High Flow Dose Controller

Research Report

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Abstract

The High Flow Dose Controller aims to provide AguaClara plants with a simple dose controller that requires minimal input and oversight from the plant operator. In keeping with AguaClara standards, this dose controller will not require the use of electricity, will be simple to understand and operate and will be constructed from robust components. Additionally, the relationship between the driving head and flow rates within the dose controller must match the relationship between plant flow rates and water elevation in the entrance tank. The mechanism for metering flow in both the dose controller and the plant must therefore be the same and will be evaluated as part of the new dose controller design. The High Flow Dose Controller will be designed for flow rates where the Linear Dose Controller is unable to meet flow demands.

Keywords: Chemical dose controller, entrance tank, variable orifice, needle valve, ball valve, exit manifold, HFOM, HFDC.

Introduction

One of the biggest hurdles in the development of AguaClara technology is the development of a method to administer process chemicals to the plant that is both accurate and simple to operate.

The Linear Dose Controller (LDC) was developed by AguaClara engineers and is currently used in AguaClara plants. The underlying principle utilizes the relationship between head loss and laminar flow through a small diameter tube to accurately meter process chemicals. The LDC provides a simple design that has been well received by plant operators. As design plant flow rates increase, however, maintaining laminar flow in the small metering tube leads to somewhat cumbersome solutions (e.g. extremely long tube length, excessive number of tubes).

AguaClara technology requires a dose controller for higher flow rates than can be handled by the LDC. This dose controller must have a relationship between head pressure and flow that can be matched to a relationship between plant flow rate and water elevation of the entrance tank. Both constraints can be met by the predictable flow rate through an orifice.

Flow through an orifice (Q) is related to the area of the orifice (A) and the square-root of the height differential (h), corrected for vena-contracta, K_{vc}. This equation holds true under both laminar and turbulent flow conditions.

$$Q = K_{vc} \mathrm{A} \sqrt{2gh} \qquad (1)$$

Previous design work in this area led to the development of the Non-Linear Dose Controller (NLDC). This device utilized an orifice whose working height, and therefore chemical flow, could be adjusted via a slide on a lever arm. The lever arm was coupled to plant flow rate via a float in the entrance tank. The entrance tank was coupled to the plant by way of an exit orifice, referred to as the Rapid Mix Orifice, which allowed water level changes in the entrance tank to reflect plant flow rate.

Challenges with this design include surface tension losses in the orifice at low head pressures and imprecise (unrepeatable between units) orifice manufacturing techniques. More importantly, this design led to an unexpected failure at Algateca when accumulated grit in the flocculator caused a change to the overall plant head loss, leading to an increase in the water level in the entrance tank. Ultimately this caused the dose controller to administer chemicals at a flow rate that did not match the plant’s flow rate. We learned from this experience that it is better to uncouple the head loss through the plant from the flow measurement.

The High Flow Dose Controller (HFDC) administers process chemicals through a metering valve, thereby providing a variable orifice for dose control. The chemical dose for the HFDC will be set by adjusting the valve opening rather than using a slide to adjust the driving head, as is the case with the LDC and the NLDC. Additionally, the connection between the entrance tank and flocculator is decoupled by supercritical flow (free fall) downstream from the flow measurement orifice to prevent head loss changes in the plant from influencing the flow rate measurements.

Research - Control Device

The High Flow Dose Controller (HFDC) has two standard components found in other AguaClara chemical dose controllers: the Constant Head Tank (CHT) and the lever arm assembly. A float valve in the CHT maintains a near-constant water level in the tank, thereby providing a near-constant head pressure to the dose controller. The lever arm assembly has an attached float that transmits entrance tank level changes to the dose controller. In the HFDC, the operator will change the coagulant concentration in the plant by adjusting the opening of the valve. This desired concentration will be maintained as the flow rate through the plant changes by the raising and lowering of the float/lever arm which lead to a corresponding change to the height differential between the constant head tank and the administering tube.

Needle Valve

The initial research in developing the HFDC involved the evaluation of a needle-valve to demonstrate its practicability for chemical dose control. A mock-up chemical dose controller was used to evaluate the flow characteristics of a needle-valve over the operating range of an AguaClara plant. Equation 2 was used to estimate the orifice diameter needed ($d_{orifice}$) to obtain the required flow rate ($Q_{alumdose}$) when available head pressure (h) is specified.

$$d_{orifice} = \sqrt{\frac{4 \cdot Q_{alum\,dose}}{\pi \cdot K_{vc} \cdot \sqrt{2gh}}} \qquad (2)$$

Since the HFDC is expected to deliver plant chemicals at flow rates where the LDC is no longer suitable, the initial assumed minimum delivery rate ($Q_{alumdose}$) was 30 mL/s at 20 cm of head (h). A 10-turn general purpose needle valve (McMaster-Carr pn 4555K15) with an orifice diameter of 5.6 mm was selected and installed in the mock-up chemical dose controller.

The orifice equation proved to be an inappropriate estimator for valve selection as the minor losses within the valve were not well represented. Measured flow rates were over 50% lower than predicted by the orifice equation. The path the fluid follows through the valve adds a significant amount of head loss (Figure 1) that would be better captured by the loss coefficient (K_L) from the minor loss equation:

$$h_{Lminor} = K_L \frac{V^2}{2g} \tag{3}$$

$$K_L = 2gh_{Lminor}\left(\frac{A_{valve}}{Q}\right)^2 \tag{4}$$

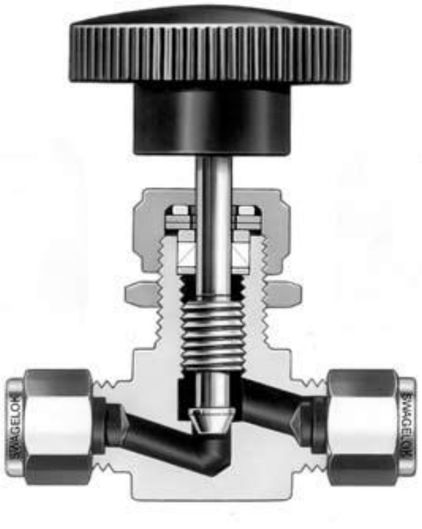

Figure 1. Typical needle valve (Courtesy of Swagelock Manufacturing)

The head loss (h_{Lminor}) or flow rate (Q) can be calculated once K_L is determined. This loss coefficient is determined empirically and changes depending on valve positioning. While a valve is partially open, there is greater resistance to flow and therefore a higher value for K_L. A fully opened valve would consequently have a lower loss coefficient. Additionally, the loss coefficient varies between valve styles, sizes and manufacturers.

To determine the K_L the needle valve was fully opened and the flow rate (Q) was measured. From this experiment, Equation 5 was used to calculate the minor loss coefficient, (K_L). as 10.62.

$$K_L = 2gh\left(\frac{A_{valve}}{Q}\right)^2 = 2 \cdot g \cdot 20\text{cm}\left(\frac{\pi \frac{5.6\text{mm}^{2}}{4}}{15\frac{\text{mL}}{\text{s}}}\right) = 10.62 \qquad (5)$$

Flow measurements were then recorded at 5 cm increments from zero to 20 cm of head pressure to demonstrate the relationship between head and flow within this fully opened valve. Figure 2. shows the relationship between measured values and the calculated values based on the derived value of K_L.

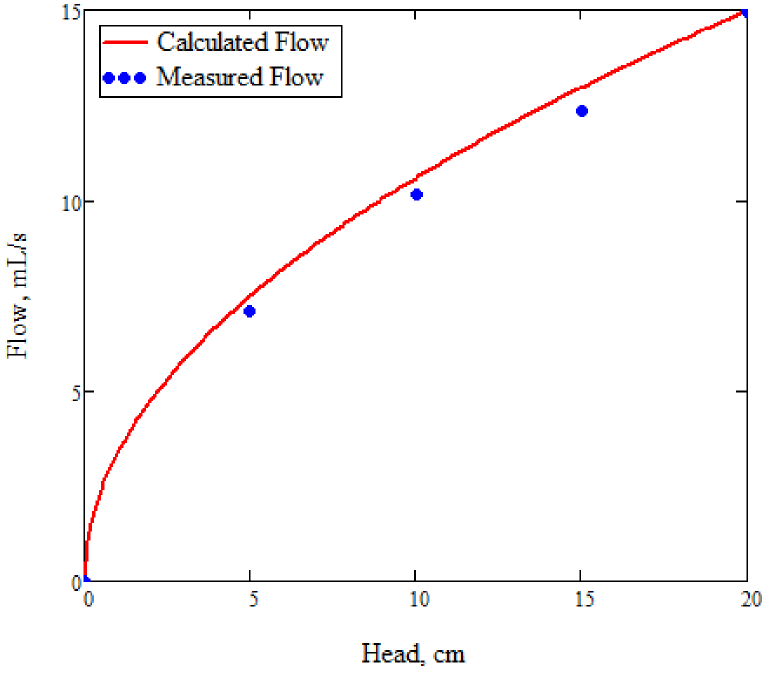

Figure 2. Comparison of expected flow rate (as calculated using Equation 5) and the actual measured flow rate within the 5.6 mm orifice needle valve.

Assuming the intention of the HFDC technology is to allow AguaClara to triple its capabilities and modifying the low end of the HFDC to accommodate a slight overlap between the LDC and HFDC technology, the metering valve should scale accurately between approximately 20 mL/s – 60 mL/s. If the minor loss coefficient of the needle valve selected for initial testing is representative of the industry standard, then for example, to provide an AguaClara plant with 60 mL/s of coagulant flow, (as may be required in a 100 L/s AguaClara plant) would require a valve with an internal orifice of 11.1 mm, as shown in Figure 3.

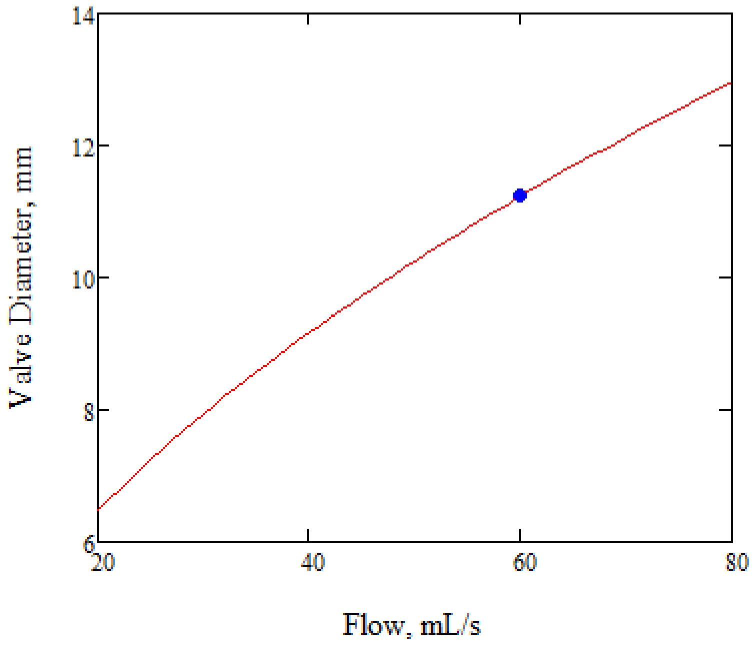

Figure 3. Assuming the head loss coefficient (K_L) of 10.61 is representative of needle valve geometry, obtaining 60 mL/s coagulant flow rate would require a valve orifice diameter of 11.1 mm if 20 cm of head pressure were available.

Although not unheard of, this is an uncommon orifice size for a needle valve. Orifice size in general application needle valves does not normally exceed 6.4 mm. Larger sizes are available but these would be considered specialty valves that would come with a higher price and longer lead time.

Metering Ball Valve

Georg Fischer Piping Systems has recently modified the standard ball valve, making it suitable for metering. They have manufactured a “characterized” opening to provide more precise flow control and to create a near linear relationship between handle position and flow rate (Figure 4). Not only will this simplify the calibration process, the operator will likely develop a better “feel” when adjusting the chemical dose.

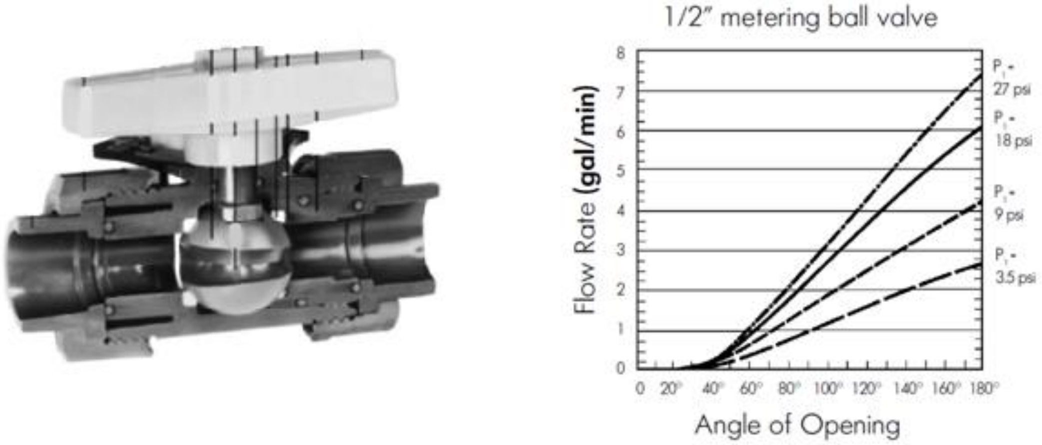

Figure 4. Cut-away view of characterized opening. Published information on valve indicates a linear relationship between flow rate and valve position can be expected. (Courtesy of Georg Fisher Piping Systems)

The Georg Fischer Type 323 Metering Ball valve (Figure 5) is manufactured from PVC, a suitable material for our applications. The valve is rated for 150 psi at 72 deg F. It is a true union style valve, meaning once mounted in the piping system, the two end unions can be loosened and the valve body removed without disrupting the piping. Socket or threaded ends are available. The valve comes in two standard National Pipe sizes, 3/8” and ½”. The smaller valve has a 16 mm metering port while the port for the larger valve is 20 mm. Standard on the Type 323 valve is a graduated scale with pointers. Additionally, the modified ball is available for installation in the Type 546 ball valve if the desired range should exceed the capabilities of the Type 323.

Figure 5. Type 323 Metering Ball Valve (Courtesy of Georg Fischer Piping Systems)

Analysis of the 3/8" meter valve provided encouraging results. The valve was installed in the mock-up chemical dose controller with 20 cm of head and flow rates were measured at varying degrees of opening. As expected, a near linear relationship exists between flow rate and valve opening (Figure 6).

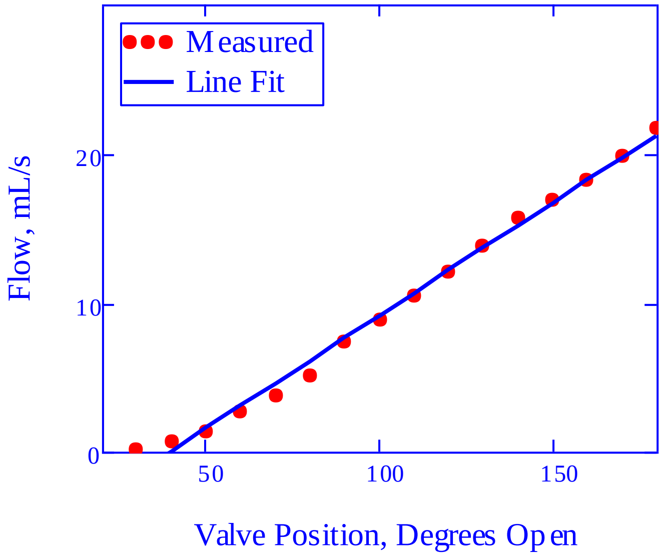

Figure 6. Relationship between Type 323 Metering Ball valve position and flow rate at a head of 20 cm. The first three points were not included in the linear fit.

Design – Control Device

Flow Coefficient

The Georg Fischer Type 323 Meter Ball valve appears to be an appropriate metering device for use as a dose controller in an AguaClara plant. As stated above, this valve is available in two nominal sizes, 3/8" and ½". Valve size selection is based upon the maximum flow rate required of the valve. Valve manufacturers publish the valve's flow coefficient, (k_v), which has been determined empirically by the manufacturer. The flow coefficient defines the flow of water (Q), through a valve (measured in $\frac{m^3}{hr}$ or $\frac{L}{min}$) with a pressure drop of 1 bar (Δp) .

$$Q = k_v\sqrt{\Delta p} \qquad (6)$$

Simply stated, this coefficient combines the effects of all restrictions within a valve and all dimensions within the equation into a single number (Swagelock Technical Bulletin.) It is important to note that most valve manufactures publish k_v as if it is a dimensionless value. In reality, kv can have units in $\frac{L}{min\sqrt{bar}}$ or $\frac{\mathrm{m}^3}{\mathrm{hr}\sqrt{\mathrm{bar}}}$ but it is frequently not clear which units were used to develop this value.

Starting with the maximum target flow rate of coagulant in the plant (Q) determine the minimum required value for k_v using the relationship shown in Equation 7,

$$k_v = \frac{Q}{\sqrt{\Delta p}} \qquad (7)$$

where Δp is the plant head loss, in bar. From this calculated flow coefficient, the correct valve can be selected. Refer to Table 1. for available published data on the Type 323 Metering Ball Valve noting that George Fischer Piping Systems reports a k_v with units of $\frac{L}{min\sqrt{bar}}$.

Table 1. Published Data for Type 323 Ball Valve

Nominal Size NPT	**k_v** $\frac{L}{min\sqrt{bar}}$	**Port Size** mm
3/8"	11	16
1/2"	20	20

As mentioned previously, the Type 546 ball valve is also available if the Type 323 valve does not have sufficient capacity for a given plant. As demonstrated in Table 2 the lowest k_v available in the Type 546 valve is 86 $\frac{L}{min\sqrt{bar}}$. These valves offer much higher possible flow rates than the Type 323 valve. At this time, these valves are oversized for our application but there may come a time when these valves are an appropriate choice.

Table 2. Published Data for Type 546 Ball Valve

Nominal Size NPT	**k_v** $\frac{L}{min\sqrt{bar}}$
1/2"	86
3/4"	232
1 1/2"	748

The design algorithms for the proper selection of the metering valve have been created using MathCad and are available for further design work.

Relationship between Minor Loss Coefficient and Flow Coefficient

The effect of fittings and valves on the flow rate (Q) within a piping system can be modeled with the use of the minor loss coefficient (K_L).

$$Q = A \cdot \sqrt{\frac{2 \cdot g \cdot h}{K_L}} \tag{8}$$

The minor loss coefficient, K_L is not normally published by the valve manufacturer. It is a generalized number used in the design of the entire piping system and is available from engineering tables and handbooks. During the design phase, a valve's flow coefficient (k_v) is used determine the capacity of the valve. As mentioned above, flow coefficient **is** a value published by the manufacturer.

$$Q = k_v \cdot \sqrt{\Delta p} \tag{9}$$

The relationship between k_V and K_L can be determined by setting the two equations equal to each other and substituting $\rho \cdot g \cdot h \text{ for } \Delta p$.

$$k_v \sqrt{\rho \cdot g \cdot h} = A\sqrt{\frac{2 \cdot g \cdot h}{K_L}} \tag{10}$$

Simplifying,

$$K_L = \left(\frac{A}{K_v}\right)^2 \cdot \frac{2}{\rho} = \left(\frac{\pi d^2}{4K_v}\right)^2 \cdot \frac{2}{\rho}$$

$$K_V = \sqrt{\frac{2 \cdot A^2}{\rho \cdot K_L}} = \sqrt{\frac{(\pi d)^2}{8 \cdot \rho \cdot K_L}} \tag{11}$$

Referring again to Equation (3), the head loss added to a system by each component is calculated by:

$$h_{L\,minor} = K_L \frac{V^2}{2g} = K_L \frac{Q^2}{2gA^2} \tag{12}$$

Minor loss through the valve can then be estimated using only the published valve of k_v. Substituting Equation 11 for K_L and simplifying, minor head loss is modeled by:

$$h_{Lminorvalve} = \frac{Q^2}{\rho g k_v^2} \qquad (13)$$

as demonstrated in Figure 7. The derivation for this equation is also shown in the attached MathCad file.

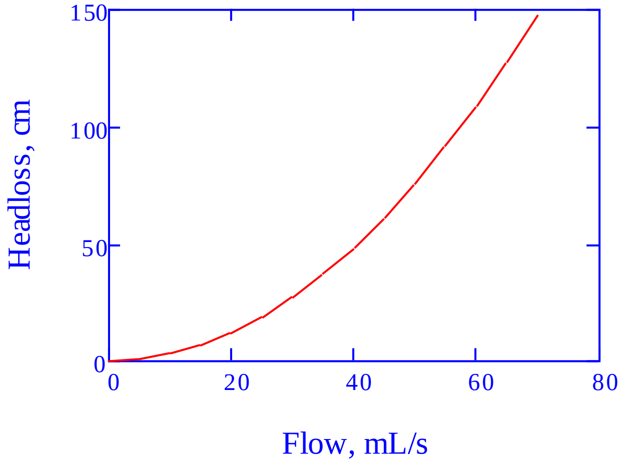

Figure 7. Calculated head loss through 3/8" Type 323 Ball Valve at different flow rates.

In addition to the valve, minor losses are also added to the design from the entrance and exit losses in various fittings (barb fittings, hose connectors etc.) .

$$h_e = K \frac{8}{g\pi} \frac{Q^2}{D^4} \qquad (14)$$

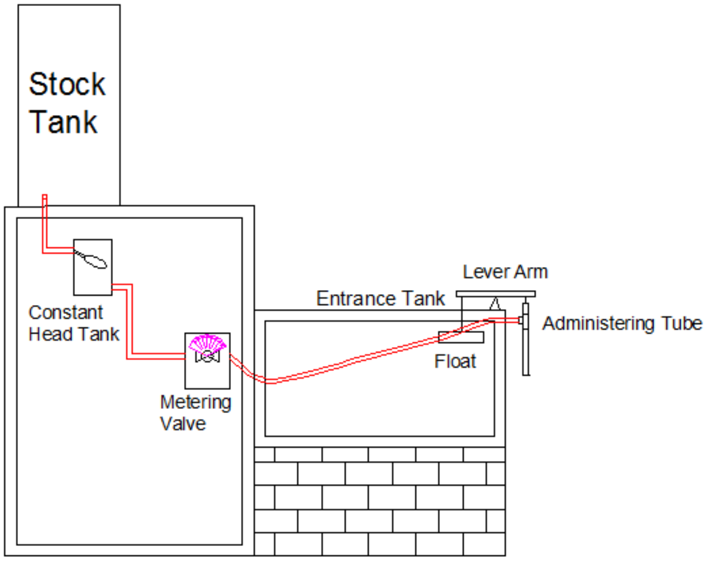

Figure 8. Plumbing connections for HFDC

Major losses (h_f) exist in any associated tubing and are dependent upon the length (L), diameter (D) and friction-factor (f) of the tubing runs as demonstrated by Equation 15.

$$h_f = f \cdot \frac{8}{g\pi^2} \cdot \frac{L \cdot Q^2}{D} \tag{15}$$

Total head loss through the chemical dose controller plumbing is modeled by adding the major head loss from the tubing to the sum of all the minor losses.

$$h_L = h_f + \sum h_e \tag{16}$$

Plumbing and associated connections can have a major impact on the expected flow rates through the dose controller. In designing how the HFDC should be plumbed, it is important to better understand this potential impact. The point at which the losses in the plumbing become the dominant factor in determining flow through the dose controller has yet to be established. Once this point is determined, the actual fittings and plumbing can be selected.

What sets the Type 323 Metering Ball valve apart from alternative styles of valves is the ease with which a calibrated scale can be incorporated into the design. The valve comes standard with graduated markings and pointers. AguaClara will be able to easily adopt this to a workable scale for our plants. Using linear regression, a model was created that demonstrates the expected flow rate from both sizes of the Type 323 valve (Figure 9). This model was validated against published data and flow rates measured in the lab. There exists a 16% difference between expected and measured flow rates. Although the current model accounts for this, once the analysis is completed on plumbing losses, the model should be updated. The valve selection model was created in MathCad and is available for future design work.

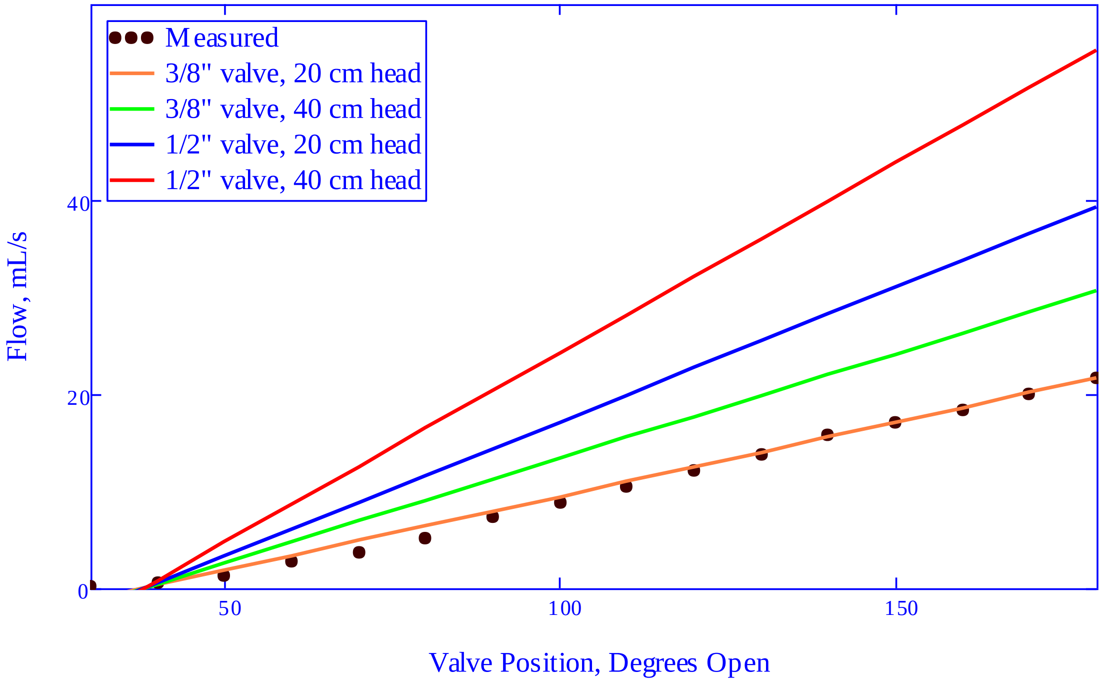

Figure 9. Mathematical model of expected flow rates at various positions of valve opening. Model was validated with empirical and manufacturers data.

Design - Entrance Tank Exit-Manifold

In response to the need to hydraulically decouple the entrance tank from the flocculator, the HFDC team developed the High Flow Orifice Meter (HFOM).

As with the Linear Flow Orifice Meter (LFOM) currently used in AguaClara plants, the relationship between flow through the dose controller and the plant flow rate must be the same. In the case where an orifice is used to meter the process chemicals, this flow rate is proportional to the square root of available head ($Q \alpha \sqrt{\Delta h}$). The Non-Linear Dose Controller (NLDC) was the first design to attempt this. In this design, the orifice served a dual purpose; not only was it used to maintain the relationship between plant flow rate and entrance tank level, this orifice also served to better mix the plant coagulant with the incoming water (Figure 10).

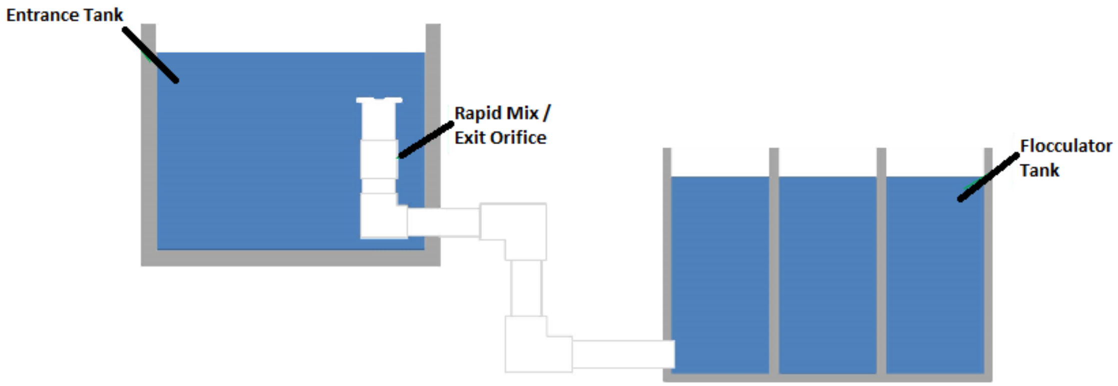

Figure 10. NLDC Design showing dual-purpose exit-orifice. In this design the orifice is used for both plant flow metering and mixing of coagulant.

One can see in Figure 10 that the entrance tank is hydraulically connected to the flocculator. As described in the introduction, this design failed when grit accumulated in the flocculator, thereby changing the expected head loss through that part of the plant. This changed the relationship between the level in the entrance tank and the flow rate through the plant, thereby causing the NLDC to dose incorrectly.

The HFDC team has solved this problem with a new design for an entrance tank exit-manifold (Figure 11). Influent free-jets through a series of orifices into an exit-manifold. The head loss through these orifices is sized to match the plant head loss so that a change in the level in the entrance tank will match a change in the plant flow rate. With the use of a lever and float, this level change will change the differential height between the constant head tank and the administering tube. This exit-manifold has been named the High Flow Orifice Meter (HFOM).

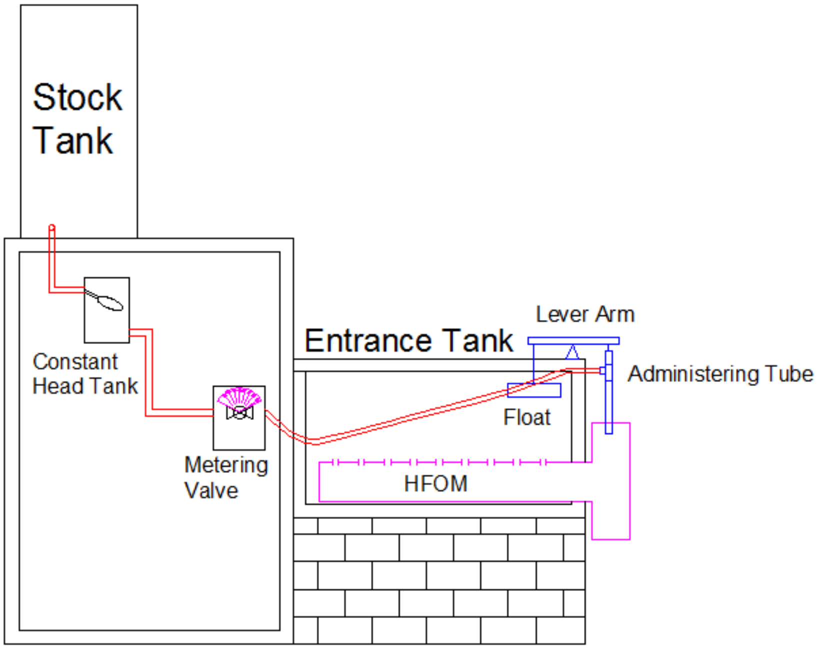

Figure 11. Illustration of HFDC components including new, hydraulically decoupled exit manifold (HFOM)

The sizing of the free-jet orifices is determined by the plant flow rate (Q) and the target head loss (h) through the orifices. This target head loss must match the designed plant head loss.

$$A_{total} = \frac{Q_{plant}}{K_{vc} \cdot \sqrt{2gh}} \tag{17}$$

This equation, however, determines the total area needed. As described, the HFOM will consist of a series of orifices in a large manifold. The length of the manifold will be constrained by the width of the entrance tank. The number of orifices needed and the spacing of the holes can be maximized to obtain the best structural stability of the pipe while obtaining the desired head loss. Once these parameters are determined, the diameter of each orifice (D) can be determined by dividing the total area (A) by the number of orifices (N).

$$D = \frac{A_{total}}{N} \tag{18}$$

The water passing through these orifices will free-jet into a manifold (pipe) that will then transport the water out of the entrance tank. This pipe must be large enough in diameter to maintain an air space at the top of the pipe thus ensuring that no hydraulic connection exists between the entrance tank and the rest of the plant.

The diameter of this manifold will be modeled by assuming that frictional losses due to shear on the wall are insignificant. The depth of water in the pipe is set by the critical depth at the pipe outfall where it drops into the vertical pipe. Knowing that critical flow occurs when specific energy is at a minimum, the depth at critical flow is determined by:

$$\frac{dE}{dy} = 1 - \frac{Q^2}{g \cdot A^3} \cdot \frac{dA}{dy} \tag{19}$$

where $\frac{dA}{dy}$ will equal the pipe diameter, D_c, at critical flow. Setting $\left(\frac{dE}{dy}\right)$ to zero, Equation 19 becomes:

$$1 = \frac{Q^2 \cdot D_c}{g \cdot A_c^3} = \frac{V^2 \cdot D_c}{g \cdot A_c} \tag{20}$$

The depth of water at the exit is constrained to half the diameter of the pipe. This assumption provides for a simplified, conservative design. Thus the critical depth, (y_c), is half of the pipe diameter, (D_c). The critical area, (A_c), therefore is described by:

$$A_c = \frac{\pi \cdot y_c^2}{4} = \frac{\pi \cdot D_c^2}{8} \tag{21}$$

Substituting Equation 21 for A_c into Equation 20 and solving for pipe diameter (D_{HFOM}):

$$D_{HFOM} = \sqrt[5]{\left(\frac{8}{\pi}\right)^3 \cdot \frac{Q^2}{g}} \qquad (22)$$

Figure 12 shows the relationship between plant flow rate (Q) and calculated inside pipe diameter of HFOM. Please note that is this the actual inside diameter of the pipe and has not been corrected for National Pipe sizes.

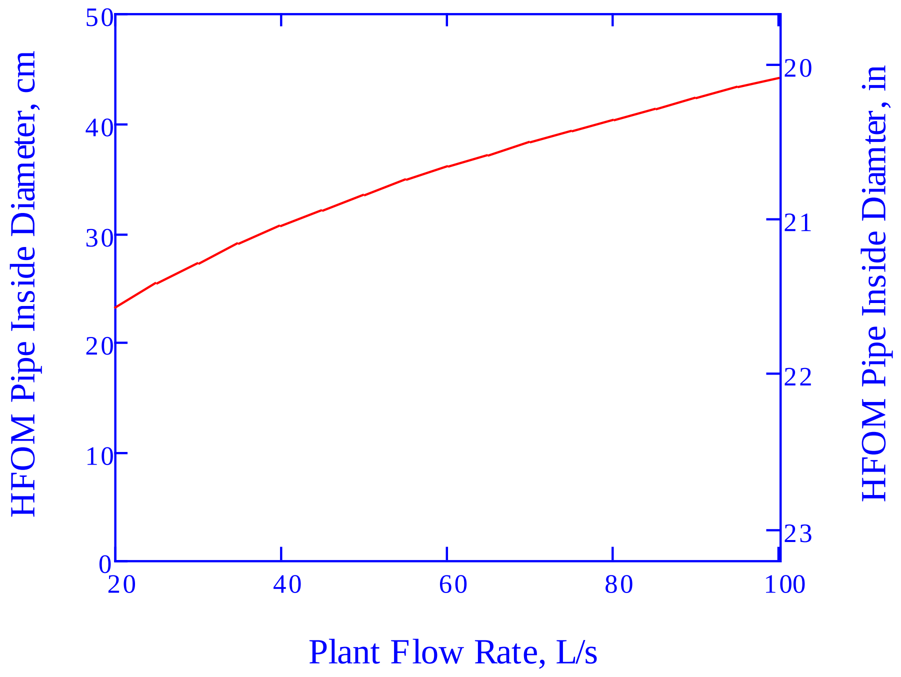

Figure 12. Calculated ID of HFOM as a function of plant flow rate.

The water depth at the upstream end of the pipe is obtained by calculating the total energy through an open channel. For the purpose of this model, we assume that all water is entering the pipe at the upstream end and is not evenly distributed through the multiple in-line orifices. The model is derived from the energy equation which states that the specific energy (E), is equal to the sum of the depth of flow, (y), and the velocity head, $\left(\frac{V^2}{g}\right)$ as shown in Equation 23.

$$\mathrm{E} = \mathrm{y} + \frac{\mathrm{V}^2}{2\mathrm{g}} \qquad (23)$$

Again, the water level, or depth of flow, is constrained at half the pipe diameter:

$$y = \frac{D}{2} \qquad (24)$$

Referring to Equation 20:

$$1 = \frac{\mathrm{Q}^2 \cdot \mathrm{D_c}}{\mathrm{g} \cdot \mathrm{A_c^3}} = \frac{\mathrm{V}^2 \cdot \mathrm{D_c}}{\mathrm{g} \cdot \mathrm{A_c}} \qquad (25)$$

Substituting in Equation 21:

$$\frac{V^2}{2g} = \frac{A_c}{2D_c} = \frac{1}{2D}\frac{\pi D^2}{8} = \frac{\pi D}{16} \qquad (26)$$

The energy equation becomes:

$$\mathrm{E} = \mathrm{y} + \frac{\mathrm{V}^2}{2\mathrm{g}}$$

$$E = \frac{D}{2} + \frac{\pi D}{16} \qquad (27)$$

Simplifying, the depth at the entrance of the HFOM is modeled as:

$$E = y_{initial} = .7D \qquad (28)$$

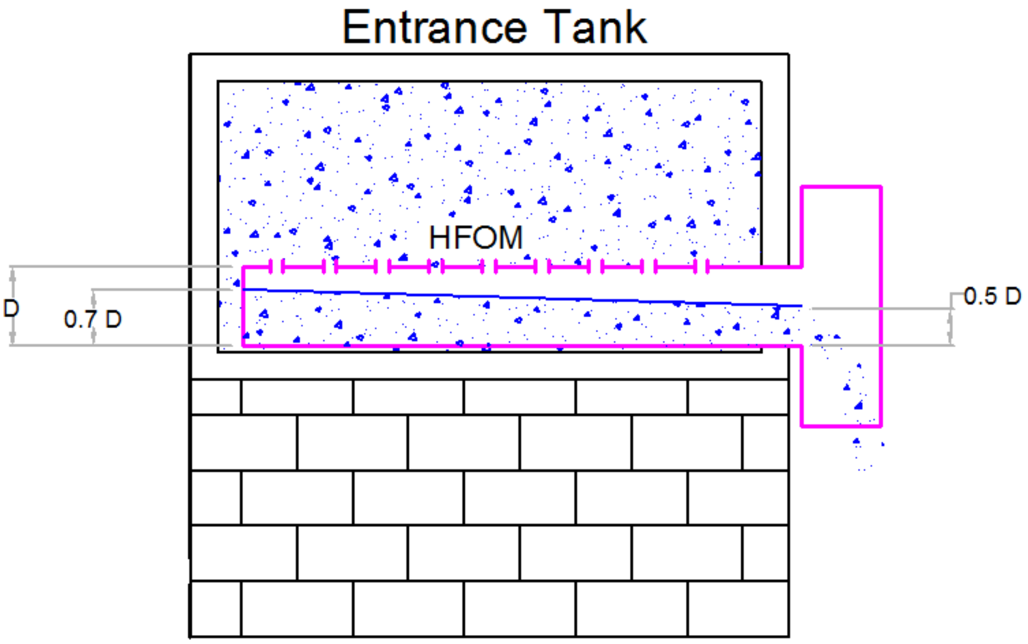

Figure 13. Illustration representing water level in HFOM. Water level at entrance of HFOM is 70% of pipe diameter. Water level at exit is constrained at half of pipe diameter.

As demonstrated by Equation 28 and Figure 13 , the water depth at the entrance of the HFOM ($y_{initial}$) is70% of the pipe diameter. However, this conservative model assumes all water enters the pipe at one end. In actuality, water enters the HFOM through the orifices along the length of the manifold. As plants increase in size, it may be worthwhile to formulate this more complicated model. The current model for the HFOM has been created in MathCad and is available for future design work.

Conclusions and Recommendations

The Georg Fischer Type 323 Meter Ball valve offers a simple solution to the high flow dosing challenges faced by AguaClara. From the valve model, the maximum flow rate expected from the Type 323 ½" valve with 40 cm of available head is approximately 55 mL/s (16%). Required coagulant flow rates for larger plants have yet to be determined, however, if the Type 323 valve series does not possess sufficient capacity, Georg Fischer offers a different valve series with a larger range. The Type 546 valve can be modified with the characteristic ball and includes a range of valves capable of supplying 200 mL/s on the low end and up to approximately 1750 mL/s for the largest valve in this series. A drawback to this valve is that the graduated face plate is not a part of the design and the valve is a "quarter turn" valve, meaning the range of opening is only 90 degrees. This may make it difficult for precise control.

The High Flow Orifice Meter, HFOM, solves the problems associated with the NLDC rapid-mix /flow meter orifice by eliminating the hydraulic connection between the entrance tank and the flocculator. In keeping with AguaClara standards, the HFOM is simple to construct and yet maintains the necessary relationship between entrance tank level and plant flow rate.

Coupled together, the Georg Fischer Meter Ball valve and the High Flow Orifice Meter make up the High Flow Dose Controller. This design allows AguaClara technology to increase in capacity, making it suitable for municipalities with larger populations.

Future Work

As referenced throughout the paper, MathCad files for various aspects of this design have been created and can be found in the "Attachments" section of this web-page. Prior to incorporating this design into the Design Tool, there are a number of outstanding design issues that require addressing.

The Type 323 Meter Ball valve has been analyzed and modeled, however, the losses within the HFDC tubing and fittings have not been included in the model. The point where major and minor losses would dominate the flow characteristics of the dose controller should be determined before the plumbing can be designed. After this analysis, minimum tubing sizes and maximum lengths can be recommended along with appropriate fittings. Once completed, the model can be updated to reflect these constraints.

The failure point of the valve has yet to be determined. If plant head loss is designed for 20 cm, then at 50% capacity, the valve will only have 5cm of head available. Recording how the valve behaves under this condition is an important consideration. In fact, only preliminary data exists on the valve. Once the plumbing is decided upon, it will be worthwhile to test the valve under a wide variety of "operating conditions."

Head loss analysis for the plumbing and further valve validation could be an appropriate project for 2 summer interns with some, but not necessarily extensive, experience with AguaClara. Fluid mechanics would be a critical prerequisite.

Additionally, the HFOM design algorithms do not increment to actual National Pipe Thread (NPT) sizes. This will need to be corrected. HFOM length, orifice sizing/spacing need to be maximized. Because these are constrained by entrance tank dimensions, this would be an appropriate project for a sub-team within the Design Team.

On a final note, because the HFOM pipe ID as calculated is quite large with this model, it may be prudent to pursue a less conservative design. The HFDC team recommends installing the HFOM/HFDC system in a plant at the lower end (20 L/s) for validation prior to scaling up to the full 100 L/s. This could provide a means for testing the optimization of the HFOM inside diameter.