Gravity Powered Flow Controllers for Chlorine and Alum Dosing

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Abstract

Development of robust sustainable drinking water treatment technologies requires improved methods of metering aqueous chemical solutions. Existing gravity powered technologies require contact with the chemical solution when adjusting the flow rate or they don't provide a calibrated method for setting the flow to the target value. We developed a low cost flow controller based on laminar pipe flow with a variable calibrated flow. The range of possible design flow rates is a function of the viscosity of the solution. For dilute solutions with viscosities similar to pure water the flow controller can be designed in the range of 10 to 400 mL/min. The flow controller has been field tested for metering chlorine and aluminum sulfate for AguaClara water treatment plants in Honduras.

Keywords: AguaClara, laminar, flow meter, gravity powered

Nomenclature

Re	Reynolds number
Re_{max}	maximum Reynolds number that reliably produces laminar flow (2100)
V	average velocity
D	diameter
ν	kinematic viscosity
Q	volumetric flow rate
Q_{max}	maximum or design flow rate
Δh	height of the water column required to overcome surface tension
σ	surface tension
ρ	fluid density

g acceleration due to gravity

h_f design maximum head loss in the dosing tube

L_{min} minimum length of the dosing tube

L_{max} maximum desirable length of the dosing tube

h water column height acting on the valve orifice

$D_{orifice}$ orifice diameter

Π_{vc} ratio of the area of the *vena contracta* to the area of the orifice

Introduction

The lack of robust and sustainable technologies for chemical dosing and flow control that don't require electrical power continues to adversely affect the ability to reliably provide safe drinking water. Conventional municipal water treatment plants often use variable speed peristaltic pumps or other positive displacement pumps to meter coagulant solutions and chlorine. Many potential water treatment plant sites in the Global South don't have ready access to electricity and frequently the electrical grid is unreliable. We recognized the need for an improved gravity powered flow control device and began evaluating the available technologies and ultimately developed and tested an improved flow controller.

We first encountered the need for an improved flow control module during site visits of community water supply systems in Honduras in 2004. The standard Honduran design for community water supply systems consists of a surface water source that is piped to a distribution tank and then distributed via a pipe network to homes. The only water treatment is chlorination. Most communities use granular calcium hypochlorite to prepare a concentrated chlorine solution in a small tank that is located on top of the distribution tank. The original design of the hypochlorinators (Figure 1) called for a floating frame that held a flexible tube with a submerged orifice. This system theoretically provided a constant flow through the submerged orifice. The orifice flow is set by the size of the orifice and the distance between the free surface and the center of the orifice. However, perhaps due to difficulty adjusting the flow rate or perhaps due to clogging problems, the design was modified and a shutoff valve was added at the exit of the chlorine supply line inside the distribution tank. The shut off valve is commonly used to control the chlorine flow rate. This system fails as a constant flow device because of the changing level of the stock solution. A conceptually similar design for a constant flow device is called a floating bowl (Brikké and Bredero, 2003). It also is difficult to use and calibrate.

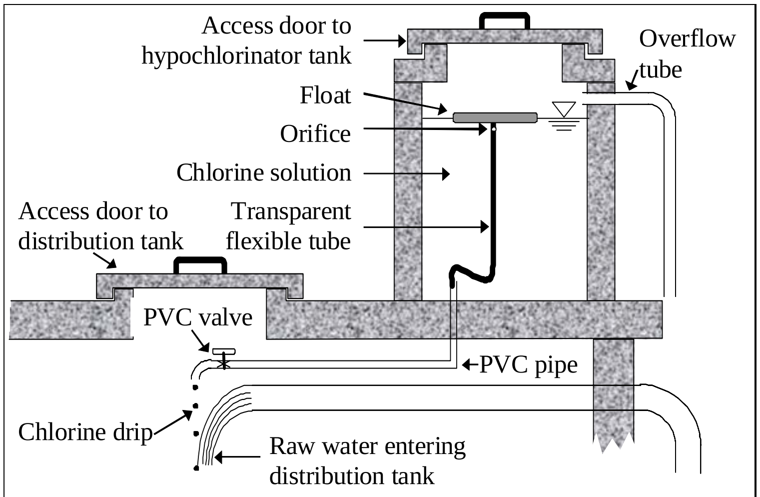

Figure 1. Hypochlorinator mounted on the top of a distribution tank as implemented in hundreds of communities in Honduras. Frequently the float components are not included and the flow is crudely controlled using the PVC shutoff valve.

Objectives

The limitations of the current flow control devices prompted us to develop a list of characteristics required for the next generation of gravity powered flow control devices. An ideal flow control device would have the following characteristics:

1. calibrated to easily vary the flow rate
2. maintain a constant flow rate independent of the chemical level in the stock tank
3. handle corrosive chemicals
4. incorporate a linear scale to facilitate setting the flow without need to use trial and error
5. be resistant to clogging
6. be easy to maintain and operate
7. be economical, small, and easily used to replace existing flow control devices
8. be easily adapted for a range of flow rates

9. be open source so that anyone can build it and use it

Theory

Maintaining a constant flow of a liquid chemical feed is difficult because of the fluctuations in the level of the liquid in the stock tank. The variable head means that any restrictions used to regulate the flow will cause a decreasing flow rate as the tank empties. One simple solution to this problem would be to use an elevated tank with a large head driving the fluid through the flow restriction. Then the small variation in the driving head as the tank emptied would not be as significant. The disadvantages of this approach are the construction and operation difficulties of the elevated tank and the clogging of the flow restriction. Thus we need a solution that isolates the flow restriction from the variable head of the stock tank and we need a flow restriction that is as large as possible to minimize clogging.

Creation of a constant flow requires a constant driving force coupled with a constant pressure coefficient or loss coefficient. Recent advances in small low cost chemical resistant float valves have made it possible to use float valves even with corrosive chlorine solutions. The float valve can be used to maintain a constant liquid level in a small tank. The constant liquid level can then be used to develop a constant flow when coupled with a constant pressure or loss coefficient. Many float valves are designed to cycle between full on and full off to minimize wear on the valve mechanism. These float valves wait for the water level to drop a significant amount (often more than 1 cm) before cycling on again. Thus these more sophisticated float valves would be a poor choice for a constant head tank. The ideal constant head tank float valve consists of a float on a lever that pushes a soft surface against an opening to close the opening. A miniature float valve with these characteristics is available (http://www.floatvalve.com/mini-floatvalves.html). The valve is made of PVC, stainless steel, and Santoprene® rubber and has a 2.36 mm diameter valve orifice.

The constant pressure coefficient or loss coefficient can be obtained by using an orifice, a valve, a tube, or a porous media column. Clogging due to precipitation of calcium carbonate in hypochlorinators or insoluble contaminants of aluminum sulfate is a significant problem. To reduce the risk of clogging the flow passage diameter should be as large as possible and should be easily cleaned. It can be shown that the diameter of a tube used to control a flow rate is significantly larger than the diameter of an orifice or the restriction in a valve. Thus we can reduce the clogging problem by using a small diameter tube rather than an orifice or a valve.

A flexible tube can be used to vary the flow from a constant head tank by simply raising or lowering the end of the tube that discharges to the atmosphere (Figure 2). Under conditions of laminar flow and neglecting entrance and exit losses, the flow rate is directly proportional to the difference in elevation between the liquid level in the constant head tank and the discharge end of the tube. The flow rate can be easily calibrated so that a particular flow can be reliably obtained by setting the elevation difference. The simple laminar flow tube is a significant improvement over a valve because the valve setting can not be easily replicated unless it has a dial indicating the valve position. The high cost of valves with position indicators in comparison with the cost of a short length of flexible tubing gives a strong advantage to the laminar flow tube.

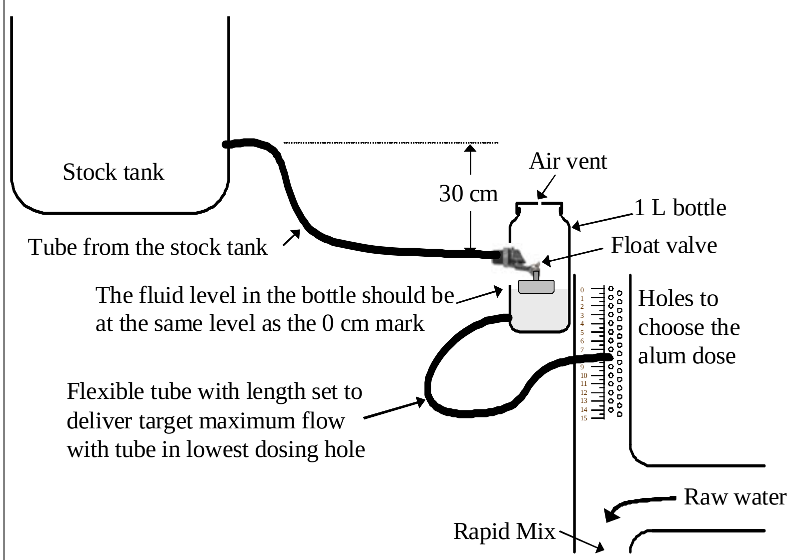

Figure 2. Schematic drawing (not to scale) of the installation of a flow controller used to add aluminum sulfate.

The design equations for a linear flow controller can be obtained by combining the equations for Reynolds number, Hagen-Poiseuille flow, and continuity with a set of reasonable design constraints. The first constraint is the requirement that the flow be laminar to obtain a linear and predictable relationship between head loss and flow rate. The Reynolds number for fluid flow in a tube is given by

$$\mathrm{Re} = \frac{VD}{\nu} \tag{1}$$

where V is the average velocity, D is the diameter, and ν is the kinematic viscosity. Continuity provides a relationship between flow rate and average velocity.

$$V = \frac{4Q}{\pi D^2} \tag{2}$$

where Q is the volumetric flow rate. Substituting equation 2 into equation 1 and solving for the diameter we obtain

$$D = \frac{4Q_{\max}}{\pi \nu \mathrm{Re}_{\max}} \tag{3}$$

where Q_{max} is the maximum or design flow rate and Re_{max} is the maximum Reynolds number that reliably produces laminar flow (2100). For a given flow rate the Reynolds number increases as the diameter decreases and thus the diameter in equation 3 is the minimum diameter that will achieve laminar flow. This constraint is shown as the “laminar” line in Figure 3.

The next constraint is the elevation range that will be used to regulate the flow from the flow controller. At small elevations surface tension can be significant. The minimum elevation required to overcome surface tension effects can be obtained from a force balance on a hemispherical droplet at the end of a tube.

$$\rho g \Delta h \left(\frac{\pi D^2}{4} \right) = \pi \mathrm{D} \sigma \tag{4}$$

Where Δh is the height of the water column required to overcome the surface tension, σ, ρ is the fluid density, and g is the acceleration due to gravity. Solving equation 4 for the minimum water column height required to overcome surface tension we obtain

$$\Delta h = \frac{4\sigma}{\rho g D} \tag{5}$$

Given a surface tension of 0.072 N/m at 25°C the height of water required to form a droplet at the end of a 3 mm diameter tube is 9.8 mm.

The resolution required for varying the flow requires a larger elevation change than that which is affected by surface tension. We recommend a minimum elevation change of 20 cm. Thus a 5% change in flow (1 cm) is still larger than the surface tension effects. The surface tension effects for aqueous stock solutions are lower than for pure water and the surface tension effect can be reduced by adding a drip surface so that droplets don't need to form at the end of the tube.

The minimum dosing tube elevation change of 20 cm sets the design maximum head loss available to produce the maximum design flow. Solving the Hagen-Poiseuille equation (for laminar flow in a circular tube) for the dosing tube diameter yields

$$D = \left(\frac{128 \nu Q_{\max} L_{\min}}{h_{\mathrm{f}} g \pi} \right)^{\frac{1}{4}} \tag{6}$$

where h_f is the design maximum head loss of 20 cm and L_{min} is the minimum length of tubing. The minimum length of tubing is set by the requirement that the end of the tube must be able to reach the full range of holes to vary the flow rate. For the design shown in Figure 2 the tube must be almost as long as h_f and for the design example here we will use a value of 20 cm. The head loss constraint is shown as the “minimum head loss” line in Figure 3. Equations 3 and 6 both return minimum values for the tube diameter and thus the maximum of the two values is the minimum value that meets both constraints. The head loss constraint, equation 6, dominates for flows less than approximately 200 mL/min and the laminar flow constraint, equation 3, dominates for larger flow rates.

An additional constraint on tubing diameter is the set of available sizes. Metric tubing is commonly available in millimeter increments. The discrete tubing diameter constraint produces the “available tube diameters” in Figure 3.

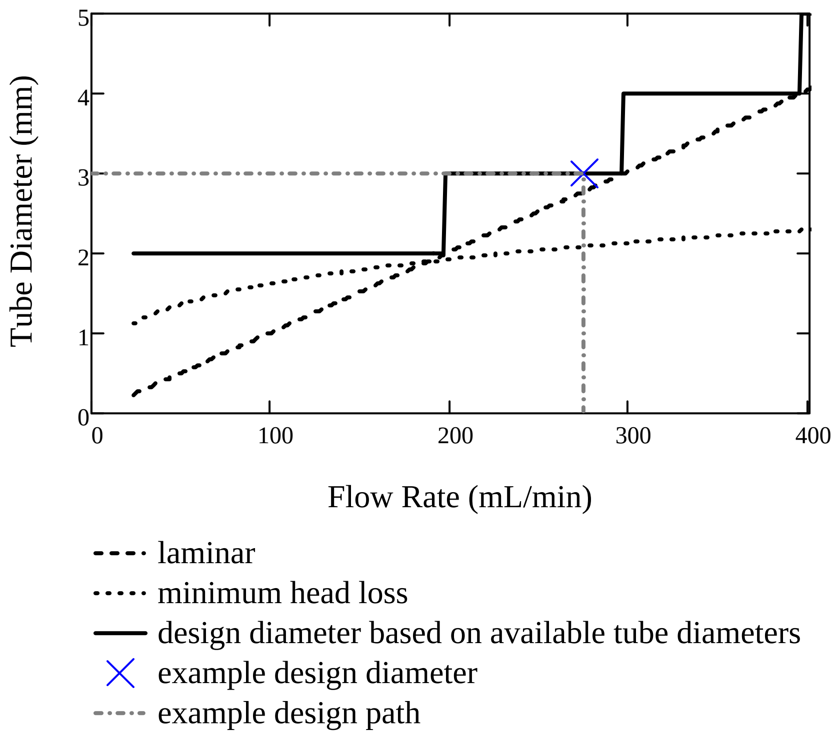

Figure 3. Solution set for tubing diameter given a maximum target head loss in the dosing tube of 20 cm and a metric set of available tubing. The example solution is for a maximum flow of 275 mL/min.

The minimum length of tubing can be obtained by substituting the maximum of the diameters obtained from equations 3 and 6 into the Hagen-Poiseuille equation and solving for the tube length. The design tube length based on available tube diameters (Figure 4) is obtained by substituting the available tube diameters (step function in Figure 3) into the Hagen-Poiseuille equation.

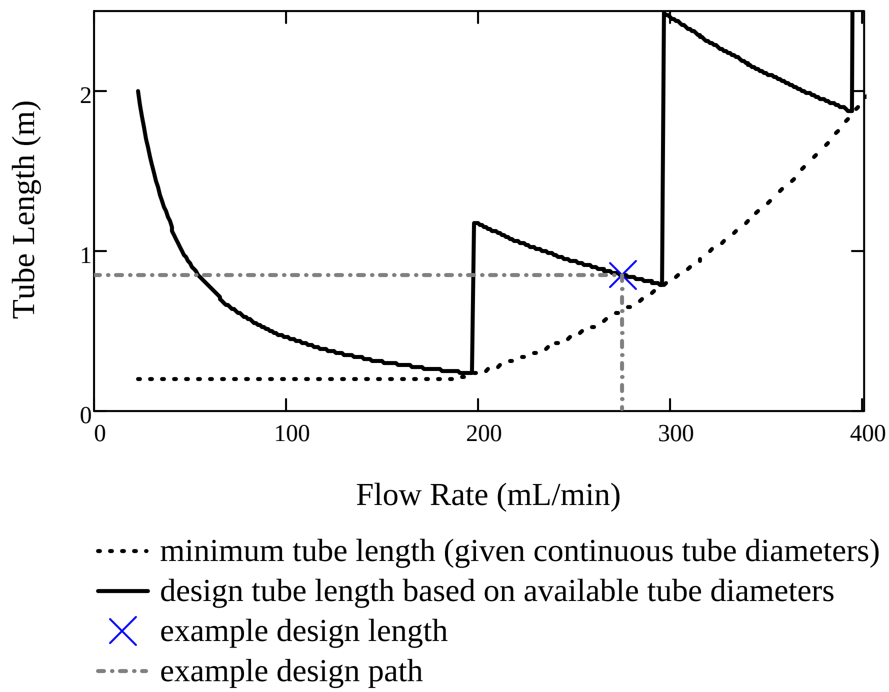

Figure 4. Solution set for tubing length given a maximum target head loss in the dosing tube of 20 cm and a metric set of available tubing. The example solution is for a maximum flow of 275 mL/min.

The maximum flow rate that can be controlled under laminar flow conditions can be calculated by combining equations 3 and 6 to eliminate the diameter.

$$Q_{\max} = \left(\frac{L_{\max} \mathrm{Re}_{\max}{}^{4} \pi^{3} \nu^{5}}{2 g h_{\mathrm{f}}} \right)^{1/3} \qquad (7)$$

where L_{max} is the maximum desirable length of the dosing tube. The maximum flow rate is achieved when the dosing tube is very long because laminar flow is achieved in large diameter tubes by having a very low head loss per unit length. Given that we require a minimum value of head loss to accurately set the flow rate, the maximum attainable flow rate will be set by the length of the dosing tube that we are willing to use. The maximum flow rate is unbounded except by the need to limit ratio of L_{max} to h_f to a reasonable value. We suggest a maximum of 2 m of tubing giving a ratio of L_{max} to h_f of 10. The maximum flow rate for a fluid with kinematic viscosity of $1x10^{-6}*m^2/s$ is then 400 mL/min. Although larger flow rates can be achieved by using even longer dosing tubes the required length increases with the cube of the flow rate and thus only marginal increases in flow rate are attainable in practice.

Expansion (or minor losses) due to the inlet and outlet conditions of the flow control tube add a nonlinear component to the relationship between flow rate and head loss. The expansion loss coefficients are 1 for the exit and approximately 0.5 for the entrance for a total expansion loss coefficient of 1.5. The corresponding head loss for a flow rate of 400 mL/min in a 4 mm diameter tube is 2 cm. The additional head loss will result in the use of a slightly shorter tube and the relationship between flow rate and head loss in the tube will deviate slightly from the linear relationship predicted by the Hagen-Poiseuille equation.

Kinematic viscosity, ν, is a critical parameter required to determine the appropriate tube diameter (equations 3 and 6). Aluminum sulfate stock solutions can be very concentrated with solubility limits exceeding 780 kg/m^3 as $Al_2(SO_4)_3*14.3H_2O$ (JTBaker. 2008). According to Gurevich, et al. (2003) the viscosity of aluminum sulfate solutions increases dramatically above 560 g/L as $Al_2(SO_4)_3*14.3H_2O$. Below that critical concentration the kinematic viscosity increases gradually from the kinematic viscosity of water to 110% of the kinematic viscosity of water. That small increase in kinematic viscosity causes a slight increase in the maximum attainable flow rate (equation 7). We do not recommend operating the flow controllers with aluminum sulfate concentrations above 560 g/L because small differences in concentration will cause large changes in the flow rate.

The minimum liquid level in the chemical stock tank must be higher than the elevation of the float valve (Figure 2). The height difference required is a function of the head loss through the supply lines and the float valve. We recommend using supply lines that are at least 6 mm in diameter. The orifice diameter in the float valve is 2.36 mm and the majority of the losses are caused by the orifice. The orifice equation can be used to estimate the required stock tank elevation.

$$Q = \Pi_{vc} \frac{\pi D_{orifice}^2}{4} \sqrt{2gh} \qquad (8)$$

where *h* represents the height corresponding to the potential energy required to generate the kinetic energy in the *vena contracta* created by the orifice, $D_{orifice}$ is the orifice diameter, and Π_{vc} is the ratio of the area of the *vena contracta* to the area of the orifice. Solving equation 8 for the height, *h*, we obtain

$$h = \frac{1}{2g} \left(\frac{4Q}{\pi D_{orifice}^2 \Pi_{vc}} \right)^2 \qquad (9)$$

At the maximum flow rate of 400 mL/min the lowest fluid level in the stock tanks must be 30 cm above the float valve.

Large water treatment plants may use chemical flow rates above 400 mL/min and thus may require multiple flow controllers in parallel. With a maximum concentration of approximately 500 g/L as $Al_2(SO_4)_3 * 14.3H_2O$, a maximum dose of 100 mg/L, and a maximum flow rate of 400 mL/min, the maximum plant flow rate for a single alum flow controller is 2000 L/min. The 2000 L/min AguaClara water treatment plant at Marcala, Honduras uses two alum flow controllers so that they can use a lower stock concentration.

Both aluminum sulfate and calcium hypochlorite solutions contain precipitates. The precipitates can accumulate in the line supplying the chemical from the stock tank or it can clog the orifice at the valve entrance or the entrance to the dosing tube. Clogging from precipitate that is present in the stock tank can be eliminated simply by creating the stock solution several hours in advance and allowing it to settle before using. The exit from the stock tank should be located several cm above the bottom of the tank to accommodate a layer of precipitate. A sediment trap can also be placed in the supply line. A sediment trap is simply a Tee and a vertical section of tubing that can be drained. The more challenging problem is chemical solutions that are supersaturated and thus continue to precipitate in the flow controller. Calcium hypochlorite that is mixed with surface waters precipitates calcium carbonate. The calcium carbonate gradually clogs tubing and valves. Flow control failure can be minimized by weekly cleaning of the flow controller with vinegar or by mechanical means. We are also investigating the possibility of adding an inline sand filter to provide plenty of surfaces for precipitation to reduce the rate of clogging of the float valve.

Results

As a design example we will find the diameter and length of tubing required to obtain a flow rate of 275 mL/min when the tube is inserted into the dosing hole (Figure 2) that corresponds to 20 cm of head loss. Select the tubing diameter by entering the x axis of Figure 3 at 275 mL/min and follow the example design path to obtain 3 mm. To determine an approximate length of the tubing enter the x axis of Figure 4 at 275 mL/min and follow the example design path to obtain 85 cm. If 41 holes (1 hole every 0.5 cm) are used as illustrated in Figure 2, the flow rate resolution will be 2.5% of the maximum flow (approximately 7 mL/min for this case).

The flow controller has been tested for both alum dosing (including unattended overnight operation of AguaClara water treatment plants) and for hypochlorinators. The alum flow controllers are in use at AguaClara water treatment plants in Ojojona (Figure 5), Tamara, and Marcala Honduras. The plant operators quickly learn how to adjust the chemical dose and the incidence of failure due to clogging is very low. A number of Honduran communities have modified their hypochlorinators to accommodate the chlorine flow controllers. This upgrade makes it possible to accurately adjust the chlorine dose. Capacity building and training are required so that system operators can monitor the chlorine residual and adjust the chlorine flow controller appropriately. The results confirm that communities are able to more reliably maintain chlorine residual using the flow controller than they were using the traditional hypochlorinators, but that further research is required to reduce the possibility of failure due to clogging from precipitate.

Figure 5. Alum flow controller installed in Ojojona, Honduras. The tank at the right is the entrance tank and the vertical pipe below the dosing tube is the rapid mix.

Conclusions and Recommendations

- A new low cost (approximately $20), gravity driven, open source flow controller with a variable maximum flowrate (maximum of 400 mL/min) is now available for metering chlorine and aluminum sulfate solutions (https://confluence.cornell.edu/display/AGUACLARA/Flow+Controller).
- The flow controller combined with hydraulic flocculation, sedimentation, and chlorination makes it possible for water treatment plants to operate without relying on electricity.
- The ability to reliably control the chlorine dose is giving communities the ability to set the residual chlorine level.

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