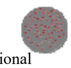
# Flocculator Design

## Floc model for viscous dominated collisions

$v_r \approx \Lambda G$

$$pC^* = \frac{3}{2}\log\left(\frac{2}{3}\pi k \frac{d_{Clay}^2}{\Lambda_0^2}\bar{G}t\alpha + 1\right)$$



Particle diameter

A function of fractional surface coverage of particle by coagulant

Rate constant (model fitting parameter)

Flocculation time

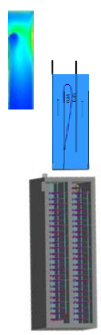
Velocity gradient $\left(\frac{\varepsilon}{\nu}\right)^{\frac{1}{2}}$

$$\bar{G}t = \frac{3}{2}\frac{(\Lambda^2 - \Lambda_0^2)}{k\pi d_{Clay}^2\alpha}$$

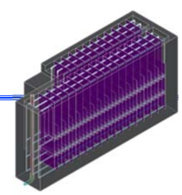
Initial particle spacing

## Overview

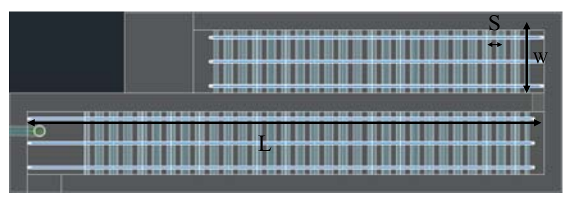
- Analysis of hydraulic flocculators
  - *Vena contracta*
  - Head loss per bend
  - The great transition at $H_e/S$=5
- Flocculator Design
  - Head loss, collision potential, residence time
  - Geometry of a baffle space to obtain desired energy dissipation rate



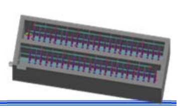
## Top View



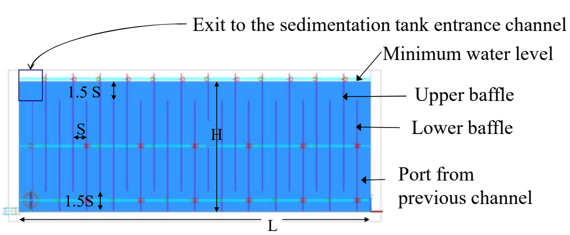
W = Width of the flocculator channel
S = Space between baffles
L = Length of a flocculator channel




## Side View

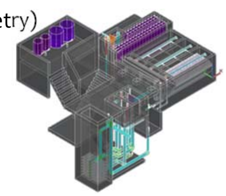


H = Water depth
L = Length of the flocculator channel
S = Space between baffles
T = Thickness of the baffles $S + T = B$
B =Perpendicular center to center distance between baffles




## Design Considerations

- The length of the flocculator channels matches the length of the sedimentation tank (thus far…)
- 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

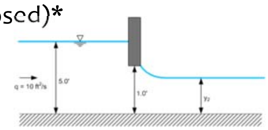


## More Design Considerations

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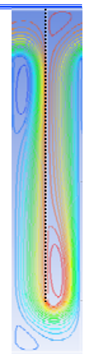
* Roberson, JA; Cassidy, JJ; Chaudhry, MH. Hydraulic Engineering. John Wiley. (1995) page 217. Original reference is Henry, H.R. "Diffusion of Submerged Jets." Discussion by M.L. Alberston, Y.B. Dai, R.A. Jensen, and Hunger Rouse, Trans. ASCE, 115, (1950)

## *Vena Contracta* ($\Pi_{VC}$) 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 $\Pi_{VC}$ is approximately 0.62
- If the change in direction for most of the fluid is 180°, then the $\Pi_{VC}$ is approximately $0.62^2$=0.384



## Head Loss coefficient for a Baffle

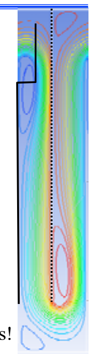
$$h_e = \frac{V_{out}^2}{2g}\left(\frac{A_{out}}{A_{in}} - 1\right)^2$$ Head loss in an expansion

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

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

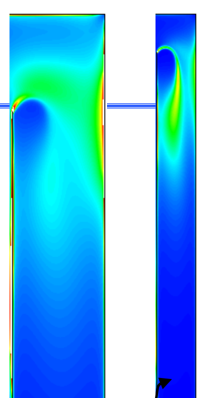
the contraction coefficient for a sharp 180° bend ($0.62^2$)

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?



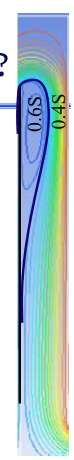
This space with very low energy dissipation rate doesn't contribute much

$H_e/S = 4$

$H_e/S = 10$

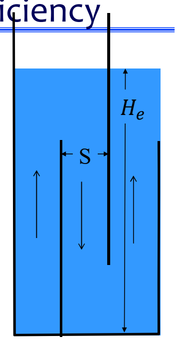
## Why a transition at $H_e/S$ of 5?

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

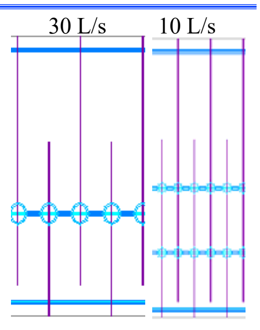



## Prior to 2015 AguaClara used designs that were far from the optimum

- 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)
- Our design equations don’t need an efficiency term




## 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

## Ten State Standards

http://10statesstandards.com/waterrev2012.pdf

- The detention time for floc formation should be at least 30 minutes with consideration to using tapered (i.e., diminishing velocity gradient) flocculation. The flow-through velocity should be not less than 0.5 nor greater than 1.5 feet per minute.
- Agitators shall be driven by variable speed drives with the peripheral speed of paddles ranging from 0.5 to 3.0 feet per second. External, non-submerged motors are preferred.
- Flocculation and sedimentation basins shall be as close together as possible. The velocity of flocculated water through pipes or conduits to settling basins shall be not less than 0.5 nor greater than 1.5 feet per second. Allowances must be made to minimize turbulence at bends and changes in direction.
- **Baffling may be used to provide for flocculation in small plants only after consultation with the reviewing authority.** The design should be such that the velocities and flows noted above will be maintained.

Hydraulic flocculators allowed only by special permission!

## Collision Potential

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

- 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

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

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

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

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

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

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

## 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 $\varepsilon_{Max}$ (assuming floc break up controls max size)

  Not yet known
- $\varepsilon_{Max}$ = 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
- We need to specify energy use
  - Velocity gradient - $\bar{G}$
  - Energy dissipation rate - $\bar{\varepsilon}$
  - **Total head loss - $h_{Floc}$**
- Or t (θ)

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

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

## Key equations that we can use to design flocculators

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

$$g h_e = \theta \bar{\varepsilon}$$ Energy dissipation rate must match the rate that mechanical energy is lost*

$$\bar{G} = \sqrt{\frac{\bar{\varepsilon}}{\nu}}$$ Fluid strain is set by the energy dissipation rate and viscosity

$$\bar{V} = \frac{H_e}{\theta} \qquad \bar{V} = \frac{Q}{WS}$$ Continuity, mass conservation

Solve to get G as a function of flow rate and geometry

*On average, potential energy lost in a flow expansion is dissipated in the residence time of that flow expansion

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

- Head loss is independent of temperature
- Velocity gradient is f(temperature)
- Option 1 Start with ($\bar{G}$, $\bar{G}$θ) and coldest temperature
  - Calculate θ
  - Calculate $h_{Floc}$
- Option 2 Start with ($h_{Floc}$, $\bar{G}$θ) and coldest temperature

  Current approach
  - Calculate $\bar{G}$
  - Calculate θ
- $\bar{G}$ (and hence $\bar{G}$θ) will increase when the flocculator is operated at warmer temperatures due to decrease in viscosity

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

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

$$\theta = \frac{G\theta}{G}$$

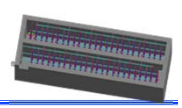
$$h_{Floc} = \bar{G}\theta \frac{\nu G}{g}$$

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

$$\theta = \frac{G\theta}{G}$$

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

## Design the reactor geometry to get the target velocity gradient



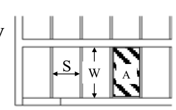
$$\bar{\varepsilon} = K_e \frac{\bar{V}^2}{2} \frac{1}{\theta}$$

$$\bar{\varepsilon} = \nu \bar{G}^2$$ Kinetic energy dissipated per residence time

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

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

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




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

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

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

This is our general equation relating velocity gradient to reactor geometry

## Solve for channel width to set constraints on viable solutions

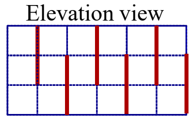
$$\nu \bar{G}^2 = \frac{K_e}{2H_e}\left(\frac{Q}{WS}\right)^3$$

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

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

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

Elevation view



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

## Meet the target H/S by decreasing the distance H between obstacles

- This design was first used at the plant in San Juan Guarita en western Honduras

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

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

$$H_{e_{Max}} = \left[\frac{K_e}{2\nu \bar{G}^2}\left(\frac{Q\Pi_{HS_{Max}}}{W}\right)^3\right]^{\frac{1}{4}}$$

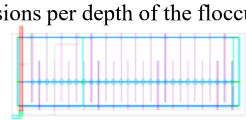
Solve for maximum distance between expansions, $H_e$, using $\Pi_{HS_{Max}} = 6$

Water depth at the end of the flocculator

$$N_{e_{Min}} = \frac{H_{Floc}}{H_{e_{Max}}}$$

Distance between flow expansions

Round **up** to get the minimum number of expansions per depth of the flocculator



## Our Design Approach

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

- Start big and then design the details
  - Calculate volume of flocculator
  - Split it into channels
  - Then design baffles, and obstacles to fill the channels to get target $\bar{\boldsymbol{G}}$

(AguaClara approach as of summer 2015)

- 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
2. Minimum channel width required to achieve $H_e/S$ >3 and required for constructability
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
6. Minimum number of expansions per baffle space
7. Actual distance between expansions
8. Baffle spacing
9. Calculate the obstacle width to obtain the same jet expansion conditions as produced by the 180 degree bend

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

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

$$H_{e_{Max}} = \left[\frac{K_e}{2\nu \bar{G}^2}\left(\frac{Q\Pi_{HS_{Max}}}{W}\right)^3\right]^{\frac{1}{4}}$$

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

$$N_{e_{Min}} = \frac{H_{Floc}}{H_{e_{Max}}}$$

## Viscous Collision Potential per Flow Expansion (the detailed perspective)

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

Collision potential for one flow expansion

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

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

Hydraulic residence time for one expansion zone

These are the average velocities through the expanded flow area

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

Energy dissipation rate is energy loss per time

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

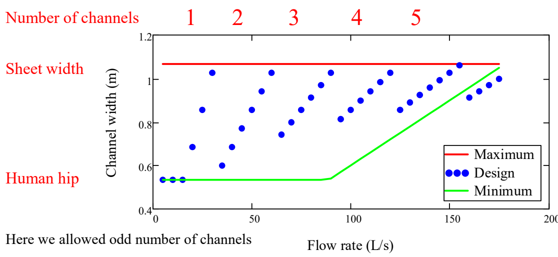
$$G\theta_e = \sqrt{\frac{H_e K_e \bar{V}}{2\nu}}$$

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

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

## Almost Real Designs (Flocculator exit depth of 2 m)

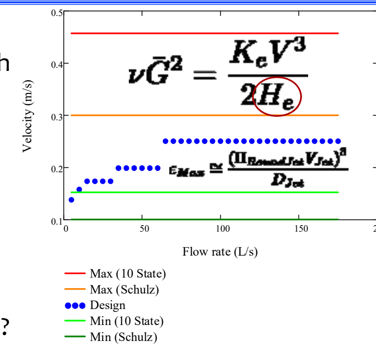
- What sets maximum channel width?
- What sets minimum channel width?
- Why this cycle of channel widths?




Here we allowed odd number of channels

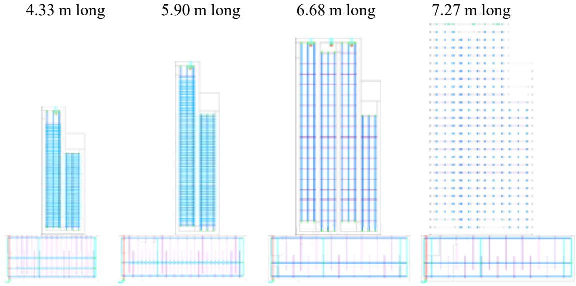
## Velocity guidelines?

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

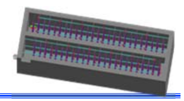



## Design Scaling (Design Engine version 7099)

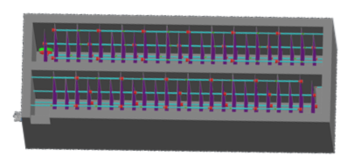
| 10 L/s | 20 L/s | 50 L/s | 70 L/s |
|---|---|---|---|
| 0.53 m wide channels | 0.55 m wide channels | 0.56 m wide channels | 0.72 m wide channels |
| 4.33 m long | 5.90 m long | 6.68 m long | 7.27 m long |



## 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?

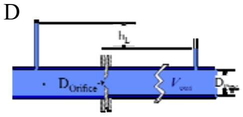


## Use a Pipe with orifices to make a flocculator for small flows (S=D)

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




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

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

Here we use Ke from typical baffled flocculators and H/S of 6 to minimize number of chips required. Round up to nearest inner pipe diameter? Or round down to get higher velocities to prevent sedimentation?

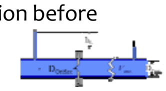
## Estimate the orifice diameter

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 required value of Ke given the actual pipe ID

extra

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

Need to find actual Ke given actual pipe diameter to develop target G. The actual Ke will increase to get the same head loss given the slower velocity in the larger diameter pipe.

$G = \sqrt{\frac{g h_e}{\theta \nu}}$  Replace residence time with volume/Q

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

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

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

https://neutrium.net/fluid_flow/pressure-loss-from-fittings-expansion-and-reduction-in-pipe-size/

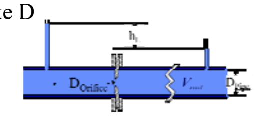
## Use a Pipe with orifices to make a flocculator for small flows (H = D)

extra

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

Here we assume that H is like D

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

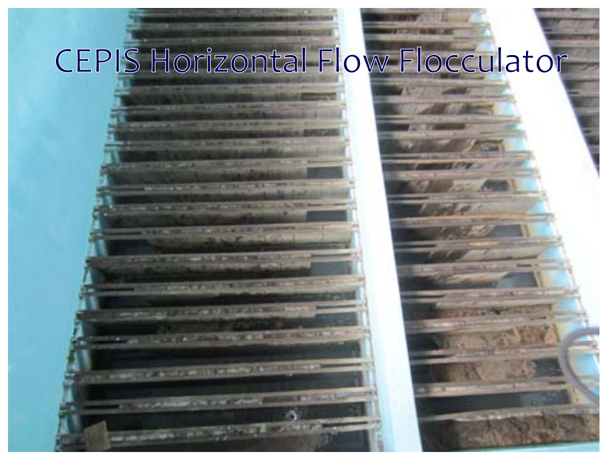



$$D_{Pipe} = \left[\frac{K_e}{2\nu G^2}\left(\frac{4Q}{\pi}\right)^3\right]^{\frac{1}{7}}$$

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

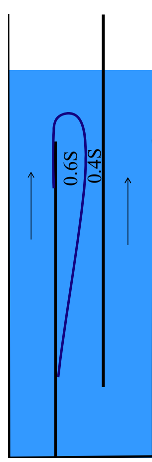
## An interesting design No this wasn't AguaClara…

## CEPIS Horizontal Flow Flocculator



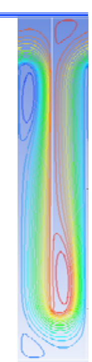
## Reflection Questions

- 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 (extra info!)?
- Why might mechanical flocculators break more flocs than hydraulic flocculators?



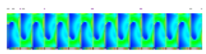

## Reflection Questions

- 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

## Shear limits the size of flocs by not allowing them to grow

extra

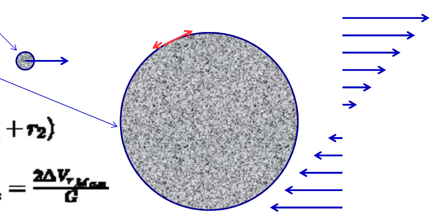
- Tangent velocities of the approaching particle surfaces increase as size of either particle increases
- Bonds formed on impact are unzipped due to rotation and high tangent velocities (perhaps a maximum relative velocity?)

$$V_{r_1} = -\frac{G r_1}{2}$$

$$V_{r_2} = +\frac{G r_2}{2}$$

$$\Delta V_r = \frac{G}{2}(r_1 + r_2)$$

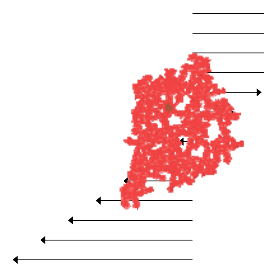
$$(r_1 + r_2)_{Max} = \frac{2\Delta V_{r_{Max}}}{G}$$



## Shear limits the size of flocs by tearing them apart

extra

- A floc in turbulent flow experiences a shear force due to the drag of the fluid on the floc caused by the velocity gradient
- The floc will also rotate and this will reduce the difference in velocity between the floc and the fluid

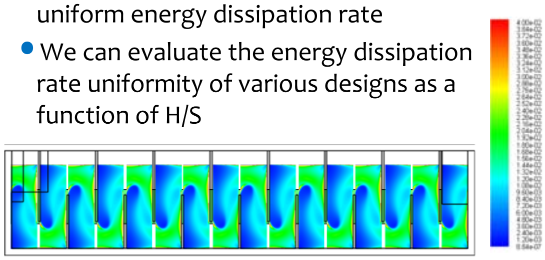


*edge of knowledge – in well designed flocculators floc breakup is likely not significant and floc growth is the limiting factor.

## The Energy Dissipation Rate isn't uniform

extra

- Ideally (for optimal efficiency) the flocculator would have a completely uniform energy dissipation rate
- We can evaluate the energy dissipation rate uniformity of various designs as a function of H/S



## Estimating the ratio $\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}} = \frac{\varepsilon_{Max}}{\bar{\varepsilon}}$

extra

$$\varepsilon_{Max} \frac{(\Pi_{JetPlane} V_{Jet})^3}{S_{Jet}}$$

← Definition of $\Pi_{JetPlane}$ $\quad \bar{V} = \frac{Q}{SW}$

$$V_{Jet} = \frac{\bar{V}}{\Pi_{VCBaffle}}$$

$$S_{Jet} = S\Pi_{VCBaffle}$$

$$\varepsilon_{Max} \frac{1}{S\Pi_{VCBaffle}} \left(\frac{\Pi_{JetPlane}\bar{V}}{\Pi_{VCBaffle}}\right)^3$$

$$\bar{\varepsilon} = K_e \frac{\bar{V}^2}{2} \frac{1}{\theta_B} = \frac{K_e}{\bar{V}^3} 2H_e$$

$\frac{\text{Energy lost}}{\text{time}}$

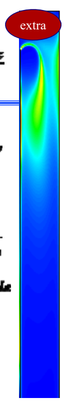
Control volume analysis

$$\theta_B = \frac{H}{\bar{V}}$$

$$\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}} = \frac{\varepsilon_{Max}}{\bar{\varepsilon}}$$

$$\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}} = \frac{\Pi_{JetPlane}^3}{\Pi_{VCBaffle}^4} \frac{2H_e}{K_e S}$$

True for large $H_e/S$ where the jet fully expands before the next turn



extra

## Estimating $\Pi_{JetPlane}$

- The transition value for H/S is at 5 (from CFD analysis) (this is our weakest assumption)
- $\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}}$ has a value of 2 for $H_e/S$<5 (CFD analysis and Haarhoff, 2001)
- $\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}}$ has a value of $\frac{\Pi_{JetPlane}^3}{\Pi_{VCBaffle}^4}\frac{2H_e}{K_e S}$ for $H_e/S$ > 5
- Solve for $\Pi_{JetPlane}$ when $H_e/S$ = 5
- $\Pi_{JetPlane} = 0.225$

$$\Pi_{JetPlane} = \left(\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}} \Pi_{VCBaffle}^4 \frac{K_e}{2}\frac{S}{H_e}\right)^{\frac{1}{3}}$$

extra

## Results of the CFD analysis and our model equations

$$\frac{\Pi_{VCBaffle}^4 K_e}{\Pi_{JetPlane}^3}$$

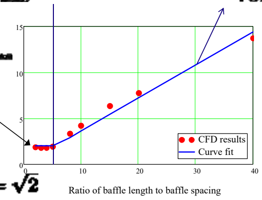
$$\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}} = \frac{\varepsilon_{Max}}{\bar{\varepsilon}} = \frac{\Pi_{JetPlane}^3}{\Pi_{VCBaffle}^4}\frac{2H_e}{K_e S}$$

$\varepsilon$ is more uniform when $H/S$ is between 3 and 6.

$\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}} = 2$

For $H_e/S$<5

$\Pi_{\bar{G}}^{G_{Max}} = \sqrt{\Pi_{\bar{\varepsilon}}^{\varepsilon_{Max}}} = \sqrt{2}$




Prior to 2015 all AguaClara designs had an H/S > 5.
Future designs will have 3 < $H_e/S$ < 6