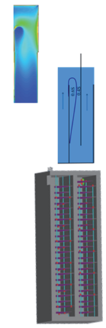
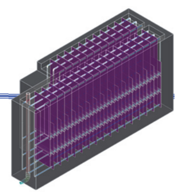
Flocculator Design

Overview

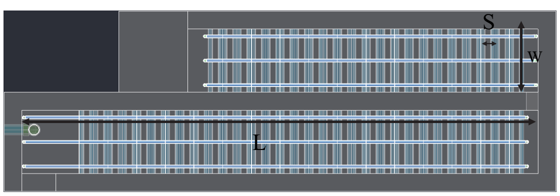
- Analysis of hydraulic flocculators
  - Ratio of maximum to average energy dissipation rate
  - Inefficiency of energy use due to nonuniformity of energy dissipation rate
  - The great transition at H_e/S=5
- Flocculator Design
  - Head loss, collision potential, residence time
  - Geometry of a baffle space to obtain desired energy dissipation rate



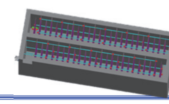
Top View



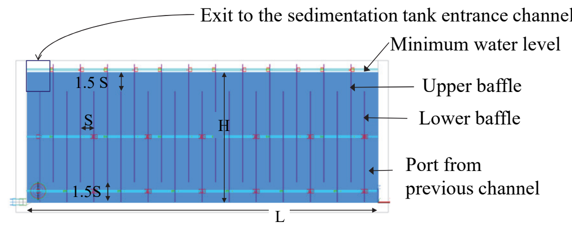
W = Width of the flocculator channel
S = Space <u>between</u> baffles
L = Length of a flocculator channel



Side View

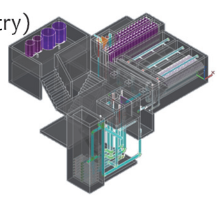


H = Water depth
L = Length of the flocculator channel
S = Space between baffles
T = Thickness of the baffles $S+T=B$
B =Perpendicular center to center distance between baffles



Design Considerations

- The length of the flocculator channels matches the length of the sedimentation tank
- Width of the flocculation channel?
  - Minimum? Human width
  - Material limitations (polycarbonate or concrete)
  - Vary to optimize flocculation efficiency (function of geometry)
- Need to determine
  - Head loss
  - Residence time
  - Baffle spacing
  - Number of baffles

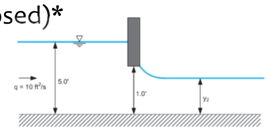


More Design Considerations

- Even number of channels for AguaClara design (to keep chemical dose controller near stock tanks), but this may change if flocculators get smaller
- Even or odd number of baffles depending on channel inlet and outlet conditions
- Begin with the energy source for the turbulence that creates shear that creates collisions: head loss for a baffle

Vena Contracta around a bend?

- Sluice gate (almost closed)*
  - 0.59
- Small hole in a tank
  - 0.62
- Exit from a pipe
  - No *Vena Contracta*



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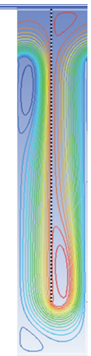
* Roberson, JA; Cassidy, JJ; Chaudhry, MH. Hydraulic Engineering. John Wiley. (1995) page 217. Original reference is Henry, H.R. "Diffusion of Submerged Jets." Discussion by M.L. Alberston, Y.B. Dai, R.A. Jensen, and Hunger Rouse, Trans. ASCE, 115, (1950)

Vena Contracta (Π_{VC}) Conclusions

- Draw the most extreme streamline through the transition and determine the total change in direction
- If the change in direction for most of the fluid is 90°, then the Π_{VC} is approximately 0.62
- If the change in direction for most of the fluid is 180°, then the Π_{VC} is approximately 0.62^2=0.384



Head Loss coefficient for a Baffle

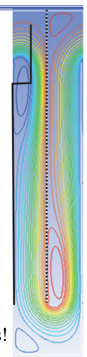
$$h_e = \frac{V_{out}^2}{2g}\left(\frac{A_{out}}{A_{in}} - 1\right)^2$$ Head loss in an expansion

$$K_e = \left(\frac{A_{out}}{A_{in}} - 1\right)^2$$ e - expansion

$$K_e = \left(\frac{1}{\Pi_{VCBaffle}} - 1\right)^2 = 2.56$$

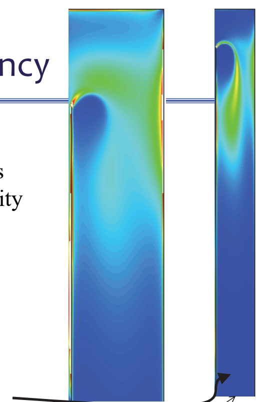
the contraction coefficient for a sharp 180° bend (0.62^2)

We need to measure this in one of the new AguaClara plants!



Flocculator Efficiency

Which space between baffles is better, considering the uniformity of the energy dissipation rate?



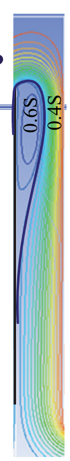
This space with very low energy dissipation rate doesn't contribute much

$H_e/S = 4$

$H_e/S = 10$

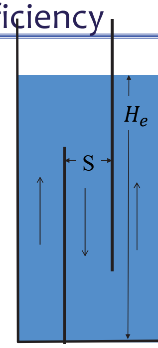
Why a transition at H_e/S of 5?

- Jets expand in width at the rate of approximately 1 unit in width per 10 units forward
- Expansion length is 10(0.6S)
- Expansion requires a distance of approximately 6S
- The H_e/S transition is related to the distance required for the jet to fully expand



Simplify flocculator design by designing for high efficiency

- Efficiency will be a function of the variability of the energy dissipation rate $\Pi_{\bar{\epsilon}}^{\epsilon Max} = \frac{\varepsilon_{Max}}{\bar{\varepsilon}}$
- We expect a relation of the form such that efficiency is 1 when $\Pi_{\bar{\epsilon}}^{\epsilon Max}$=1 and efficiency is less than 1 for higher values of $\Pi_{\bar{\epsilon}}^{\epsilon Max}$
- We "solve" this unknown by **always designing efficient flocculators with 3<H/S<6**

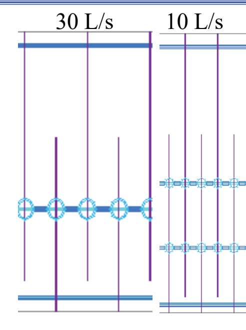


Prior to 2015 AguaClara used designs that were far from the optimum

- A compact plant layout was possible for small flows by using a vertical flow flocculator with a high H_e/S ratio
- For small plants the width of the channel was determined by the need to construct the channel using humans (45 cm or more)
- The space between baffles was very narrow and thus H_e/S was very high (for low flow plants)
- Small plants needed longer residence time and more baffles to achieve adequate flocculation because efficiency was reduced.

New Approach: Always efficient

- Add obstacles to have a maximum H_e/S ratio of between 3 and 6.
- Flocculation efficiency can be considered constant (and close to 1)



Viscous collisions or inertial collisions

- Prior to 2016 I had assumed that the appropriate length scale comparison was particle separation distance and Kolmogorov length scale – thus concluded inertia was important

2016

- Particle separation distances are smaller than inner viscous length scale
- Collisions in turbulent flocculators are dominated by viscosity (fluid shear, not turbulent eddies)*

* Edge of knowledge

Collision Potential

$$\bar{G}\theta = \frac{3}{2}\frac{(\Lambda^2-\Lambda_0^2)}{k\pi d_P^2\alpha}$$

- The target collision potential used for the design of AguaClara plants since about 2013 has been 37,000
- The actual collision potential in operating AguaClara plants may be lower because the head loss per baffle may be lower than we assumed

Energy use (head loss) in flocculation controls velocity gradient

- Head loss
  - High head loss results in a taller building for the water treatment plant
  - High head loss means higher velocities and that reduces settling of flocs in the flocculator
  - Some gravity flow water supplies don't have much elevation difference between source and storage tank
- Velocity gradient (G)
  - Higher $\bar{G}$ allows lower residence time
  - Higher $\bar{G}$ results in smaller flocs

$$h_{Floc} = \frac{\theta\bar{\varepsilon}}{g}$$

$$h_e = K_e\frac{V^2}{2g}$$

$$h_{Floc} = \sum K_e\frac{V^2}{2g}$$

$$\bar{G} = \sqrt{\frac{\bar{\varepsilon}}{\nu}}$$

$$\bar{\varepsilon} = \nu\bar{G}^2$$

$$h_{Floc} = \bar{G}\theta\frac{\nu G}{g}$$

The Influence of $\bar{G}$ or G_{Max}

- The value of $\bar{G}$ or $\bar{\varepsilon}$ determines the head loss through the flocculator
- Maximum size of the flocs is controlled by
  - $\bar{G}$ or $\bar{\varepsilon}$ (assuming shear limits attachment)
  - G_{Max} or ε_{Max} (assuming floc break up controls max size)

  Not yet known
- ε_{Max} = 10 mW/kg (G_{Max} = 100 Hz) was the AguaClara standard (2011-2015)
- Summer 2015 new designs have head loss of approximately 40 cm
  - Expect smaller flocs (but still captured by plate settlers)
  - Less sedimentation of flocs in flocculator
  - Smaller flocculator
- Casey Garland has tested $\bar{G}$ values as high as 340 Hz

The design inputs for flocculation

- We need collisions and thus Gθ is a logical design specification $\bar{G}\theta = \frac{3}{2}\frac{\left(\Lambda^2 - \Lambda_0^2\right)}{k\pi d_P^2 \alpha}$
- We need to specify energy use
  - Velocity gradient - $\bar{G}$
  - Energy dissipation rate - $\bar{\varepsilon}$
  - **Total head loss - h_{Floc}**
- Or t (θ)

Higher G means smaller flocs and more elevation drop (head loss) through flocculator

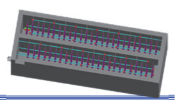
More time helps diffusion of coagulant nanoparticles to clay surfaces

Current approach

Our current choice of parameter that sets energy input is head loss

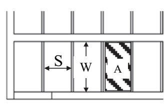
- Head loss is independent of temperature $h_e = K_e \frac{V^2}{2g}$
- Velocity gradient is f(temperature) $\bar{G} = \sqrt{\frac{g h_e}{\theta \nu}}$
- Option 1 Start with ($\bar{G}$, $\bar{G}\theta$) and coldest temperature
  - Calculate θ $\theta = \frac{G\theta}{G}$
  - Calculate h_{Floc} $h_{Floc} = \bar{G}\theta \frac{\nu G}{g}$
- Option 2 Start with (h_{Floc}, $\bar{G}\theta$) and coldest temperature
  - Current approach
  - Calculate $\bar{G}$ $\bar{G} = \frac{g h_{Floc}}{(\bar{G}\theta)\nu}$
  - Calculate θ $\theta = \frac{G\theta}{G}$
- $\bar{G}$ (and hence $\bar{G}\theta$) will increase when the flocculator is operated at warmer temperatures due to decrease in viscosity $\bar{G}\theta = \sqrt{\frac{g h_e \theta}{\nu}}$

Design the reactor geometry to get the target velocity gradient



$\bar{\varepsilon} = K_e \frac{\bar{V}^2}{2} \frac{1}{\theta}$ $\bar{\varepsilon} = \nu \bar{G}^2$ Kinetic energy dissipated per residence time

$\theta = \frac{H_e}{V}$ Continuity



$\nu \bar{G}^2 = \frac{K_e V^3}{2H_e}$

$\bar{V} = \frac{Q}{WS}$ Rectangular geometry

$\nu \bar{G}^2 = \frac{K_e}{2H_e}\left(\frac{Q}{WS}\right)^3$

H_e is height of one expansion zone. Could be the depth of water if the only expansion is from the 180 degree bend

$\bar{G} = \sqrt{\frac{K_e}{2\nu H_e}\left(\frac{Q}{WS}\right)^3}$

This is our general equation relating velocity gradient to reactor geometry

Solve for channel width to set constraints on viable solutions

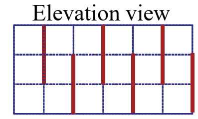
$\nu \bar{G}^2 = \frac{K_e}{2H_e}\left(\frac{Q}{WS}\right)^3$

$W = \frac{Q}{S}\left(\frac{K_e}{2H_e \nu \bar{G}^2}\right)^{\frac{1}{3}}$ $S = \frac{H_e}{\Pi_{HS}}$ $H_e = \Pi_{HS} S$

$W_{Min} = \frac{\Pi_{HS} Q}{H_e}\left(\frac{K_e}{2H_e \nu \bar{G}^2}\right)^{\frac{1}{3}}$

This is the minimum channel width if we set Π_{HS} = 3 and set the expansion height to equal water depth

Elevation view



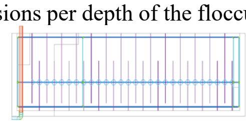
As channel gets narrower the spacing between baffles gets larger.
Channels narrower than this would have barely any or negative baffle overlap!

Minimum number of expansions per depth of flocculator (given W)

$\nu \bar{G}^2 = \frac{K_e}{2H_e}\left(\frac{Q}{WS}\right)^3$ $\Pi_{HS} = \frac{H_e}{S}$ $S = \frac{H_{e_{Max}}}{\Pi_{HS_{Max}}}$ Eliminate S

$H_{e_{Max}} = \left[\frac{K_e}{2\nu \bar{G}^2}\left(\frac{Q \Pi_{HS_{Max}}}{W}\right)^3\right]^{\frac{1}{4}}$ Solve for maximum distance between expansions, H_e, using $\Pi_{HS_{Max}}$ = 6

$N_{e_{Min}} = \frac{H_{Floc}}{H_{e_{Max}}}$ Round **up** to get the minimum number of expansions per depth of the flocculator



Our Design Approach

Given energy ($\boldsymbol{h_{Floc}}$ or $\boldsymbol{\bar{G}}$) and Gθ

- Start big and then design the details
  - Calculate volume of flocculator (AguaClara approach as of summer 2015)
  - Split it into channels
  - Then design baffles, and obstacles to fill the channels to get target $\boldsymbol{\bar{G}}$
- We can use this design approach because we are assuming that we will design for high efficiency (3< H_e/S <6) and thus we don't have to add extra volume to account for inefficiencies. (Don't forget this requirement!)

Design Algorithm (as of 2016) Start with h_{Floc} and $G\theta$

1. Velocity gradient and flocculator volume given head loss and collision potential $\bar{G} = \frac{g h_{Floc}}{(\bar{G}\theta)\nu}$ $\theta = \frac{G\theta}{G}$
2. Minimum channel width required to achieve H_e/S >3 and required for constructability $W_{Min} = \frac{\Pi_{HS} Q}{H_e}\left(\frac{K_e}{2 H_e \nu \bar{G}^2}\right)^{\frac{1}{3}}$
3. Number of channels by taking the total width and dividing by the minimum channel width (floor)
4. Channel width (total width over number of channels)
5. Maximum distance between expansions $H_{e_{Max}} = \left[\frac{K_e}{2\nu\bar{G}^2}\left(\frac{Q \Pi_{HS_{Max}}}{W}\right)^3\right]^{\frac{1}{4}}$
6. Minimum number of expansions per baffle space
7. Actual distance between expansions
8. Baffle spacing $S = \left(\frac{K_e}{2 H_e \bar{G}^2 \nu}\right)^{\frac{1}{3}} \frac{Q}{W}$
9. Calculate the obstacle width to obtain the same jet expansion conditions as produced by the 180 degree bend $N_{e_{Min}} = \frac{H_{Floc}}{H_{e_{Max}}}$

Viscous Collision Potential per Flow Expansion (the detailed perspective)

$$G\theta = \theta\sqrt{\frac{\varepsilon}{\nu}}$$

Collision potential for one flow expansion

$$\theta_e = \frac{H_e}{\bar{V}}$$

Height of one expansion zone (in a vertical flow flocculator)

Hydraulic residence time for one expansion zone

These are the average velocities through the expanded flow area

$$\bar{\varepsilon} = K_e \frac{\bar{V}^2}{2} \frac{\bar{V}}{H_e}$$

Energy dissipation rate is energy loss per time

$$G\theta_e = \frac{H_e}{\bar{V}}\sqrt{\frac{K_e}{\nu}\frac{\bar{V}^2}{2}\frac{\bar{V}}{H_e}}$$

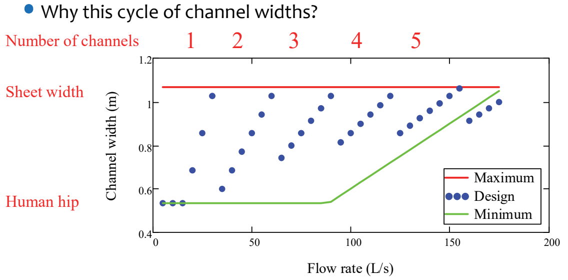
$$G\theta_e = \sqrt{\frac{H_e K_e \bar{V}}{2\nu}}$$

$$G\theta_e = \sqrt{\frac{H_e K_e Q}{2\nu W S}}$$

Collision potential is a function of velocity. This suggests that a flocculator would perform poorly if the flow rate were decreases. I don't know if anyone has ever demonstrated that!

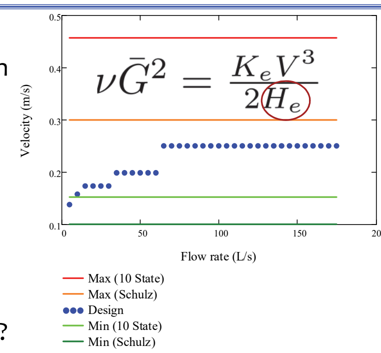
Almost Real Designs (Flocculator exit depth of 2 m)

- What sets maximum channel width?
- What sets minimum channel width?
- Why this cycle of channel widths?



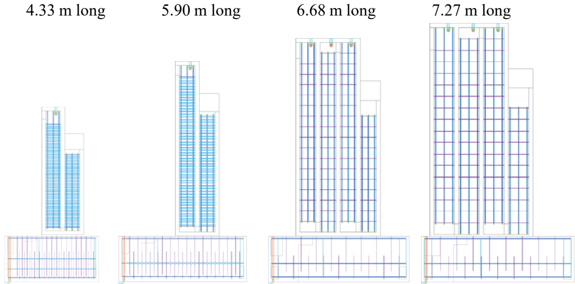
Velocity guidelines?

- Why does V increase with flow rate?
- Why does V increase in steps?
- Why does V remain constant above 70 L/s?

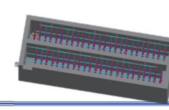


Design Scaling (Design Engine version 7099)

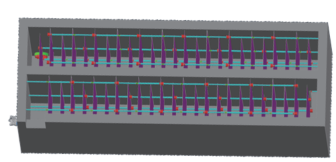
10 L/s	20 L/s	50 L/s	70 L/s
0.53 m wide channels	0.55 m wide channels	0.56 m wide channels	0.72 m wide channels
4.33 m long	5.90 m long	6.68 m long	7.27 m long



More details



- The ports between channels should have the same cross sectional area as WS
- The number of chambers per canal (except in the last canal) is even – the number of baffles is odd
- The number of chambers in the last canal is odd – the number of baffles is even
- Why?



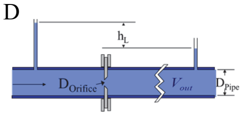
Use a Pipe with orifices to make a flocculator for small flows (S=D)

extra

$$\nu \bar{G}^2 = \frac{K_e V^3}{2H_e} \qquad \bar{V} = \frac{4Q}{\pi D_{Pipe}^{\ 2}} \text{ Continuity} \qquad H_e = \Pi_{HS} D_{Pipe}$$

Here we assume that S is like D

$$\nu \bar{G}^2 = \frac{K_e}{2\Pi_{HS} D_{Pipe}} \left(\frac{4Q}{\pi D_{Pipe}^{\ 2}}\right)^3$$



$$D_{Pipe} = \left[\frac{K_e}{2\Pi_{HS} \nu \bar{G}^2} \left(\frac{4Q}{\pi}\right)^3\right]^{\frac{1}{7}}$$

Round to nearest inner pipe diameter? Or round down to get higher velocities to prevent sedimentation?

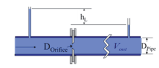
Estimate the orifice diameter

extra

$$K_{e_{orifice}} = \left(\frac{D_{Pipe}^2}{\Pi_{vc} D_{Orifice}^2} - 1\right)^2 \longrightarrow D_{Orifice} = \frac{D_{Pipe}}{\sqrt{\Pi_{vc}\left(\sqrt{K_{e_{orifice}}} + 1\right)}}$$

We need to estimate Ke!

- The head loss for these orifices spaced so closely may be less than what we calculate
  - *Vena contracta* may not be as severe for orifices that are close to the inner diameter of the pipe
  - Insufficient length for full expansion before next orifice



Estimate the orifice diameter using the correct value of Ke

extra

$$H_e = \Pi_{HS} D_{Pipe} \qquad h_e = K_e \frac{V^2}{2g}$$

Need to find actual Ke given pipe diameter to develop target G

$$\bar{G} = \sqrt{\frac{g h_e}{\theta \nu}}$$

Replace residence time with volume/Q

$$\bar{G} = \sqrt{\frac{4 g h_e Q}{\nu \pi H_e D_{Pipe}^2}} \longrightarrow h_e = \frac{\bar{G}^2 \nu \pi H_e D_{Pipe}^2}{4gQ}$$

$$h_e = K_e \frac{V^2}{2g} = K_e \frac{16Q^2}{2g\pi^2 D_{Pipe}^4} = \frac{\bar{G}^2 \nu \pi H_e D_{Pipe}^2}{4gQ} \longrightarrow K_e = \frac{\pi^3 D_{Pipe}^7 \bar{G}^2 \nu \Pi_{HSMax}}{32Q^3}$$

$$D_{Orifice} = \frac{D_{Pipe}}{\sqrt{\Pi_{vc}\left(\sqrt{K_{e_{orifice}}} + 1\right)}}$$

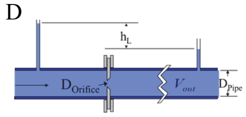
Use a Pipe with orifices to make a flocculator for small flows (H=D)

extra

$$\nu \bar{G}^2 = \frac{K_e V^3}{2H_e} \qquad \bar{V} = \frac{4Q}{\pi D_{Pipe}^{\ 2}} \text{ Continuity} \qquad H_e = D_{Pipe}$$

Here we assume that S is like D

$$\nu \bar{G}^2 = \frac{K_e}{2 D_{Pipe}} \left(\frac{4Q}{\pi D_{Pipe}^{\ 2}}\right)^3$$



$$D_{Pipe} = \left[\frac{K_e}{2 \nu \bar{G}^2} \left(\frac{4Q}{\pi}\right)^3\right]^{\frac{1}{7}}$$

Round to nearest inner pipe diameter? Or round down to get higher velocities to prevent sedimentation?

An interesting design
No this wasn't AguaClara…

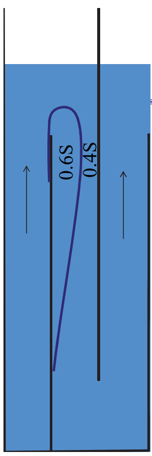
CEPIS Horizontal Flow Flocculator

A few Reflections

- Floc size doesn't seem to be a significant constraint for flocculator design
- We may increase energy dissipation rate significantly as we experiment with maintaining small flocs that primary particles can attach to
- Our broad goal is to maximize performance at minimum cost. Thus cost minimization may be an important constraint for setting the target velocity gradient.
- Maintaining the flocs in suspension is another important constraint

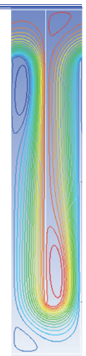
Reflection Questions

- How does the collision potential in a flocculator change with flow rate?
- What is the ratio of G_{Max} to $\bar{G}$ for well designed hydraulic flocculators?
- Why might mechanical flocculators break more flocs than hydraulic flocculators?



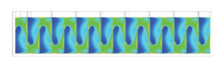
Reflection Questions

- What are some alternate geometries?
- How else could you generate head loss to create collisions?



Reflection Questions

- What is the relationship between potential energy loss and the average velocity gradient in a flocculator?
- How did AguaClara get around the 45 cm limitation?
- How does the non uniformity of ε (or G) influence efficiency of energy use?



Conclusions

- Energy dissipation rate determines the spacing of the baffles.
- Energy is used most efficiently to create collisions when the energy dissipation rate is uniform. Therefore H/S between 3 and 6 is best.
- Collision potential is a function of geometry and a function of flow rate