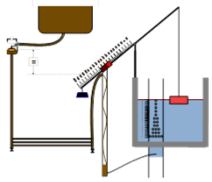
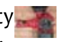
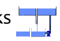
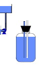
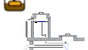
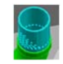
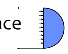
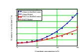
Flow Control and Measurement

Creativity without a trip
Variations on a drip
Giving head loss the slip
Chemical doses that don't dip



Here's a tip!
We can use smart fluids to eliminate software, computers, and electronics!

Overview

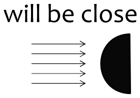
- Fluids Review
- Applications of flow control
- If you had electricity 
- Constant head devices
  - Overflow tanks 
  - Marriot bottle 
  - Float valve 
- Floating bowl 
- Hypochlorinators in Honduras 
- AguaClara Flow Controller 
- Linear Flow Orifice Meter 
- AguaClara Linear Dose Controller 
- Extra
  - Orifices and surface tension 
  - Viscosity 

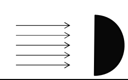
Fluids Review

- What causes drag?
- Best orientation to reduce drag?

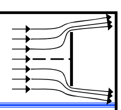
Streamlines

- Draw the streamlines that begin on the upstream side of the object for these two cases
- Which object has the larger wake?
- Which object has the lower pressure in the wake? (if streamlines are bending hard at the point of separation, then the streamlines will be close together…)





Why is there drag?



- Fluid separates from solid body and forms a recirculation zone

$$\frac{p_1}{\gamma}+z_1+\frac{v_1^2}{2g}=\frac{p_2}{\gamma}+z_2+\frac{v_2^2}{2g}$$

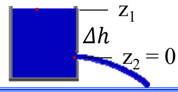
- Pressure in the recirculation zone must be low because velocity in the adjacent flowing fluid at the point of separation is high
- Pressure in recirculation zone (the wake) is relatively constant because velocities in recirculation zone are low
- Pressure behind object is low - DRAG

Fluids Review

- Where should the luggage go?
- Which equation for head loss?
- Which process is inefficient?
- Pipeline design

Orifice Equation

Flow contraction!



$$\frac{p_1}{\rho g}+z_1+\frac{V_1^2}{2g}=\frac{p_2}{\rho g}+z_2+\frac{V_2^2}{2g}$$ Bernoulli equation (no mechanical energy loss)

$A_{vc}=\Pi_{vc}A_{or}$ Area of the constricted flow

$Q=VA$ Continuity equation

$Q=\Pi_{vc}A_{or}\sqrt{2g\Delta h}$ Orifice Equation (memorize this!)

This equation applies to a horizontal orifice (so that the depth of submergence is constant). For depth of submergence larger than the diameter of the orifice this equation can be applied to vertical orifices. There is a general equation for vertical orifices in the AguaClara fluids functions.

Two kinds of drag
Two kinds of head loss

Drag (external flows)

- Skin (or shear) friction
  - **Shear** on solid surface
  - Classic example is flat plate
- Form (or pressure) drag
  - Separation of streamlines from solid surface and wake results in a...
  - Flow **expansion** (behind object)

Head loss (internal flows)

- Major losses (h_f – friction)
  - **Shear** on solid surface
  - Shear on pipe walls
- Minor losses (h_e – expansion)
  - Separation of streamlines from solid surface results in a...
  - Flow **expansion**

$$h_L=h_f+h_e$$

Energy equation (NOT THE BERNOULLI EQUATION)

$$\frac{p_{in}}{\rho g}+z_{in}+\alpha_{in}\frac{V_{in}^2}{2g}+h_p=\frac{p_{out}}{\rho g}+z_{out}+\alpha_{out}\frac{V_{out}^2}{2g}+h_T+h_L$$

Head Loss in a Long STRAIGHT Tube (due to wall shear)

- Laminar flow ________________

$$h_f=\frac{32\mu LV}{\rho g D^2}=\frac{128\mu LQ}{\rho g\pi D^4}\qquad f=\frac{64}{\text{Re}}$$ ________________

- Turbulent Flow

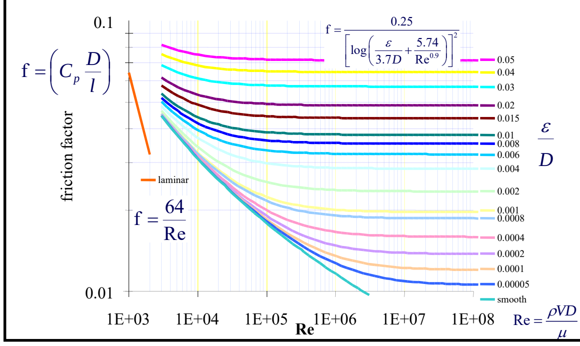
$$\text{Re}=\frac{4Q}{\pi D\nu}\qquad f=\frac{0.25}{\left[\log\left(\frac{\varepsilon}{3.7D}+\frac{5.74}{\text{Re}^{0.9}}\right)\right]^2}\qquad h_f=f\frac{8}{g\pi^2}\frac{LQ^2}{D^5}$$

Wall roughness ________________ ________________

f for friction (wall shear)

Transition from turbulent to laminar occurs at about 2100

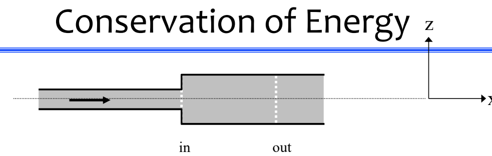
Frictional Losses in Straight Pipes



Head Loss: Minor Losses

- Head (or energy) loss (h_L) due to: outlets, inlets, bends, elbows, valves, pipe size changes
- Losses are due to expansions ________________
- Losses can be minimized by gradual expansions
- Minor Losses have the form $h_e=K_e\frac{V^2}{2g}$ where K_e is the loss coefficient and V is some characteristic velocity (could be contracted flow or expanded flow)

Head Loss due to Sudden Expansion: Conservation of Energy



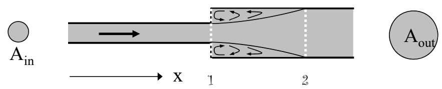
Where is p measured? ________________

$$\frac{p_{in}}{\rho g}+z_{in}+\alpha_{in}\frac{V_{in}^2}{2g}+h_p=\frac{p_{out}}{\rho g}+z_{out}+\alpha_{out}\frac{V_{out}^2}{2g}+h_T+h_L$$

$$\frac{p_{in}-p_{out}}{\rho g}=\frac{V_{out}^2-V_{in}^2}{2g}+h_{ex}$$ ________

$$h_e=\frac{p_{in}-p_{out}}{\rho g}+\frac{V_{in}^2-V_{out}^2}{2g}$$ ________________ ________________

Head Loss due to Sudden Expansion: Conservation of Momentum



$$\mathbf{M}_1 + \mathbf{M}_2 = \mathbf{W} + \mathbf{F}_{p_1} + \mathbf{F}_{p_2} + \mathbf{F}_{ss} \quad \_\_\_\_\_\_\_\_$$

$$M_{1x} + M_{2x} = F_{p_{1x}} + F_{p_{2x}} \quad \_\_\_\_\_\_\_\_$$

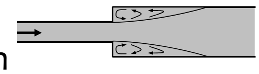
$$M_{1x} = -\rho V_{in}^2 A_{in} \qquad M_{2x} = \rho V_{out}^2 A_{out}$$

$$-\rho V_{in}^2 A_{in} + \rho V_{out}^2 A_{out} = p_{in} A_{out} - p_{out} A_{out}$$

$$\frac{p_{in} - p_{out}}{\rho g} = \frac{V_{out}^2 - V_{in}^2 \frac{A_{in}}{A_{out}}}{g}$$

Pressure is applied over all of section 1.
Momentum is transferred over area corresponding to upstream pipe diameter.
V_{in} is velocity upstream.

Head Loss due to Sudden Expansion



$$\_\_\_\_\_\_ \quad h_e = \frac{p_{in} - p_{out}}{\rho g} + \frac{V_{in}^2 - V_{out}^2}{2g} \qquad \_\_\_\_\_\_ \quad \frac{A_{in}}{A_{out}} = \frac{V_{out}}{V_{in}}$$

$$\_\_\_\_\_\_ \quad \frac{p_{in} - p_{out}}{\rho g} = \frac{V_{out}^2 - V_{in}^2 \frac{A_{in}}{A_{out}}}{g}$$

$$h_e = \frac{V_{out}^2 - V_{in}^2 \frac{V_{out}}{V_{in}}}{g} + \frac{V_{in}^2 - V_{out}^2}{2g} \qquad h_e = \frac{V_{out}^2 - 2V_{in}V_{out} + V_{in}^2}{2g}$$

$$h_e = \frac{(V_{in} - V_{out})^2}{2g} \qquad h_e = \frac{V_{in}^2}{2g}\overbrace{\left(1 - \frac{A_{in}}{A_{out}}\right)^2}^{K_e} \qquad h_e = \frac{V_{out}^2}{2g}\overbrace{\left(\frac{A_{out}}{A_{in}} - 1\right)^2}^{K_e'}$$

Discharge into a reservoir?_________________

Minor Loss Coefficient for an Orifice in a Pipe ($D_{Orifice} << D_{pipe}$)

extra

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

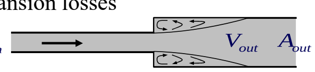
Minor loss coefficient

e for expansion

$$h_e = K_e \frac{Q^2}{2gA^2}$$

Expansion losses

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

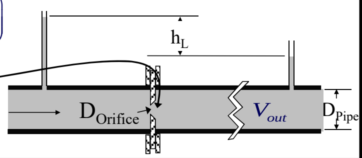


This is V_{out}, not V_{in}

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

Vena contracta area

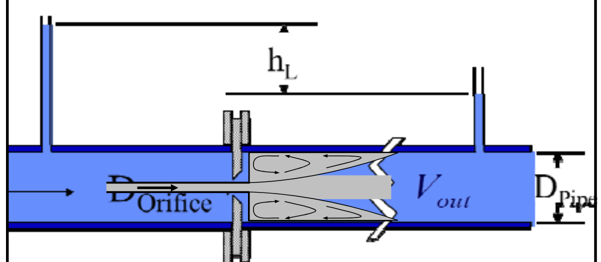
$$K_{e_{orifice}} = \left(\frac{D_{Pipe}^2}{\Pi_{vc} D_{Orifice}^2} - 1\right)^2$$



Minor Loss Coefficient for an Orifice in a pipe

extra

The expansion starts from the vena contracta



Equation for the diameter of an orifice in a pipe given a head loss

extra

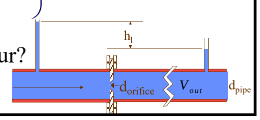
$$h_e = K_e \frac{V^2}{2g} \qquad K_{e_{orifice}} = \left(\frac{D_{Pipe}^2}{\Pi_{vc} D_{Orifice}^2} - 1\right)^2$$

$$h_e = \left(\frac{D_{Pipe}^2}{\Pi_{vc} D_{Orifice}^2} - 1\right)^2 \frac{8Q^2}{g\pi^2 D_{Pipe}^4}$$

$$D_{Orifice} = \frac{D_{Pipe}}{\sqrt{\Pi_{vc}\left(\sqrt{\frac{h_e g}{8}}\frac{\pi D_{Pipe}^2}{Q} + 1\right)}}$$

Minor losses dominate, thus $h_e = h_L$

Where do changes in pressure occur?
Where does head loss occur?

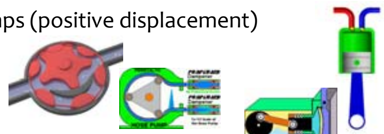


Applications of Constant Flow

- POU treatment devices (Point of Use)
  - clay pot filters
  - SSF (slow sand filters)
  - Arsenic and fluoride removal devices
- Reagent addition for community treatment processes
  - Alum or Poly Aluminum Chloride (PACl) ____________
  - Calcium or sodium hypochlorite for ____________
  - Sodium carbonate for _____________
- A flow control device that maintains a constant dose as the main flow varies

If you had electricity…

- Metering pumps (positive displacement)
  - Pistons
  - Gears
  - Peristaltic
  - Diaphragm
- Valves with feedback from flow sensors
- So an alternative would be to raise the per capita income and provide RELIABLE electrical service to everyone…
- But a simpler solution with fewer moving parts would be better!

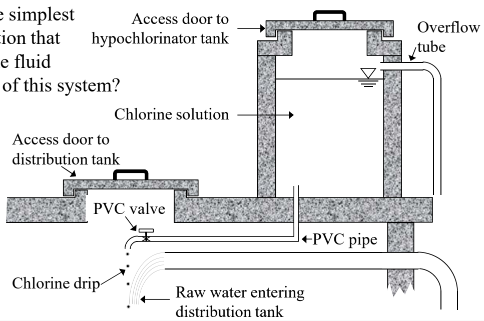


A couple of observations…

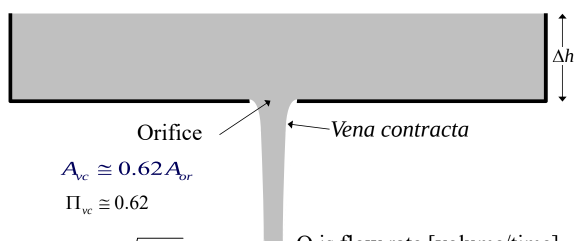
- Municipal water treatment often fails due to unreliable chemical dosing of chlorine and coagulants
- Failure modes include
  - Inability to easily set the target dose
  - Lack of easy method for operators to monitor flow
  - Poor designs that don't maintain a constant dose

The Challenge of Chemical Metering (Hypochlorinator)

What is the simplest representation that captures the fluid mechanics of this system?



Hole in a bucket doesn't give a constant flow rate



$A_{vc} \cong 0.62 A_{or}$

$\Pi_{vc} \cong 0.62$

$Q = \Pi_{vc} A_{or} \sqrt{2g\Delta h}$

Q is flow rate [volume/time]

Use Conservation of Mass and Minor Loss equation [Two unknowns (Q, h)]

Mass conservation on liquid in tank

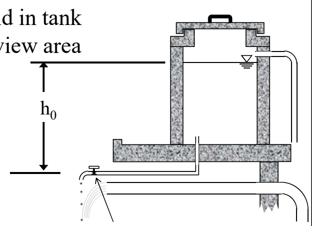
$$Q = -\frac{d\underbrace{V}_{\text{volume}}}{dt} = -\underbrace{A_{Tank}}_{\text{Plan view area}}\frac{dh}{dt}$$

Minor loss equation

$$h_e = K_e \frac{V^2}{2g} \qquad h_e = K_e \frac{Q^2}{2gA_{Valve}^2}$$

$$Q = A_{Valve}\sqrt{\frac{2h_e g}{K_e}}$$

$$A_{Tank}\frac{dh}{dt} + A_{Valve}\sqrt{\frac{2gh}{K_e}} = 0$$



Orifice in the PVC valve

Integrate to get h as f(t)

Finding the chlorine depth as f(t)

$$\frac{-A_{Tank}}{A_{Valve}\sqrt{\frac{2g}{K_e}}}\int_{h_0}^{h}\frac{dh}{\sqrt{h}} = \int_0^t dt$$

Separate variables

$$\frac{-A_{Tank}}{A_{Valve}\sqrt{\frac{2g}{K_e}}}2\left(h^{1/2} - h_0^{1/2}\right) = t$$

Integrate

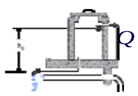
$$\sqrt{h} = \sqrt{h_0} - t\frac{A_{Valve}}{2A_{tank}}\sqrt{\frac{2g}{K_e}}$$

Solve for height

Finding Q as f(t)

$$Q = A_{Valve}\sqrt{\frac{2h_e g}{K_e}} \longleftarrow \sqrt{h_e} = \sqrt{h_0} - t\frac{A_{Valve}}{2A_{Tank}}\sqrt{\frac{2g}{K_e}}$$

$$Q = A_{Valve}\sqrt{\frac{2g}{K_e}}\left(\sqrt{h_0} - t\frac{A_{Valve}}{2A_{tank}}\sqrt{\frac{2g}{K_e}}\right)$$



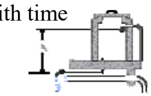
Find A_{Valve} as function of initial target flow rate

$$A_{Valve} = \frac{Q_0}{\sqrt{\frac{2h_0 g}{K_e}}}$$

Surprise… Q and chlorine dose decrease linearly with time!

$$Q = A_{Valve}\sqrt{\frac{2g}{K_e}}\left(\sqrt{h_0} - t\frac{A_{Valve}}{2A_{Tank}}\sqrt{\frac{2g}{K_e}}\right) \qquad A_{Valve} = \frac{Q_0}{\sqrt{\frac{2h_0 g}{K_e}}}$$

$$\frac{Q}{Q_0} = 1 - \frac{tQ_0}{2A_{Tank}h_0}$$ Linear decrease in flow with time



Relationship between Q_0 and A_{Tank}?
Assume flow at Q_0 for time (t_{Design}) would empty reservoir

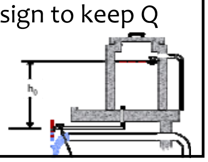
$$Q_0 t_{Design} = A_{Tank}h_{Tank} \qquad \frac{Q_0}{A_{Tank}} = \frac{h_{Tank}}{t_{Design}}$$

$$\frac{Q}{Q_0} = 1 - \frac{1}{2}\frac{t}{t_{Design}}\frac{h_{Tank}}{h_0} \qquad \frac{C_{Cl_2}}{C_{Cl_{2_0}}} = 1 - \frac{1}{2}\frac{t}{t_{Design}}\frac{h_{Tank}}{h_0}$$

Reflections

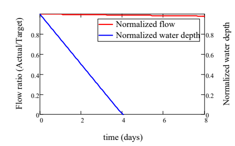
$$\frac{Q}{Q_0} = 1 - \frac{1}{2}\frac{t}{t_{Design}}\frac{h_{Tank}}{h_0}$$

- Let the discharge to atmosphere be located at the elevation of the bottom of the tank…
- When does the flow rate go to zero?
- What is the average flow rate during this process if the tank is drained completely?
- How could you modify the design to keep Q more constant?

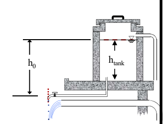


Effect of tank height above valve

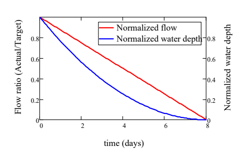
Case 1, h_0=50 m,
h_{tank} = 1 m,
t_{design}=4 days



$$h = \frac{Q^2}{Q_0^2}h_0$$



Case 2, h_0=1 m,
h_{tank} = 1 m,
t_{design}=4 days



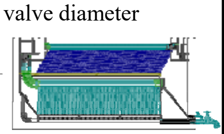
A related tangent… Design a drain system for a tank

$$\sqrt{h} = \sqrt{h_0} - t\frac{A_{Valve}}{2A_{tank}}\sqrt{\frac{2g}{K_e}}$$ Integrated results giving h as f(t)

$$\cancel{\sqrt{h}}^{\,0} = \sqrt{h_0} - t_{Drain}\frac{A_{Valve}}{2A_{Tank}}\sqrt{\frac{2g}{K_e}}$$ Empty the tank completely

$$A_{Valve} = \frac{\pi D_{Valve}^2}{4}$$ Substitute valve diameter

$$D_{Valve} = \sqrt{\frac{8L_{Tank}W_{Tank}}{\pi t_{Drain}}}\left(\frac{K_e H_{Tank}}{2g}\right)^{\frac{1}{4}}$$



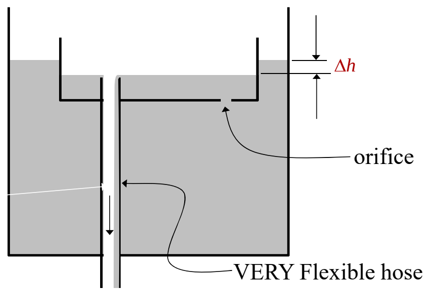
Here K_e is the total minor loss for the drain system

Brainstorm: Constant Flow

- Why did the previous systems not provide constant flow of chlorine?
- Why is this hard?
- What are the desired properties of the device that meters chemicals into a water treatment plant?

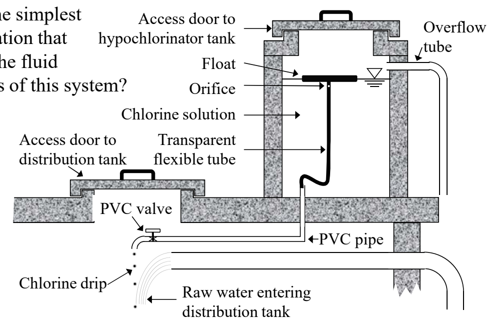
Constant Head: Floats

Head can be varied by changing buoyancy of float



Hypochlorinator with float design

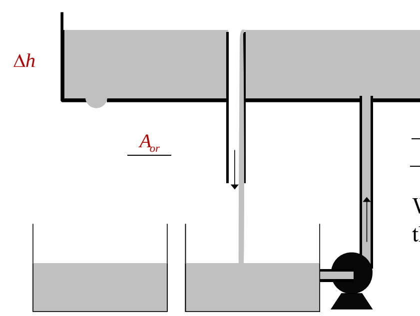
What is the simplest representation that captures the fluid mechanics of this system?



Floating Bowl

- Adjust the flow by changing the rocks
  - Need to make adjustments (INSIDE) the chemical tank
  - Rocks are submerged in the chemical
  - Safety issues

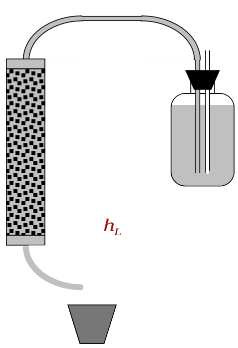
Constant Head: Overflow Tanks



What controls the flow?

$$Q = \Pi_{vc} A_{or} \sqrt{2g\Delta h}$$

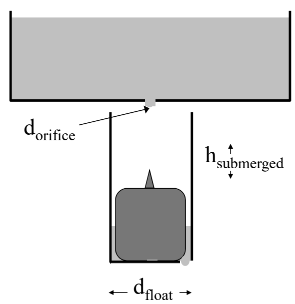
Constant Head: Marriot bottle



- A simple constant head device
- Why is pressure at the top of the filter independent of water level in the Marriot bottle?
- What is the head loss for this filter?
- Disadvantage? ____________

$$\frac{p_{in}}{\rho g} + z_{in} + \alpha_{in}\frac{V_{in}^2}{2g} + h_P = \frac{p_{out}}{\rho g} + z_{out} + \alpha_{out}\frac{V_{out}^2}{2g} + h_T + h_L$$

Constant Head: Float Valve



Float adjusts opening to maintain relatively constant water level in lower tank (independent of upper tank level) NOT Flow Control!

Force balance on float valve?

$$d_{float}^2 \cdot h_{submerged} = d_{orifice}^2 \cdot h_{tank}$$

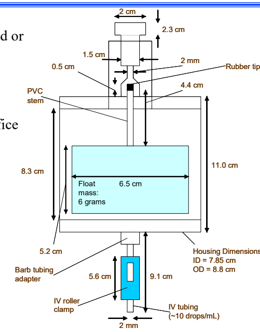
$$\frac{h_{tank}}{h_{submerged}} = \frac{d_{float}^2}{d_{orifice}^2}$$

Our goal is to adjust the flowrate and then maintain constant flow

- Head (or available energy to push fluid through the flow resistance) (voltage drop)
- Flow resistance (resistor)
  - ______________________________
  - ______________________________
  - ______________________________
- Vary either the head or the flow resistance to vary the flow rate (current)
  - Vary head by adjusting the constant head tank elevation or the outlet elevation of a flexible tube
  - Vary orifice size by adjusting a valve

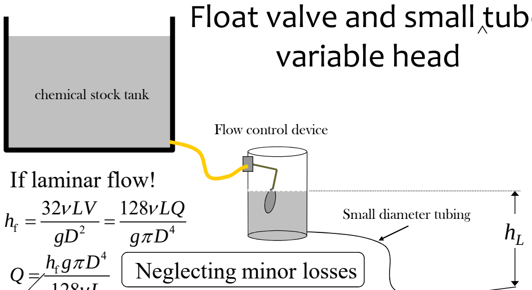
Variable Orifice

Variable head or variable resistance?
How is flow varied?
Variable orifice area



How would you figure out the required size of the orifice?

Float valve and small straight tube variable head



If laminar flow!

$$h_f = \frac{32\nu LV}{gD^2} = \frac{128\nu LQ}{g\pi D^4}$$

$$Q = \frac{h_f g\pi D^4}{128\nu L}$$

Neglecting minor losses

$$\frac{p_{in}}{\rho g} + z_{in} + \alpha_{in}\frac{V_{in}^2}{2g} + h_P = \frac{p_{out}}{\rho g} + z_{out} + \alpha_{out}\frac{V_{out}^2}{2g} + h_T + h_L$$

$$h_L = z_{in} - z_{out}$$

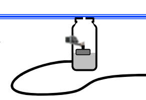
Hypochorinator Fix

http://web.mit.edu/d-lab/honduras.htm

What is good?
How could you improve this system?
What might fail?
Safety hazards?

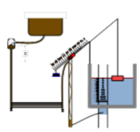
AguaClara Technologies

- "Almost linear" Flow Controller



- Linear Flow Orifice Meter

- Linear Chemical Dose Controller

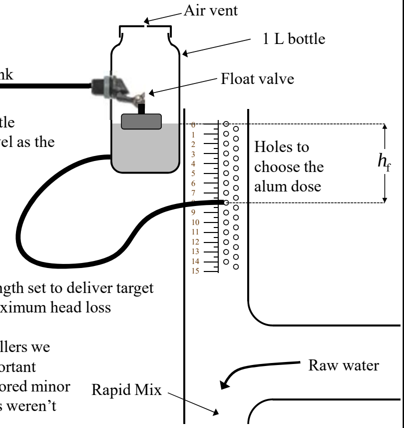


AguaClara approach to flow control

- Controlled variable head
  - Float valve creates constant elevation of fluid at inlet to flow control system
  - Vary head loss by varying elevation of the end of a flexible tube
- Head loss element
  - Long **straight** small diameter tube
  - We didn't realize the necessity of keeping the tube straight until 2012 and thus our early flow controllers had curved dosing tubes

Early Flow Controllers

Nonlinear relationship between flow and height of end of tube



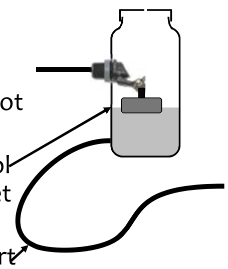
$$Q = \frac{h_f g \pi D^4}{128 \nu L}$$

Hagen–Poiseuille

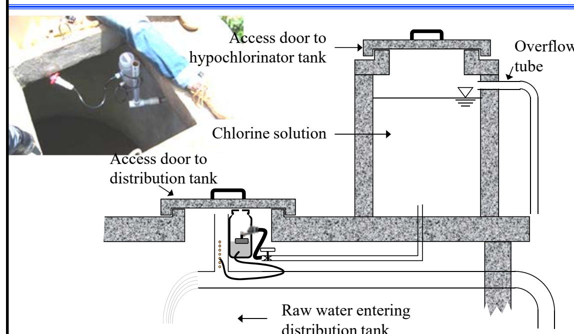
In our first flow controllers we didn't realize how important "straight" was! We ignored minor losses and minor losses weren't minor!

Requirements for a Flow Controller

- Easy to Maintain
- Easy to change the flow in using a method that does not require trial and error
- Needs something to control the level of the liquid (to get a constant pressure)
- Needs something to convert that constant liquid level into a constant flow



Hypochlorinator Fix



Installing a Flow Controller for dosing Chlorine

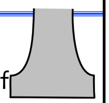
Dose Controller: The QC Control Problem

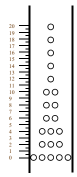
- How could we design a device that would maintain the chemical dose (C) as the flow (Q) through the plant varies?
- Somehow connect a flow measurement device to a flow controller (lever!)
- Flow controller has a (mostly) linear response
- Need height in entrance tank to vary linearly with the plant flow rate – solution is The Linear Flow Orifice Meter (LFOM)

Dose is the chemical concentration in the water

Linear Flow Orifice Meter

- Sutro Weir is difficult to machine
- Mimic the Sutro weir using a pattern of holes that are easily machined on site
- Install on a section of PVC pipe in the entrance tank
- Used at all AguaClara Plants except the first plant (Ojojona)



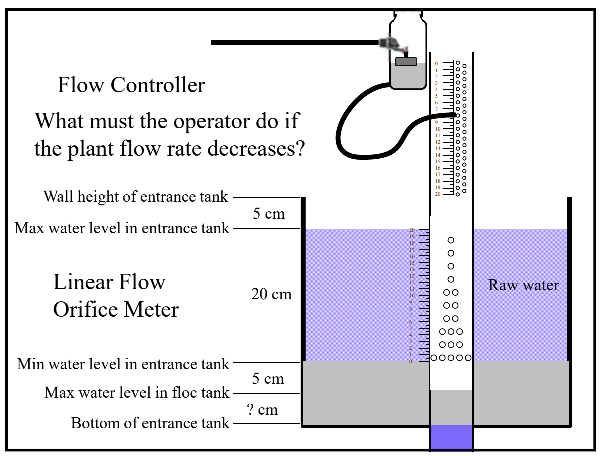


Invented by AguaClara team member David Railsback, 2007

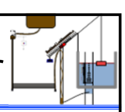
Linear Orifice Meter

Linear Flow Orifice Meter

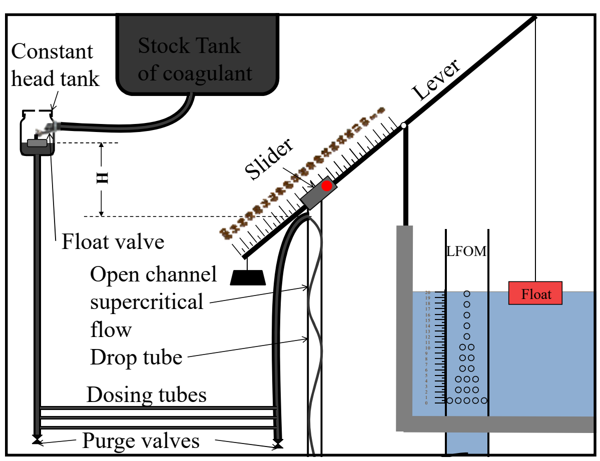
- Holes must be drilled with a bit that leaves a clean hole with a sharp entrance (hole saws are not a good choice) (Don't deburr the hole!)
- The sharp entrance into the hole is critical because that defines the point of flow separation for the *vena contracta*
- The zero point for the LFOM is the bottom of the bottom row of orifices

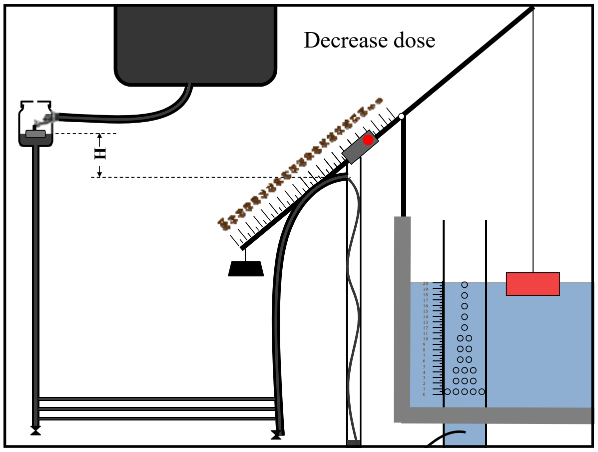


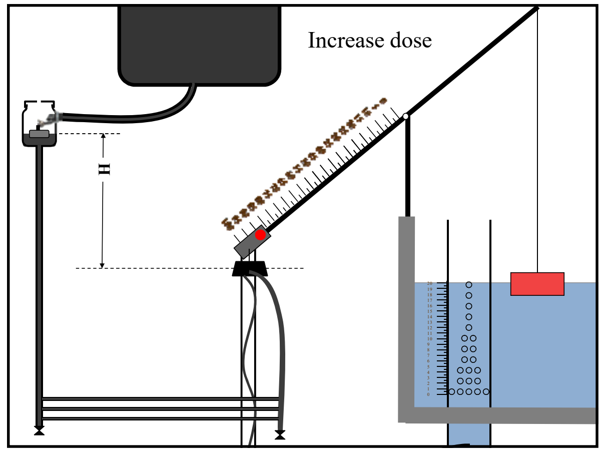
Linear Dose Controller

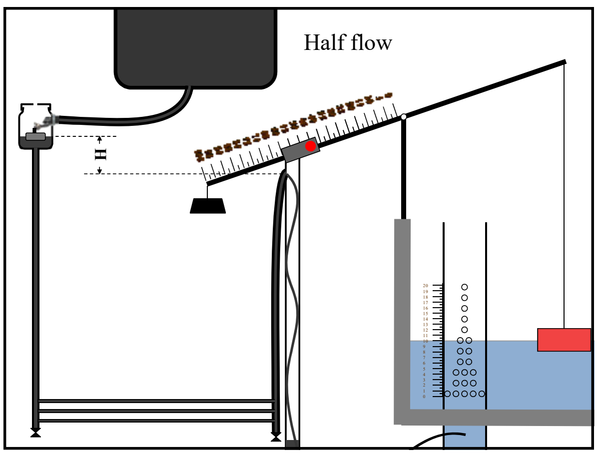


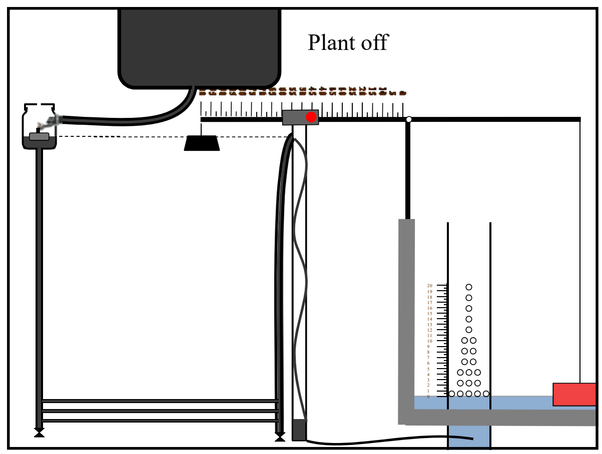
- Combine the linear flow controller and the linear flow orifice meter to create a Linear Dose Controller
- Flow of chemical proportional to flow of plant (chemical turns off when plant turns off)
- Directly adjustable chemical dose
- Can be applied to all chemical feeds (coagulant and chlorine)
- Note: This is NOT an automated dose device because the operator still has to set the dose

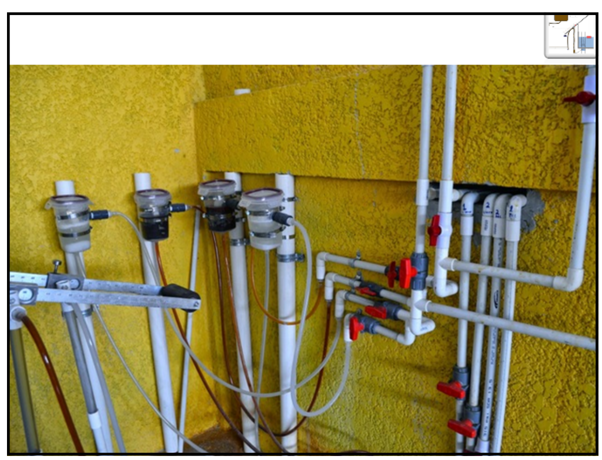


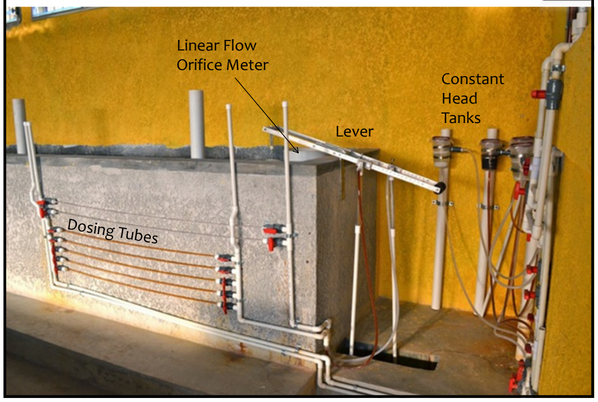

Decrease dose
H


Increase dose
H

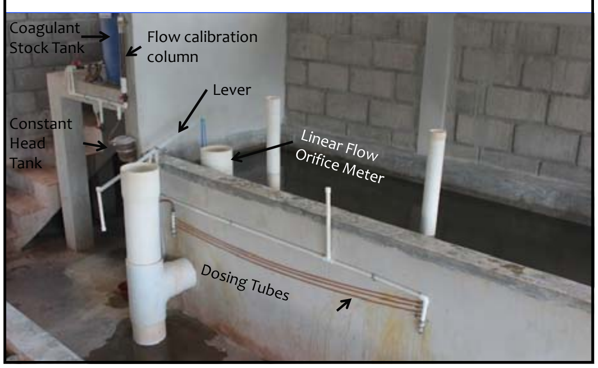

Half flow
H


Plant off





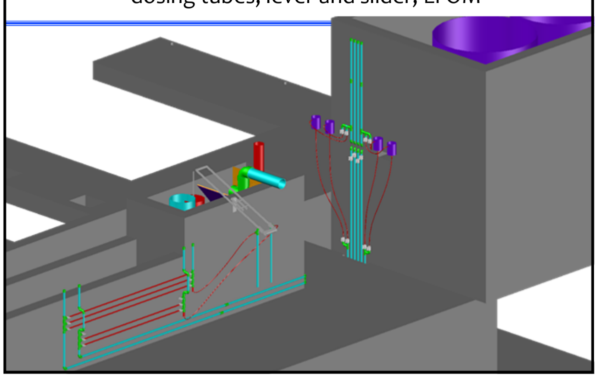
Atima doser: Three 1/8” diameter tubes, 1.93 m long, 187.5 g/L stock solution of PACl, 5 to 48 mg/L dose range.



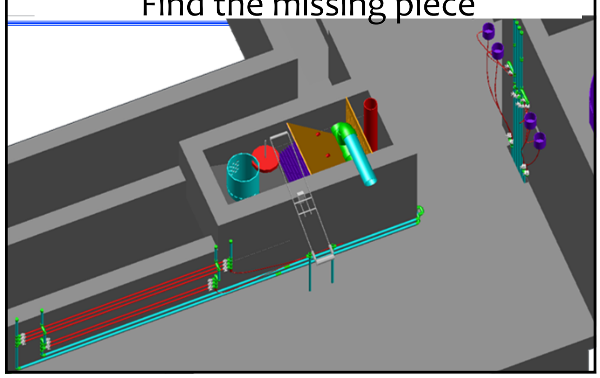
Chemical Dose Controller

- The operator sets the dose directly
- No need for calculations
- Visual confirmation
- A key technology for high performing plants
- More improvements are possible!

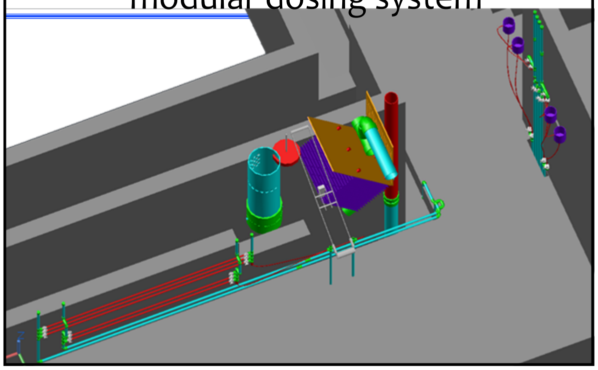
Stock tanks, calibration columns, constant head tanks, dosing tubes, lever and slider, LFOM



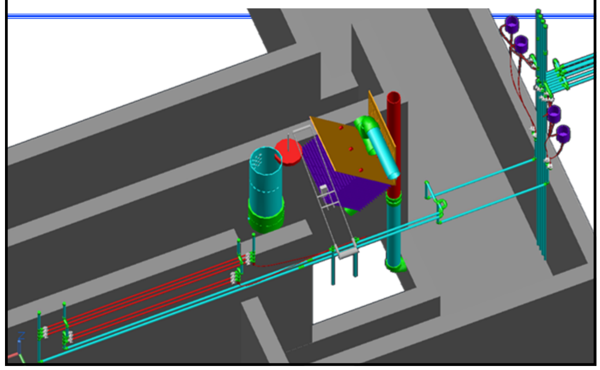
What’s wrong with this drawing? Find the missing piece



Our goal is to design a more modular dosing system

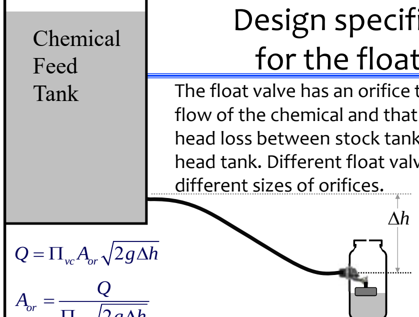


Identify everything!



Design specifications for the float valve

The float valve has an orifice that restricts the flow of the chemical and that dominates the head loss between stock tank and constant head tank. Different float valves have different sizes of orifices.



Why not increase Δh?

$$A_{or} = \pi \frac{D_{or}^2}{4}$$

$$Q = \Pi_{vc} A_{or} \sqrt{2g\Delta h}$$

$$A_{or} = \frac{Q}{\Pi_{vc}\sqrt{2g\Delta h}}$$

$$D_{or} = \sqrt{\frac{4Q}{\pi \Pi_{vc}\sqrt{2g\Delta h}}}$$

Why are we concerned with the orifice head loss?
Where else is there head loss?
Is this a minimum or a maximum orifice diameter?

Constraints on flow controller Dosing tube design

- Flow must be laminar (Re<2100)
- Minor losses must be small (small V!)
  - It took us a while to discover how critical this constraint is!
- Dosing tube must "be reasonable" length which might mean shorter than an available wall in the plant. How can I get a shorter tube?
- Designing dose controllers over a wide range of chemical flow rates requires good engineering

Nonlinearity Error Analysis: The problem caused by minor losses

$$\boxed{h_f = \frac{128\nu QL}{g\pi D^4}} \qquad h_e = \frac{8Q^2}{g\pi^2 D^4}\sum K_e$$

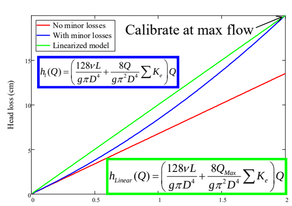
Actual head loss

$$h_L(Q) = \left(\frac{128\nu L}{g\pi D^4} + \frac{8Q}{g\pi^2 D^4}\sum K_e\right)Q$$

Linearized model of head loss

$$h_{Linear}(Q) = \left(\frac{128\nu L}{g\pi D^4} + \frac{8Q_{Max}}{g\pi^2 D^4}\sum K_e\right)Q$$

$$y = \underbrace{\quad m \quad}\quad x$$



Relationship between Q and L given error constraint

$$\Pi_{Error} = \frac{h_{Linear} - h_L}{h_{Linear}} = 1 - \frac{h_L}{h_{Linear}}$$

Set a limit on the error caused by nonlinearity (we use 0.1)

$$1 - \Pi_{Error} = \frac{\left(\frac{128\nu L}{g\pi D^4} + \cancel{\frac{8Q}{g\pi^2 D^4}\sum K_e}\right)}{\left(\frac{128\nu L}{g\pi D^4} + \frac{8Q_{Max}}{g\pi^2 D^4}\sum K_e\right)} = \frac{\left(\frac{128\nu L}{g\pi D^4}\right)}{\left(\frac{128\nu L}{g\pi D^4} + \frac{8Q_{Max}}{g\pi^2 D^4}\sum K_e\right)}$$

Plug in head loss equations. Take the limit as Q→0.

$$(1-\Pi_{Error})\frac{128\nu L}{g\pi D^4} + (1-\Pi_{Error})\frac{8Q_{Max}}{g\pi^2 D^4}\sum K_e = \frac{128\nu L}{g\pi D^4}$$

$$-\Pi_{Error}\frac{128\nu L}{g\pi D^4} + (1-\Pi_{Error})\frac{8Q_{Max}}{g\pi^2 D^4}\sum K_e = 0$$

Solve for L

$$L = \left(\frac{1-\Pi_{Error}}{\Pi_{Error}}\right)\frac{Q_{Max}}{16\nu\pi}\sum K_e$$

Relationship between minimum tube length and maximum flow from the error constraint (both unknowns – we need another equation between Q and L!)

Relationship between Q and L given head loss constraint

$$h_L = \left(\frac{128\nu L Q_{Max}}{g\pi D^4} + \frac{8Q_{Max}^2}{g\pi^2 D^4}\sum K_e\right)$$

2nd equation relating Q and L is total head loss

$$L = \left(\frac{1-\Pi_{Error}}{\Pi_{Error}}\right)\frac{Q_{Max}}{16\nu\pi}\sum K_e$$

1st equation relating Q and L – error constraint

$$h_L = \left(\frac{8\sum K_e}{g\pi^2 D^4}\left(\frac{1}{\Pi_{Error}}\right)\right)Q_{Max}^2$$

Combine two equations

$$Q_{Max} = \frac{\pi D^2}{4}\sqrt{\frac{2h_L g\Pi_{Error}}{\sum K_e}}$$

Solve for Max Q

$$V_{Max} = \sqrt{\frac{2h_L g\Pi_{Error}}{\sum K_e}}$$

$$\boxed{D = \left[\frac{8KQ^2}{\Pi_{Error} h_l g\pi^2}\right]^{\frac{1}{4}}}$$

This is the minimum D that we can use assuming we use the shortest tube possible.

Dosing Tube Lengths

$$L = \left(\frac{1-\Pi_{Error}}{\Pi_{Error}}\right)\frac{Q_{Max}}{16\nu\pi}\sum K_e \qquad Q_{Max} = \frac{\pi D^2}{4}\sqrt{\frac{2h_L g\Pi_{Error}}{\sum K_e}}$$

$$L = \frac{(1-\Pi_{Error})D^2}{64\nu}\sqrt{\frac{2h_L g\sum K_e}{\Pi_{Error}}}$$

This is the shortest tube that can be used assuming that the velocity is the maximum allowed.

$$h_L = \left(\underbrace{\frac{128\nu L Q_{Max}}{g\pi D^4}}_{\text{major}} + \underbrace{\frac{8Q_{Max}^2}{g\pi^2 D^4}\sum K_e}_{\text{minor}}\right)$$

This is for laminar flow!

$$L = \left(\frac{gh_{L_{Max}}\pi D^4}{128\nu Q_{Max}} - \frac{Q_{Max}}{16\pi\nu}\sum K_e\right)$$

If the tube isn't operating at its maximum flow (for error constraint) then use this equation.

Does tube length increase or decrease if you decrease the flow while holding head loss constant?

Tube Diameter for Flow/Dose Controller (English tube sizes)

$$\text{Re} = \frac{VD}{\nu} \qquad V = \frac{4Q}{\pi D^2}$$

$$\boxed{D = \frac{4Q_{max}}{\pi\nu \text{Re}_{max}}}$$

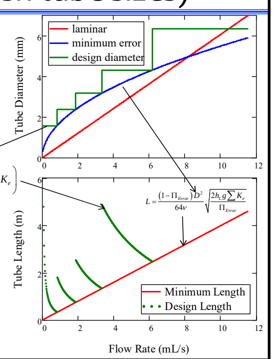
Is this a min or max D?

$$L = \left(\frac{gh_L\pi D^4}{128\nu Q_{Max}} - \frac{Q_{Max}}{16\pi\nu}\sum K_e\right)$$

$$\boxed{D = \left[\frac{8KQ^2}{\Pi_{Error} h_l g\pi^2}\right]^{\frac{1}{4}}}$$

$$D_{available} = \begin{pmatrix} 2 \\ 3 \\ 4 \\ 5.44 \\ 8 \end{pmatrix}\frac{in}{32}$$

$$h_l = 20cm \qquad \Pi_{Error} = 0.1$$

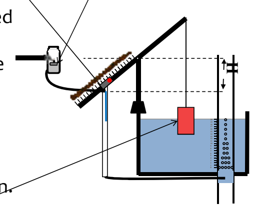


Viscosity = 1.0 mm²/s, ΣK$_e$ = 2

Dose Controller Accuracy

- Float valves only attenuate the fluctuations in level of the fluid surface
- Surface tension effects at the location where the fluid switches from closed conduit to open channel flow (the end of the dosing tube) could cause errors of a few millimeters
- The weight of the tubing and slide supported by the lever will apply different amounts of torque to the lever depending on the dose chosen. This determines the required diameter of the float

$$\Delta h_{SubmergedFloat} = \frac{\Delta h_{StockTank}}{\frac{d_{Float}^2}{d_{Orifice}^2}\Pi_{Lever}}$$



Maximum Plant Flow Rate Using Linear Flow Controller

- Assume the PACl concentration is 160 g/L, the maximum PACl dose is 30 mg/L, and the maximum flow in a 5 mm diameter dosing tube is about 8.7 mL/s.

$$Q_C C_C = Q_P C_P \qquad \text{Mass conservation}$$

P = Plant
C = Chemical Feed

$$Q_P = Q_C\frac{C_C}{C_P} \qquad Q_P = 0.0087\frac{L}{s}\frac{\left(160\frac{g}{L}\right)}{\left(0.03\frac{g}{L}\right)} \qquad Q_P = 46\frac{L}{s}$$

What is the solution for larger plants? ____________

Dose Control Summary

- Laminar tube flow and linear flow orifice meters
  - Coagulant dosing for plants with flow rates less than about 200 L/s
  - Chlorine dose controllers even for larger plants
- These devices are robust AND a good design requires excellent attention to details
  - No small parts to lose
  - No leaks
  - Compatible with harsh chemicals
  - Locally sourced materials if possible
  - Dosing tubes must be straight
  - Must account for viscosity of the chemical
  - Minor losses must be minor!

Extras!

Extending the range of the flow controllers

extra

- A single laminar flow controller will not be able to deliver sufficient alum for a large plant
- Could you design a turbulent flow flow controller?
- Could we go non linear with both flow measurement and flow control to get a simple design for larger water treatment plants?
- Clogging will be less of an issue with larger flows
- What are our options for relationships between flow rate and head loss?

Closed Conduit Flow options for Flow Controllers

extra

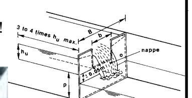
Governing equation	$Q \propto$	Range Limitations
Laminar flow in a tube: $h_f = \frac{128 \mu L Q}{\rho g \pi D^4}$		Low flow rates
Turbulent flow in a tube: $h_f = f \frac{8}{g \pi^2} \frac{L Q^2}{D^5}$		High flow rates to achieve constant f
Orifice flow: $Q = \Pi_{vc} A_{or} \sqrt{2 g \Delta h}$		Valid for both laminar and turbulent flow!

Open Channel Flow Relationships

extra

- Sharp-Crested Weir

Explain the exponents of H!



$$Q = \frac{2}{3} C_d W \sqrt{2g} H^{3/2}$$

- V-Notch Weir

$$Q = \frac{8}{15} C_d \sqrt{2g} \tan\left(\frac{\theta}{2}\right) H^{5/2}$$

- Broad-Crested Weir

$$Q = C_d W \sqrt{g} \left(\frac{2}{3} H\right)^{3/2}$$

- Sluice Gate (orifice)

$$Q = C_d W y_g \sqrt{2 g y_1}$$

$$V = \sqrt{2gH}$$

Dose Controller with nonlinear scale

extra

$Q_C = K_C h_C^{n_C}$

$Q_P = K_P h_P^{n_P}$

General Flow – Head Loss relationships for chemical feed and plant flow

$C_P = \frac{C_C Q_C}{Q_P}$

Concentration of the chemical in the plant

$C_P = \frac{C_C K_C h_C^{n_C}}{K_P h_P^{n_P}}$

$h_C = K_L h_P$

Connect the two heads with a lever, therefore the two heads must be proportional

$C_P = \frac{C_C K_C K_L^{n_C} h_P^{n_C}}{K_P h_P^{n_P}}$

Is the plant concentration constant as the plant flow rate changes?

Constant dose with changing plant flow requirement

extra

$C_P = \frac{C_C K_C K_L^{n_C} h_P^{n_C}}{K_P h_P^{n_P}}$

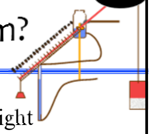
$C_P \propto \frac{K_L^{n_C} h_P^{n_C}}{h_P^{n_P}}$

What must be true for C_p to be constant as head loss, h_p changes? $Q_P = K_P h_P^{n_P}$

What does this mean?
What are our options?

Dose scale on the lever arm?

extra



$$C_P = \frac{C_C K_C K_L^{n_C} h_P^{n_C}}{K_P h_P^{n_P}}$$

$$C_P = \sqrt{K_L}\,\frac{C_C K_C}{K_P}$$

$$\sqrt{K_L} \propto C_P$$

K_L is the ratio of the height change of the float to the height change of the flow controller

This relationship makes it difficult to accurate control a wide range of alum dosages on a reasonable length lever

Pivot Point

8	10	12	14	16	18	20

Alum dose (mg/L)

AguaClara Dose Control History

extra

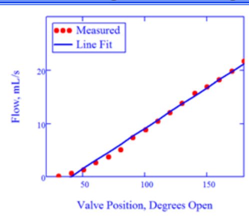
control measurement

- Laminar tube flow and simple orifice
- Laminar tube flow and linear flow orifice meter
- Dose controller that combines laminar tube flow and linear flow orifice meter
- ~~Dose controller with orifice flow for both flow control and measurement~~
- Dose controller with variable valve and simple orifice

Variable dosing valve:

extra

For coagulant dosing for plant flows above 100 L/s



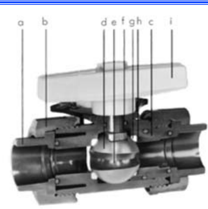


Photo courtesy of Georg Fischer Piping Systems

This method has not yet been attempted. The dose will be set by turning the valve. The valve will replace the head loss tube. The transition to open channel flow will be on a lever that tracks plant flow rate but no slider will be required. The exit from the entrance tank will be a simple orifice system. The system will still respond to plant flow changes correctly.

Surface Tension

extra

Will the droplet drop?

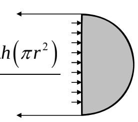
Is the force of gravity stronger than surface tension?

Δh

$$F_g = \frac{4\pi r^3}{3\cdot 2}\rho g \downarrow$$

F_σ=_____ $\uparrow$

$\downarrow F_p = \rho g \Delta h\left(\pi r^2\right)$



$$\frac{4\pi r^3}{3\cdot 2}\rho g + \rho g \Delta h\left(\pi r^2\right) = 2\pi r\sigma$$

Surface Tension can prevent flow!

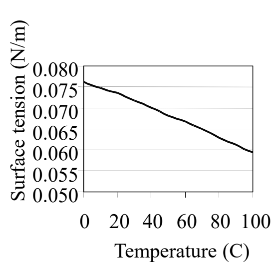
extra

$$\frac{4\pi r^3}{3\cdot 2}\rho g + \rho g \Delta h\left(\pi r^2\right) = 2\pi r\sigma$$

Solve for height of water required to form droplet

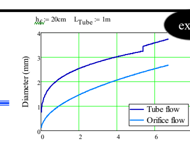
$$\Delta h = \frac{2\pi r\sigma - \frac{4\pi r^3}{3\cdot 2}\rho g}{\rho g\left(\pi r^2\right)}$$

$$\Delta h = \frac{2\sigma}{\rho g r} - \frac{2r}{3}$$



A constraint for flow control devices: Surface Tension

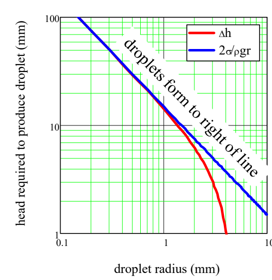
extra



$$\Delta h = \frac{2\sigma}{\rho g r} - \frac{2r}{3}$$

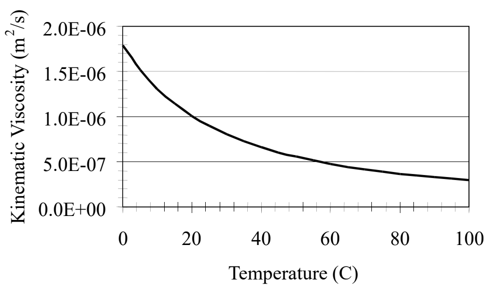
Delineates the boundary between stable and unstable

Flow control devices need to be designed to operate to the right of the red line!



extra

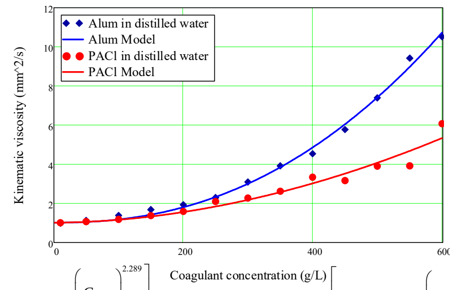
Kinematic Viscosity of Water



This is another good reason to have a building around AguaClara facilities!

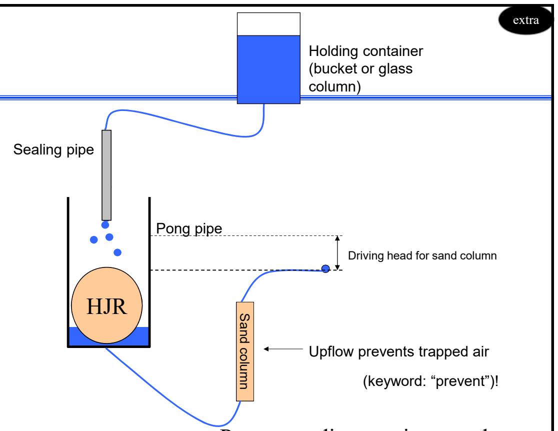
extra

Kinematic Viscosity of Coagulants



$$\nu_{Alum} = \left[1+4.225\times10^{-6}\left(\frac{C_{Alum}}{\frac{kg}{m^3}}\right)^{2.289}\right]\nu_{H_2O} \qquad \nu_{PACl} = \left[1+2.383\times10^{-5}\left(\frac{C_{PACl}}{\frac{kg}{m^3}}\right)^{1.893}\right]\nu_{H_2O}$$

extra



Porous media as resistance element

extra

Porous Media Head Loss: Kozeny equation

$V_{pore} = \frac{V_a}{\varepsilon}$ → Velocity of fluid above the porous media

Dynamic viscosity Kinematic viscosity

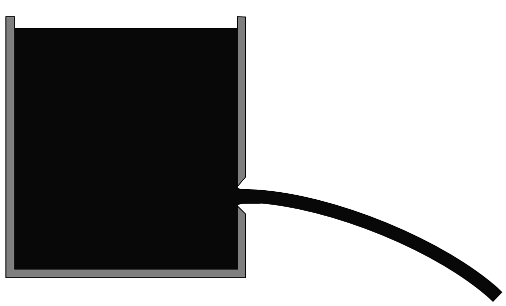
$$h_f \approx \frac{32\mu L V_{pore}}{\rho g d_{pore}^2} \qquad \nu = \frac{\mu}{\rho}$$

$$\frac{h_f}{L} = 36k\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\nu V_a}{g d_{sand}^2}$$

k = Kozeny constant
Approximately 5 for most filtration conditions

extra

Orifice Image



extra

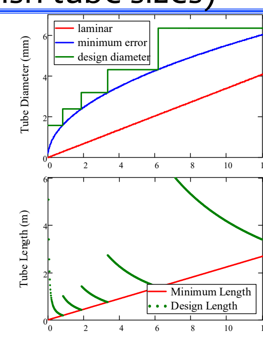
Tube Diameter for Flow/Dose Controller (English tube sizes)

- Increasing the viscosity decreases the length of the tubes
- Higher flow rates can be attained

$$D_{available} = \begin{pmatrix} 2 \\ 3 \\ 4 \\ 5.44 \\ 8 \end{pmatrix} \frac{in}{32}$$

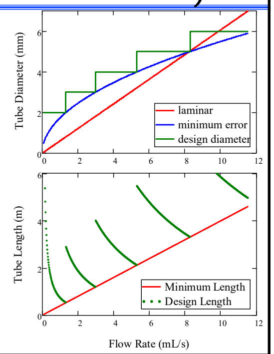
$h_l = 20cm \qquad \Pi_{Error} = 0.1$

Viscosity = 1.8 mm²/s, $\Sigma K_e = 2$



Tube Diameter for Flow/Dose Controller (Metric tube sizes)

extra



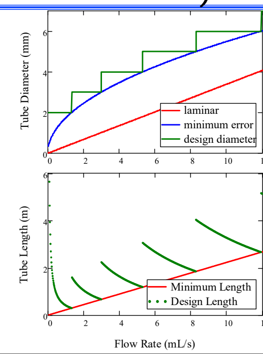
$h_l = 20cm \quad \Pi_{Error} = 0.1$

Viscosity = 1.0 mm²/s, $\Sigma K_e = 2$

Tube Diameter for Flow/Dose Controller (Metric tube sizes)

extra

- It should be possible to achieve flows of 8.7 mL/s using the 5 mm diameter tubes



$h_l = 20cm \quad \Pi_{Error} = 0.1$

Viscosity = 1.8 mm²/s, $\Sigma K_e = 2$

Design Algorithm

extra

1. Calculate the maximum flow rate through each available dosing tube diameter that keeps error due to minor losses below 10%. $Q_{Max} = \frac{\pi D^2}{4}\sqrt{\frac{2h_L g \Pi_{Error}}{\sum K_e}}$
2. Calculate the total chemical flow rate that would be required by the treatment system for the maximum chemical dose and the maximum allowable stock concentration.
3. Calculate the number of dosing tubes required if the tubes flow at maximum capacity (round up)
4. Calculate the length of dosing tube(s) that correspond to each available tube diameter. $L = \left(\frac{g h_L \pi D^4}{128 \nu Q_{Max}} - \frac{Q_{Max}}{16 \pi \nu}\sum K_e\right)$
5. Select the longest dosing tube that is shorter than the maximum tube length allowable based on geometric constraints.
6. Select the dosing tube diameter, flow rate, and stock concentration corresponding to the selected tube length.

Making Minor Losses Minor

extra

- Eliminate curvature in the dosing tubes; keep them straight and taut (in tension)
- Use fittings that have a larger ID than the tube; it will be necessary to stretch the tubing to get it on the larger diameter barbed fittings

Doser Calibration Steps

extra

(whenever the dosing tubes are replaced or elevations are varied)

- Make sure the lever is level at zero flow (adjust the length of the cable to the float)
- The doser is a linear device and thus when we calibrate it we have ____ adjustments
  - ________ the zero flow setting (adjust the height of the constant head tank)
  - _________ maximum flow rate (we will adjust this by adjusting the length of the dosing tubes if needed)

Float Valve Head Loss

extra

- What orifice diameter is required for a flow of 7.5 mL/s if we don't want more than 30 cm of head loss?

$$D_{or} = \sqrt{\frac{4Q}{\pi \Pi_{vc}\sqrt{2g\Delta h}}}$$

$$D_{or} = \sqrt{\frac{4\left(0.0000075\frac{m^3}{s}\right)}{\pi(0.62)\sqrt{2\left(9.8\frac{m}{s^2}\right)(0.3m)}}} = 2.5mm$$

http://www.edivalve.com/products/float-valves/pvc-float-valves