludge mixing show that CFD can establish important conclusions for process engineering.