Chemical Dose Controller/Linear Flow Orifice Meter Reflection Report

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AguaClara Reflection Report

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Date Submitted: 11/05/2011

Abstract

Accurate chemical dosing is important in water treatment plants to ensure optimal conditions for flocculation, sedimentation and disinfection of the treated water. The linear chemical dose controller uses laminar flow through a small diameter tube to create a linear relationship between head loss and chemical flow. The linear flow orifice meter then maintains a linear relationship between plant flow and water elevation. The linear relationships simplify chemical dosing for plant operators who may have a limited education. Our team is researching the upper-flow limit of the linear dose controller and developing innovative designs to increase the capacity of this system to function in plants with flow rates approaching and above 100 L/s. Furthermore, we are redesigning and simplifying the linear flow orifice meter algorithm to improve its precision and performance in the field.

Brief History

The AguaClara team began developing a hydraulic system to add coagulant during the water treatment process when the project commenced in 2005. The chemical dose controller (CDC) system relates flow and head loss in either a linear or non-linear relationship. Initially, a linear dosing system, using a linear chemical dose controller and a linear flow orifice meter, was preferred because it was simple for the operator to understand and operate. Early research efforts concluded that the linear dosing system could not be used for plants with high flow rates because the maximum chemical flow rate, for which laminar flow could be maintained, was only 7 mL/s. This limitation led the AguaClara team to adapt their design to a non-linear model, designed with orifices to control chemical flow. This model was installed at an AguaClara plant in Agalteca, Honduras. Operators' feedback suggested that this system was more complicated to understand and operate because: (1) it used multiple orifices and scales, (2) the orifices used were not easily fabricated in Honduras, and (3) the system employed a rapid mix orifice which, at times during rainy season, would allow sediment to build up in the flocculator, causing increased head loss through the plant and resulting in the system over-dosing. This semester, our team has been assembled to continue prior semesters' teams' research on the linear chemical dosing system and determine its ability to perform in plants with high flow rates.

Introduction to Current Research

Major head losses are frictional energy losses which depend upon the fluid's Reynolds number. The CDC regulates flow with major head loss from a small diameter tube. A linear relationship between flow and head loss is preserved when chemical flow through the tube is laminar. To be laminar, the Reynolds number of the flow must remain below 2100. Equation 1 allows for the calculation of a minimum inner diameter to maintain a Reynolds number in the laminar range. The minimum inner diameter of the small tube (ID_{Tube}) to maintain laminar flow is a function of the maximum chemical flow rate (Q_{CDCmax}) and viscosity of the fluid (ν_{H2O}) (Equation 1)

$$ID_{Tube} = \frac{4Q_{CDCmax}}{\nu_{H2O}\pi \mathrm{Re}_{\mathrm{Number}}} \qquad (1)$$

Tube length sets the total major head losses and the length of the small diameter tube (L_{Tube}) is a function of the maximum head loss (H_{max}), the minimum inner diameter of the small tube (ID_{Tube}), the maximum chemical flow rate (Q_{CDCmax}) and the viscosity of the chemical solution (ν_{H2O}) (Equation 2).

$$L_{Tube} = \frac{H_{Max} \mathrm{g} \pi ID_{Tube}^4}{128\nu_{H20}Q_{CDCmax}} \qquad (2)$$

Adding parallel small diameter tubes will circumvent the laminar flow constraint by allowing for higher total chemical flow rates through the system while maintaining laminar flow. This will allow the linear CDC to function in plants with flow rates approaching 100 L/s.

The linear relationship between head loss and flow rate is preserved via the linear flow orifice meter (LFOM) (Figure 19). The LFOM maintains an approximate linear relationship between the surrounding water's head and flow through the LFOM. As the depth of water in the entrance tank changes to reflect a changing plant flow rate, the LFOM is designed so that the water flow rate through it is also adjusted to maintain a linear relationship between this water depth and flow rate. Redesigning the LFOM algorithm to redefine its "zero-point," the point at which there is zero flow through the LFOM, will improve its ability to deliver predicted flow rates.

Experimental Design

The chemical dose controller system controls flow using several components. As seen in Figure 1, the chemical flows from a stock tank, through a large-diameter tube into the constant head tank (CHT). The tube leading into the CHT should have a large diameter so that major head loss is negligible. The chemical depth in the CHT is maintained at a constant level by a float valve. To maintain a constant chemical dose over time, it is imperative that the chemical depth in the CHT remain constant. From the CHT, the chemical flows through one (or several) small diameter tube(s) to the drop tube. The small diameter tube(s) is connected to the CHT by a barbed fitting. The small diameter tube(s) have a very specific diameter and length to control total head loss through the system. Although it is not always attained (see Minor Loss Modeling section below), the goal is to have negligible minor losses so that flow remains laminar and is controlled via major head losses through this small diameter tube.

To serve plants with higher total flow rates, more than one small diameter tube can be used. The small diameter tube(s) is connected with a barbed fitting to the drop tube. The chemical exits the small diameter tube and flows supercritically into the drop tube. The drop tube is designed so that the chemical exits and flows directly into the entrance tank, where it is mixed with incoming plant flow. The drop tube is connected to a lever via a slider. At its other end, the lever is connected to a float which sits in the entrance tank (our lab setup uses the elevation setting board instead of a float to simulate changes in plant flow rate). The lever has a scale which tells the plant operator where to set the slider to receive the desired chemical dose. After the plant operator sets the position of the slider to receive the desired chemical dose, the float changes elevation, and therefore changes the chemical flow rate through the CDC, as the plant flow rate changes. Therefore, the dose set by the plant operator is maintained as the plant flow rate changes.

Our experiments to test the effect of adding parallel small diameter tubes to the CDC system are completed with a newly-fabricated model in our lab. Our lab setup uses many components in the same roles as they have been used previously in the CDC, including a stock tank, CHT with a float valve, a lever and a slider (see previous paragraph which describes roles of each component).

However, there are several novel innovations:

- Three ports near the base of the CHT connect three ports at the top of the chemical drop by a small diameter tube. We can now test the effects of having three small diameter tubes in parallel in attaining laminar chemical flow rates.
- Although our lab apparatus is mounted on an aluminum frame structure, called an 80/20 (pronounced “eighty twenty”), it simulates the most current design installed in AguaClara plants where an 80/20 frame is no longer used.
- Additionally, we are using a strong, rectangular piece of plastic and a pin on one side of the lever so that we are able to set the angle of the lever arm.

Inserting the pin in the plastic sheet sets standard elevations which will improve our experiments' precision and allow us to easily reproduce our results.

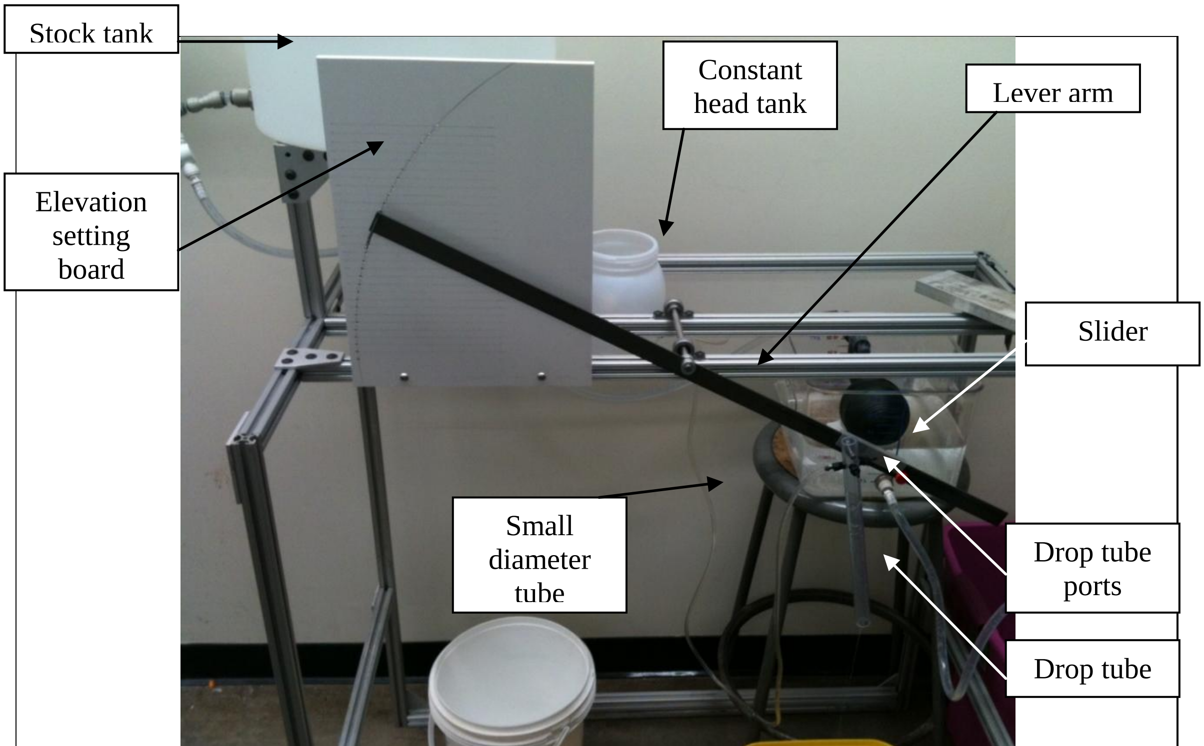

Figure 1: Spring 2011 Linear Chemical Dose Controller Lab Setup

Chemical flow rates are measured with the CDC apparatus seen in Figure 1. To set total head loss at zero, the CHT's water elevation must be set equal to the small diameter tubes' outlet elevation into the drop tube. At this elevation, when the lever is set to reflect zero total head loss, there is zero flow through the system.

To measure flow rates, the total head loss was set (on the elevation setting board as seen in Figure 1) at settings ranging from 1 to 20 centimeters. After setting the elevation, the experimenter then collects the total volume of flow through the system in a graduated cylinder during a sixty second interval. The mass of the accumulated flow is measured with a mass balance, and dividing mass by the density of water, the total volume of the flow is known. This volume is divided by the length of the time interval to determine the observed flow rate.

In contrast to the CDC experimental methods described above, our LFOM research will largely be analytical and mathematical modeling with Mathcad. Nonetheless, as our improved LFOM design progresses, we will have the opportunity to fabricate the design and test it in the remains of a demo AguaClara plant located at the Cornell water treatment plant.

Theoretical Calculations

We theoretically determined the range of plant flow rates for which we can use 1, 2 and 3 small diameter tubes in parallel. We plotted the optimal length of the small diameter tube at different coagulant flow rates (Figure 2). For these coagulant flow rates, we estimate that the linear chemical dose controller could theoretically serve plants with flow rates up to 100 L/s while maintaining laminar flow within small tubes with diameters between 0.096 in – 0.16 in. We designed an algorithm that would select an available tube diameter given the calculation's stated optimal tube diameter. For this reason, the graph appears to be a sort of step function.

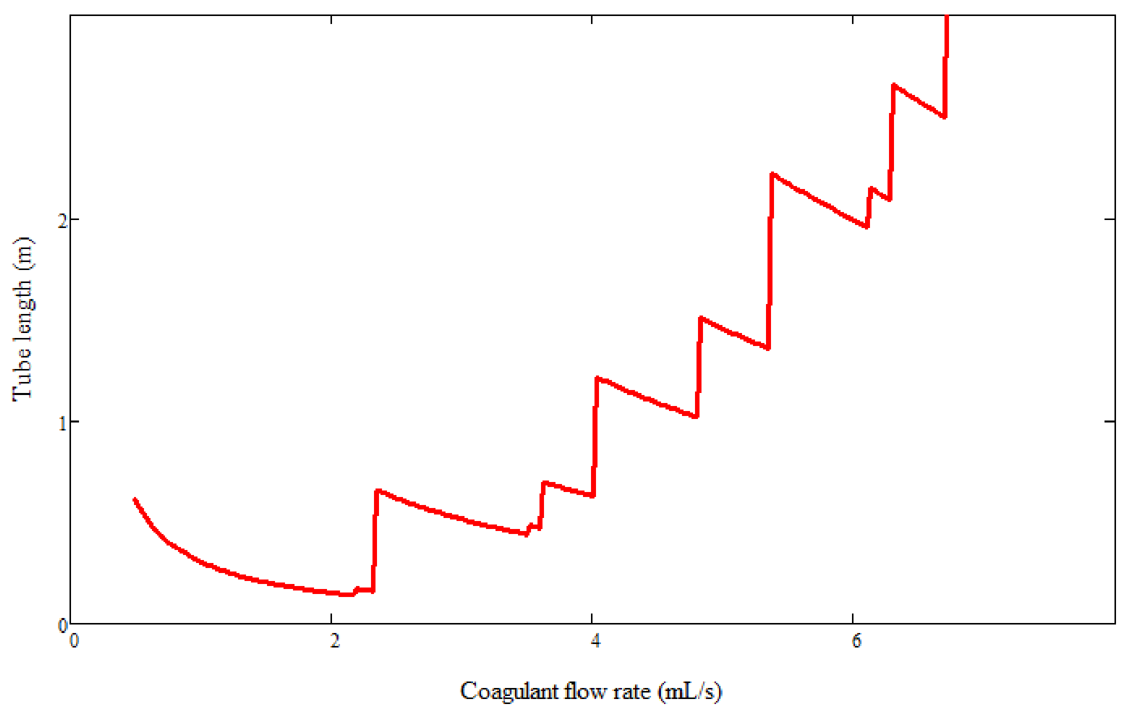

Figure 2: Necessary small diameter tube length at different coagulant flow rates

Increasing the number of parallel small diameter tubes from one to three would triple the total allowable chemical flow rate. Furthermore, increasing the stock concentration of the chemical can dramatically expand the capacity of the linear chemical dosing system.

There is an upper limit to the length of the small diameter tubes near 2 m to 2.5 m. This limit exists for several practice reasons: (1) longer the tubes are more apt to get tangled or interfere with the movement of the lever arm, (2) operators in the past have cut the tubes if they are too long, which changes the system's design by altering the major head loss through the system, and (3) if the operator coils the tubes, it could lead to additional head losses from secondary flow effects which would reduce the true linearity of the system.

Results and Discussion

Initial Laboratory Results

Several sets of experiments have been performed with our lab apparatus presented above (Figure 1). These experiments were designed to test the new components of the CDC system including the drop tube, the barbed fittings on the CHT and on the drop tube and the use of multiple small diameter tubes in parallel. The expectations were to observe flow rates comparable to those calculated by the Hagen-Poiseuille equation where the chemical flow rate (Q_{CDC}) is a function of major head loss (h_f), small tube diameter (D_{Tube}), kinematic viscosity (ν) and the length of the small diameter tube (L_{Tube}) (Equation 3).

$$Q_{\mathrm{CDC}} = \frac{h_f g \pi D_{Tube}^4}{128 \nu L_{Tube}} \tag{3}$$

Experiments were conducted with one, two and three small diameter tubes in parallel. The elevation of the lever is adjusted and flow rates are calculated for multiple settings.

The experimental results appear below in Figure 3, Figure 4, and Figure 5. (Note: the figures' captions detail the number of small diameter tubes used during each experiment.)

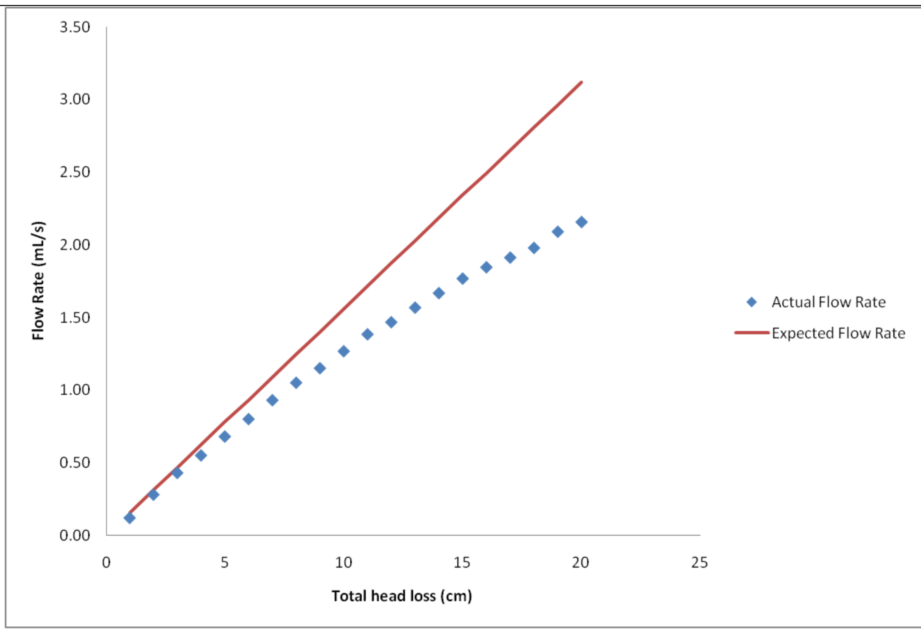

Figure 3: Experimental Results with 1 small diameter tube (March 13, 2011)

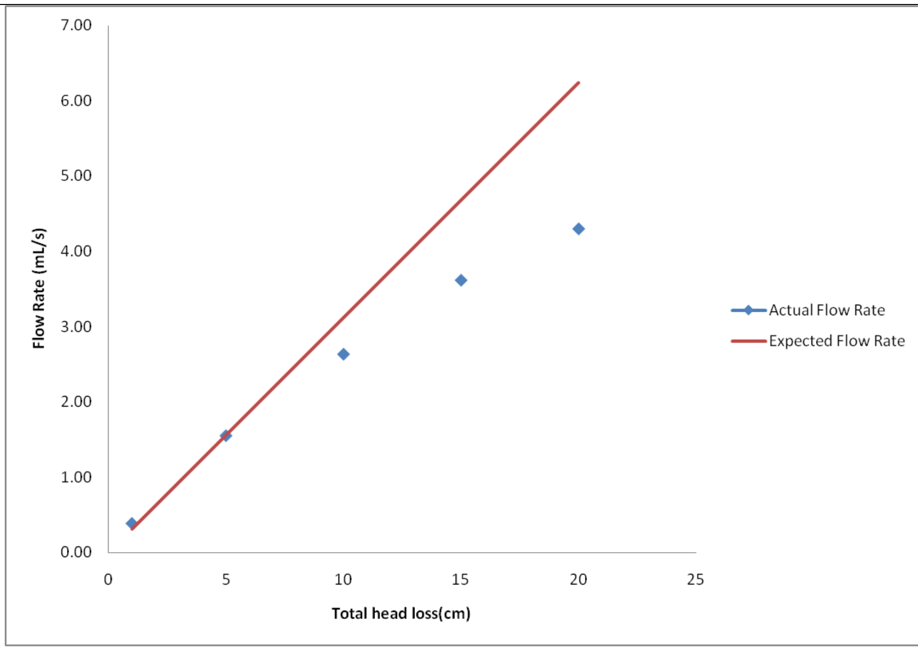

Figure 4: Experimental results with 2 small diameter tubes (March 17, 2011)

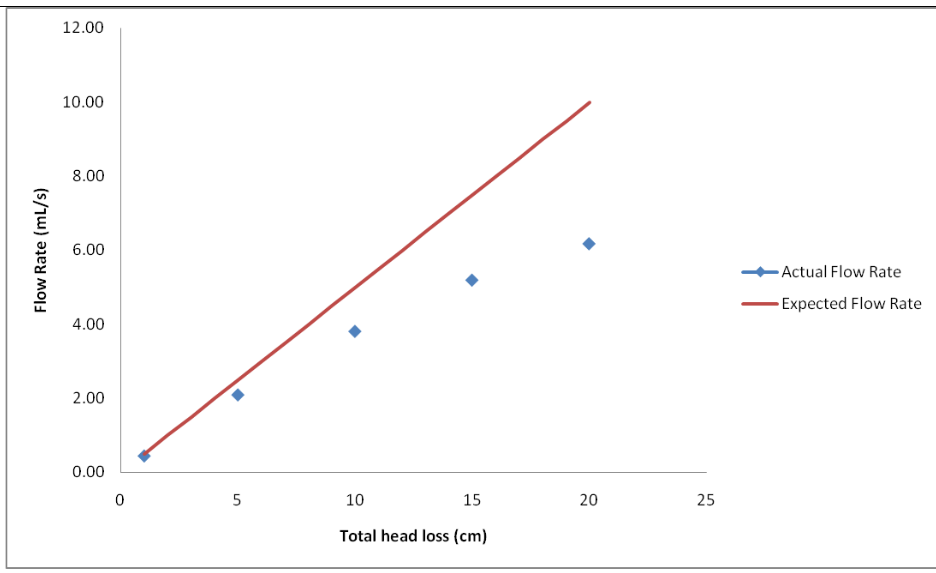

Figure 5: Experimental results with 3 small diameter tubes (March 15, 2011)

The data was expected to be linear with respect to elevation. However, a non-linear deviation was noted that increases as the head loss increases. As a result, the actual flow rates are much lower than the expected flow rates through the system at the majority of settings, including all settings above 5 centimeters.

The team's current hypothesis is that specific components of the lab apparatus are restricting flow through the system and causing minor head losses From three sources: (1) barbed fittings which connect the end of the small diameter tube(s) to the drop tube could be restricting flow, (2) the size of the small diameter tube's curve radius at its low point, and where it connects to the CHT and (3) the development of the parabolic flow distribution in the entrance region at the beginning of the small diameter tube(s) near the CHT.

Minor Loss Modeling

To explain minor losses, the team performed three flow rate measurement trials at different settings of total head loss for a number of different experimental setups. The different experimental apparatus setups are presented in Table 1 below.

Table 1: Lab experimental setups

Lab Setup	Inner tube diameter (in)	Tube length (m)	Number of tubes
1	0.124	1.47	1
2	0.124	1.47	2
3	0.124	1.47	3
4	0.124	2.95	1
5	0.124	3.06	1

The team then averaged the flow rate measurements from the three trials to find an average observed flow rate at a given total head loss setting for a given lab setup.

The goal of accumulating this experimental data was to find the minor loss coefficient at each of the aforementioned lab setups. Determining a minor loss coefficient will improve the team's efforts in mathematically modeling the minor losses for future CDC arrangements. The team derived a formula to find the chemical flow rate as a function of total head loss and the minor loss coefficient. First, the total head loss (H_{total}) is the sum of major (h_f) and minor (h_e) head losses.

$$H_{total} = h_f + h_e \qquad (4)$$

Major head losses for laminar flow are a function the kinematic viscosity of the chemical (ν), the chemical flow rate (Q), the length of the small diameter tube (L) and the inner diameter of the small diameter tube (D).

$$h_f = \frac{128\nu QL}{g\pi D^4} \qquad (5)$$

Minor head losses are a function of the chemical flow rate (Q), the minor loss coefficient (k_e) and the inner diameter of the small diameter tube (D).

$$h_e = \frac{8Q^2 k_e}{g\pi^2 D^4} \tag{6}$$

Therefore the total head loss is:

$$H_{total} = \frac{128\nu QL}{g\pi D^4} + \frac{8Q^2 k_e}{g\pi^2 D^4} \tag{7}$$

For ease of use with the experimental data, one must alter this formula to express the chemical flow rate (Q) as a function of the kinematic viscosity of the chemical (ν), the length of the small diameter tube (L), the inner diameter of the small diameter tube (D) and the minor loss coefficient (k_e). To do so, the team applied the quadratic equation:

$$Q = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{8}$$

Where:

$$a = \frac{8k_e}{g\pi^2 D^4}$$

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

$$c = -H_{total}$$

Applying the quadratic equation, one finally arrives at Equation 9 below.

$$Q = \frac{-\frac{128\nu L}{g\pi D^4} + \sqrt{\left(\frac{128\nu L}{g\pi D^4}\right)^2 + 4\left(\frac{8k_e}{g\pi^2 D^4}\right)(H_{total})}}{2\left(\frac{8k_e}{g\pi^2 D^4}\right)} \tag{9}$$

For each experimental setup, the team inserted given values of tube length (L), tube inner diameter (D), and kinematic viscosity (ν), along with the total head loss (H_{total}) that was set. Finally, Excel's Solver tool, was used to find the minor loss coefficient (k_e) which produces the flow rate that minimizes the total absolute percent error for the given experimental setup. The only constraint set within the Solver tool was that the minor loss coefficient (k_e) must be greater than or equal to zero. The minor loss coefficients that minimized the total absolute percent error between the measured actual flow rate (from laboratory flow rate measurements) and the calculated flow rate using Equation 9 above for each experimental setup are presented below in Table 2.

Table 2: Minor loss coefficients

Lab Setup	Characteristics	Minor loss coefficient (k_e)
1	D = 0.124 in, L = 1.47 m, 1 tube	19.87
2	D = 0.124 in, L = 1.47 m, 2 tubes	16.53
3	D = 0.124 in, L = 1.47 m, 3 tubes	18.92
4	D = 0.124 in, L = 2.95 m, 1 tube	9.53
5	D = 0.124 in, L = 3.06 m, 1 tube	9.80

To demonstrate that these minor loss coefficients provide a good fit with the actual flow rates measured in the lab, Figure 6 below shows actual flow rates observed in the lab and calculated flow rates with the above minor loss coefficient for lab setup 1.

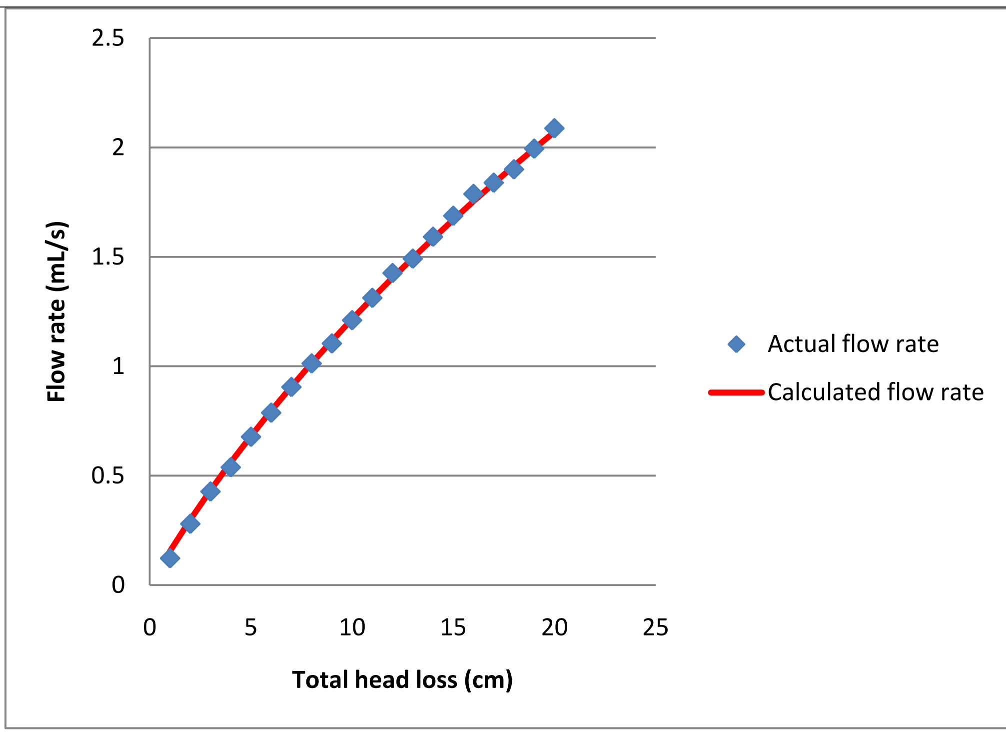

Figure 6: Actual and calculated flow rates with lab setup 1

It is important to stress that the minor loss coefficients presented in Table 2 and Figure 6 are the values which minimize total absolute percent error *over an entire range* of total head loss settings, and therefore, different flow rates, at each experimental setup.

It is natural then to inquire about the minor loss coefficient values at each total head loss setting for a given experimental arrangement.

Table 3: Minor losses at each total head loss setting (for lab setup 1)

Total head loss (cm)	K_e (at each setting)	Percent difference (between K_{avg} = 19.87 and K_e at each setting)
1	190.866	-860.69%
2	40.079	-101.73%
3	22.758	-14.55%
4	27.209	-36.95%
5	20.736	-4.37%
6	21.456	-7.99%
7	20.194	-1.64%
8	19.962	-0.48%
9	21.042	-5.91%
10	20.285	-2.10%
11	19.790	0.39%
12	18.498	6.89%
13	20.083	-1.08%
14	19.425	2.23%
15	18.979	4.47%
16	18.332	7.73%
17	19.722	0.73%
18	20.524	-3.30%
19	19.867	0.00%
20	19.292	2.90%

The very high minor loss coefficients for total head losses of 1 to 4 centimeters (seen in Table 3) may be large because the flow rate through the tube(s) is very low at those total head loss settings. This is likely evidence that surface tension is affecting flow rates at low chemical flows. Minor loss coefficient values will increase substantially at flow rates at which surface tension has an effect. The data collected during additional experiments indicates that at chemical flow rates above 0.5 mL/s, surface tension has little influence on chemical flow rate. Because extensive experimentation was not conducted with flow rates below 0.5 mL/s, this may be a conservative upper limit for the flow rate below which surface tension has an effect on chemical flow rate.

If one neglects the values which are likely associated with surface tension effects (values for total head loss equal to 1 to 4 cm), the minor loss coefficient values appear fairly similar at different total head loss settings in Table 2 and the majority is near the average minor loss coefficient presented for lab setup 1 in Table 2. One can make several preliminary conclusions. First, although the length of the tube should have no effect on the minor loss coefficient, it appears that the length of the small diameter tube is indeed having an effect on the minor losses through the system. The length of the tube could have an effect because: (1) the tube's radius of curvature between the CHT and the drop tube changes as the tube's length changes and (2) the length of the entrance region (the region before the parabolic velocity distribution has developed) changes as flow rate a change, which is a function of tube length.

To investigate the effects of changing the length of the small diameter tube on the minor losses through the system, our group compiled experimental results into graphs showing small diameter tube length against the average calculated minor loss coefficient for a given laboratory setup. We performed the experiments for a variety of tube lengths, a variety of number of small diameter tubes (1, 2 or 3) and two different sizes of barbed fitting. The two graphs appear below (Figure 7 and Figure 8).

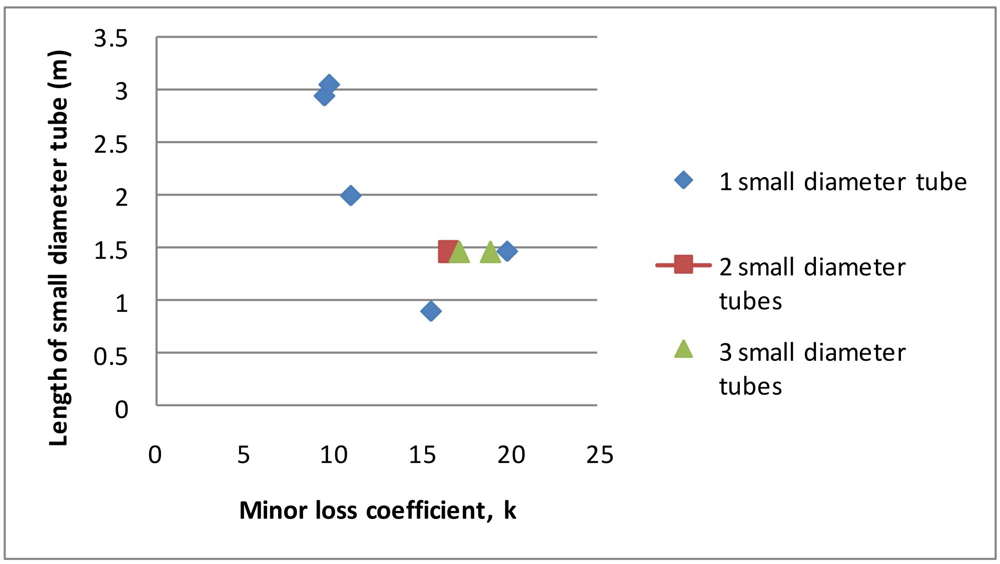

Figure 7: Minor loss coefficient for various tube lengths (using barbed fittings with inner D = 0.075 in)

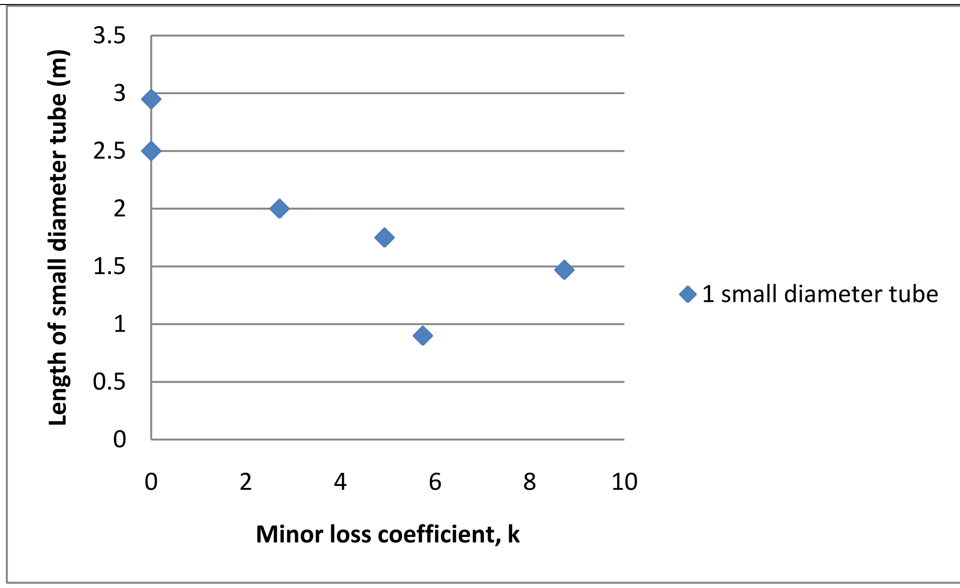

Figure 8: Minor loss coefficient for various tube lengths (using barbed fittings with inner D = 0.117 in)

One can make several preliminary observations regarding Figure 7 and Figure 8. First, there is indeed significant minor head loss through the barbed fittings. Increasing the inner diameter of the barbed fittings reduces the minor losses through them. Second, the minor loss coefficient is clearly changing as length changes. However, Figure 7 and Figure 8 do not clarify whether the minor loss coefficient is changing due to change in length or due to a change in chemical flow rate.

The suspicion that the minor loss coefficient could change with chemical flow rate stems from the fact that there exists an entrance region in the small diameter tube wherein the parabolic velocity distribution has yet to develop. The length (L) of this region is a function of the inner diameter of the tube (D) and the Reynolds number (Re).

$$L = 0.06\mathrm{Re} * \mathrm{D} \qquad (10)$$

Using our experimental diameter (D) value (0.124 in = 0.00315 m) and a Reynolds number (Re), 1900, which is near the upper-limit of laminar flow, the length (L) of the entrance region could extend to roughly 35 centimeters. This is a significant fraction of the total length of the small diameter tube. Within this entrance region, major head losses will be higher because the velocity profile is steeper. The group has previously assumed that the small diameter tube was long enough that the increased head loss through this entrance region could be ignored, but this is potentially a misplaced assumption.

Based upon the previous paragraph's investigative entrance length calculation, the group considered the relationship between Reynolds number and flow rate for a number of lab setups. The results are plotted below in Figure 9.

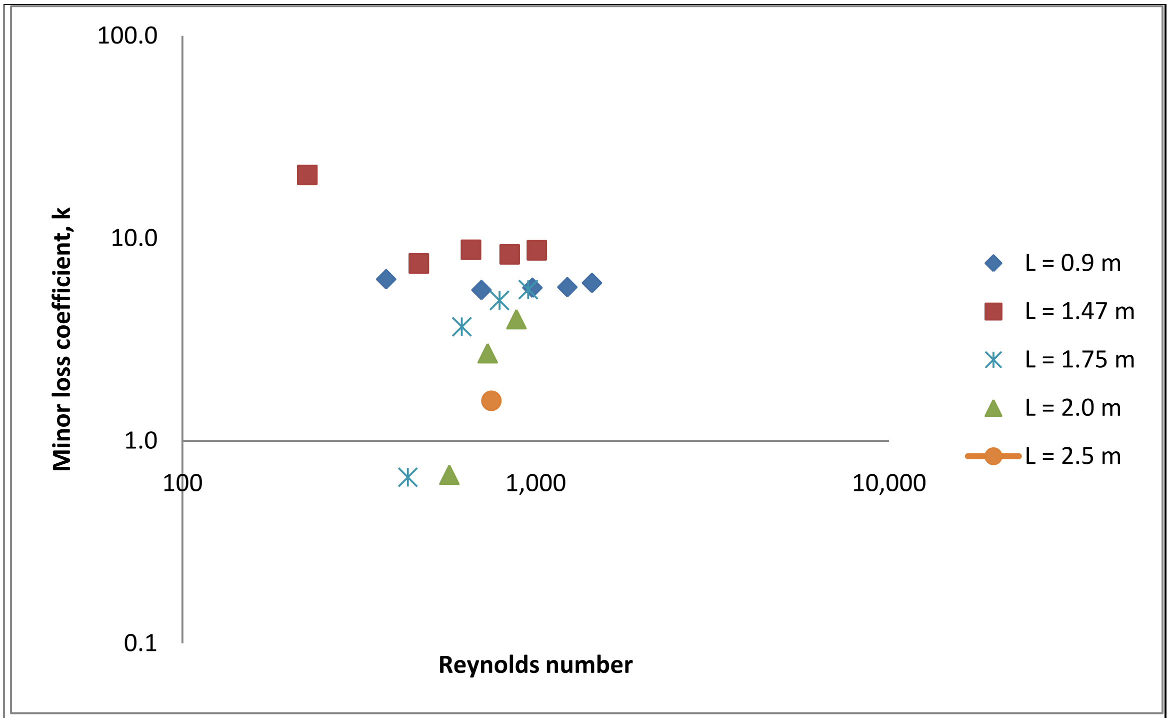

Figure 9: Investigation of relationship between minor loss coefficient and Reynolds number (length of small diameter tube indicated in the legend)

Figure 9 does not show a distinct trend between Reynolds number and minor loss coefficient. The conclusion can be made that the minor loss coefficient is not changing due to the change in the entrance region length, which is a function of Reynolds number.

More broadly, the group was concerned that the minor losses were changing as chemical flow rate through the tube changed. With this line of thought, we re-analyzed previously collected flow rate data to find not the average minor loss coefficient for a given lab setup (as was calculated previously), but rather the minor loss coefficient for each measured flow rate (as seen in Table 3). The results were organized into Figure 10 below.

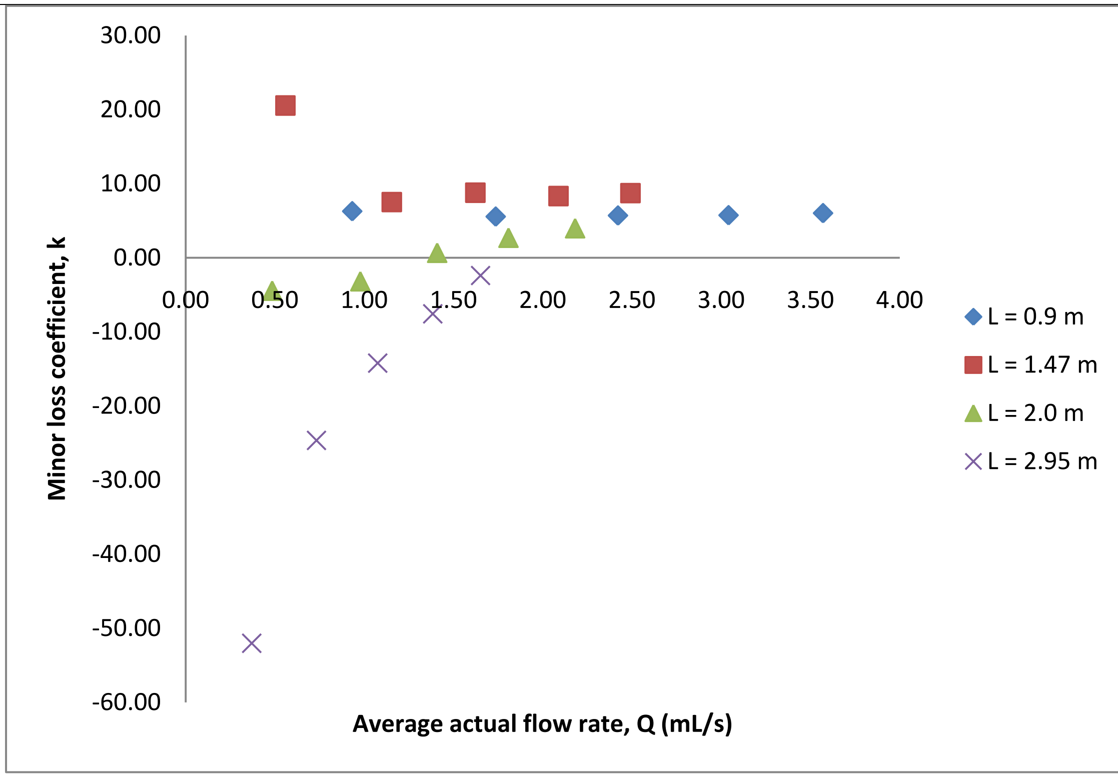

Figure 10: Minor loss coefficients at various flow rates

Figure 10 shows a general trend that the minor loss coefficient does not change with changing chemical flow rate (this trend is especially evident for small tube diameter length of 0.9 m and 1.47 m). The negative minor loss coefficient values for small tube diameter lengths of 2.0 m and 2.95 m are believed to be due to error in the group's experimental apparatus (for example, errors when setting the exact total head loss elevation while taking flow measurements or errors in measuring the exact diameter of the small diameter tube).

Prior to conducting this set of experiments, the team believed the main sources of minor head loss to be entrance losses as the chemical flows from the CHT into the barbed fitting leading into the small diameter tube, expansion losses into the small diameter tube from the barbed fitting, and exit losses as the flow leaves the drop tube's barbed fitting and flows into the drop tube. If these three sources were the only causes of minor losses, the minor loss coefficient would be roughly 3. The experiments suggest that additional sources exist, including minor losses in the entrance region before the velocity distribution is fully-developed and minor losses due to the small diameter tube's changing radius of curvature as the length of the small diameter tube is changed.

Calibration technique results

In the past, engineers and plant operators had been instructed to calibrate the CDC in an AguaClara plant by first finding the elevation at which there is zero plant flow through the LFOM and setting that elevation as the height where there is zero chemical flow through the CDC. Then the flow rate where the total head loss through the CDC system is 20 centimeters, the point where maximum chemical flow rate should be observed, would also be measured. If the chemical flow is less than the maximum chemical flow desired for the plant, the length of the small diameter tube would be decreased until the chemical flow rate increased to the desired value. The relationship between length of the small diameter tube and the chemical flow rate is presented in Equation 2.

If the CDC was perfectly linear, the second calibration point (ie. the measurement when total head loss is 20 cm as presented in the paragraph above) would not matter. However, because there are non-linear components in the CDC system, the second calibration point must be chosen because it is the point which will minimize the maximum percent error between the actual flow rates measured in the laboratory and a linear fit with a y-intercept of zero. To illustrate this method, Figure 11 is presented below. To minimize the total percent error for this setup, the second calibration point should be the point where the calculated flow rate (using the quadratic method described in the above Minor Loss Modeling section) intersects the linear fit. This point is 11 centimeters in Figure 11 below.

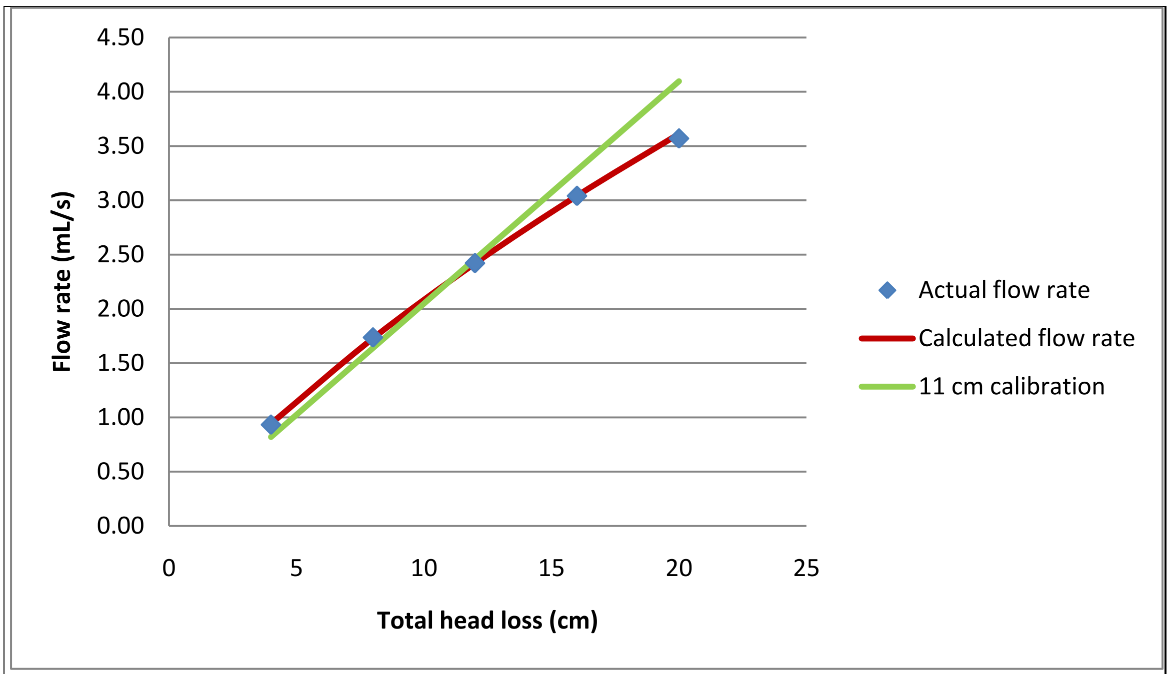

Figure 11: Laboratory results for a small diameter tube length L = 0.9 m

Figure 12 below shows percent errors between the calculated flow rate and the linear fit for various small diameter tube lengths. The optimal second calibration point is the point where the percent error line intersects zero. For each of the small diameter tube lengths below, the second calibration point should be at an elevation where total head loss is 11 to 13 centimeters.

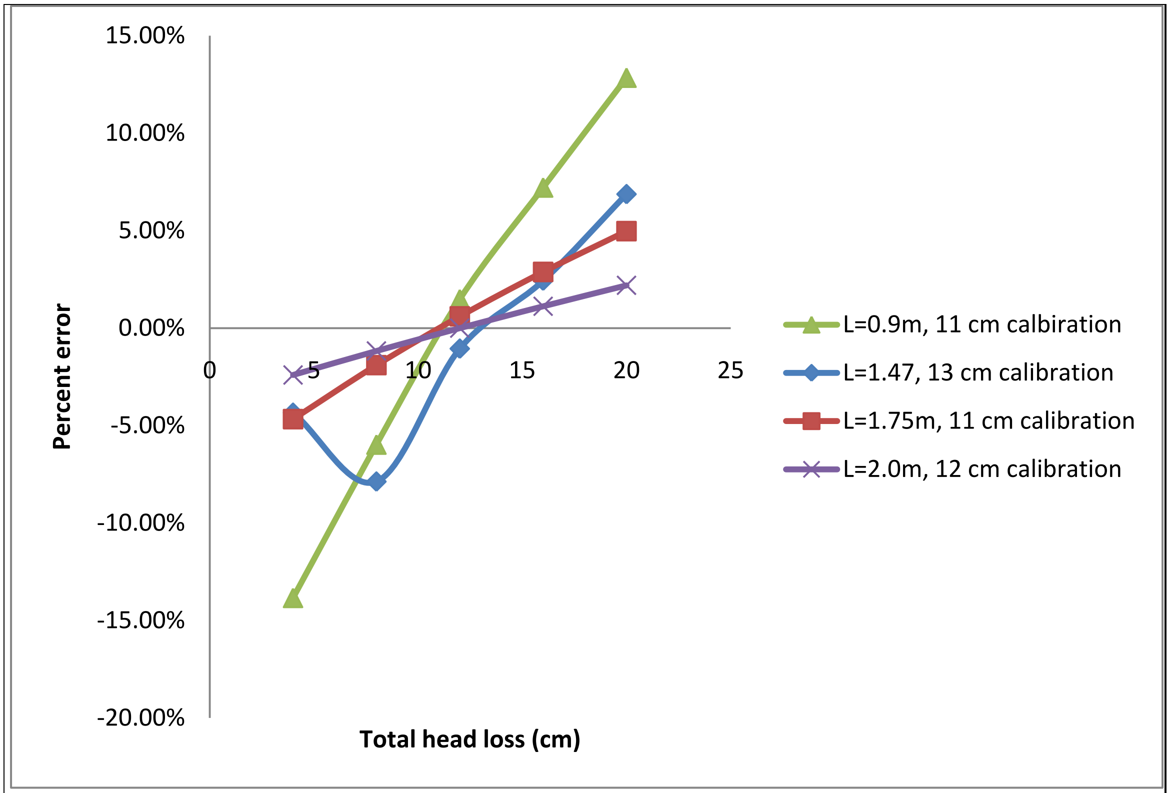

Figure 12: Percent error with different small diameter tube lengths

For ease of calibration, it would be convenient to calibrate the CDC at half of the maximum head loss, 10 centimeters. The team investigated the increase in percent error between the optimal calibration point, seen above in Figure 12, and the percent error at a total head loss of 10 centimeters (Table 4).

Table 4: Percent error at optimal calibration point and where total head loss is 10 cm

L_{Tube} (m)	H_{total} at optimal calibration point (cm)	Percent error at optimal point	Percent error at H_{Total} = 10 cm
0.9	11	13.84%	14.31%
1.47	13	7.87%	10.10%
1.75	11	4.98%	5.56%
2.0	12	2.40%	2.76%

Table 4 indicates that calibration where total head loss is 10 centimeters rather than at the optimal calibration point does not significantly increases the maximum percent error. These results can improve the CDC system’s overall accuracy while also facilitating calibration.

Chemical Dosing Technology Applications

Chlorine Flow Controller Design

Currently, AguaClara plants employ a flow controller to add chlorine to treated water as it leaves the plant. The flow controller system includes a stock tank, a CHT regulated by a float valve and a small diameter tube. The chlorine flow controller in the Cuatro Comunidades AguaClara plant appears below (Figure 13).

Figure 13: Chlorine flow controller in Cuatro Comunidades AguaClara plant (taken Jan. 2011)

The vertical row of orifices allows the plant operator to set the desired flow of chlorine based upon the incoming water flowing into the plant. The flow rate from the CHT to the water ($Q_{FlowController}$) is based upon the head difference between the water level in the CHT and the small diameter tube's outlet (h_f) the inner diameter of the small diameter tube (D_{Tube}) the viscosity of the chlorine solution (ν) and the length of the small diameter tube (L_{Tube}). This relationship was presented above in Equation (3) and is given again below.

$$Q_{FlowController} = \frac{h_f g \pi D_{Tube}^4}{128 \nu L_{Tube}} \quad (3)$$

The diameter of the tube must be large enough to maintain laminar flow. Therefore, by rearranging Equation 3, one can see that the diameter of the tube (D_{Tube}) is a function of the maximum flow rate (Q_{max}) and minimum length (L_{min}) (Equation 11).

$$D_{Tube} = \left(\frac{128\nu L_{Min} Q_{Max}}{h_f g \pi}\right)^{\frac{1}{4}} \tag{11}$$

Finally, a second reorganization of Equation 3 yields a relationship that gives the optimal small diameter tube length (L_{Tube}), given the calculated tube diameter (D_{Tube}) and the maximum desired flow rate (Q_{Max}). This relationship was previously presented as Equation (2) and is given again below.

$$L_{Tube} = \frac{h_f g \pi D_{Tube}^4}{128\nu Q_{Max}} \tag{2}$$

The current design is not optimal because the vertical row of orifices allows the chlorine flow to escape the inner part of the PVC pipe and, instead of being added to the water, settle on the pipe's exterior and creating an unkempt appearance.

Chlorine application is not regulated with a dose controller is because past research teams have found it difficult to design a way to read the plant's flow rate from the entrance tank and transfer that reading to the chlorine application system. The challenge is based upon the geometrical layout of the water treatment plant and the particularities of AguaClara's dose control system, which must have a method to couple the chemical flow rate with the plant flow rate.

While a semi-automated chlorine dose controller has not yet been designed, an improved chlorine flow controller design has been created (Figure 14) based upon Equations 2, 3 and 11.

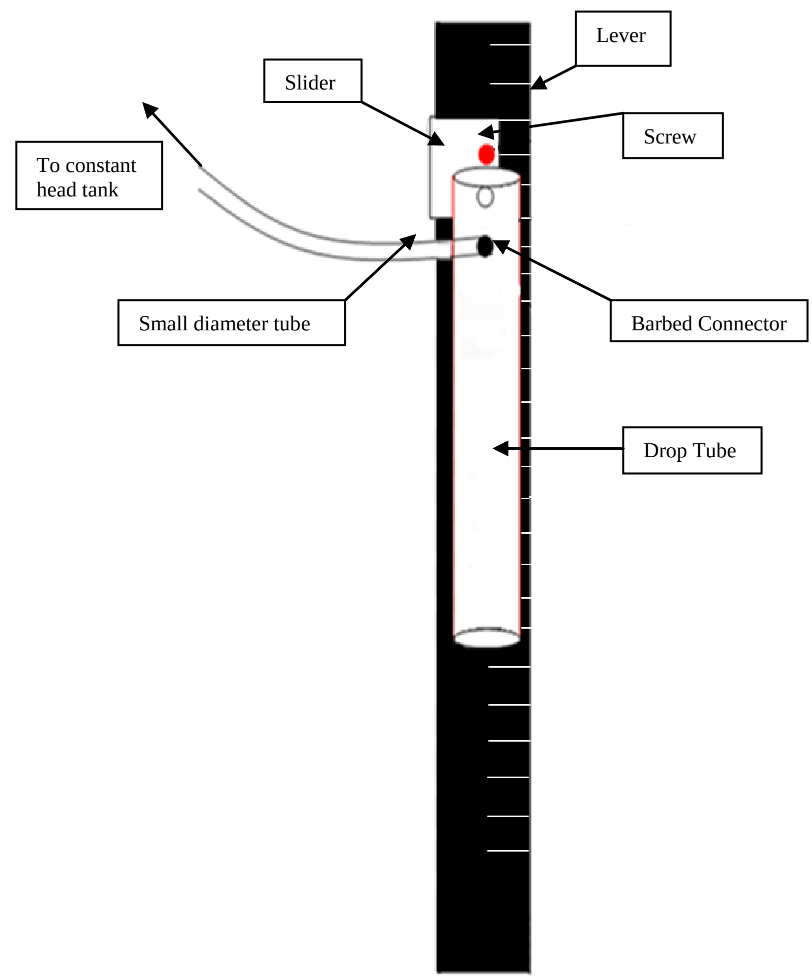

Figure 14: Vertical chlorine flow controller design

The lever would be mounted on a wall and the drop tube would drip chlorine out of its bottom. The slider would be the same type as currently used with the chemical dose controller and would be hung at an elevation on the lever by a screw drilled through the slider. It would hang at a certain position when the operator tightens the screw against the lever. The new design would work very similarly to the current flow controller. The lever would have a vertical label informing the plant operator at which elevation to set the slider to achieve the desired chlorine flow. It would improve the aesthetics of the chlorine application system while maintaining its simplicity.

One concern is that the design shown in Figure 14 might allow the drop tube to fall off or slide down over time because the lever is vertical. To address this problem, one could set the lever at a fixed angle on a wall (Figure 15). In this design, the slider would be more likely to retain its set position over time.

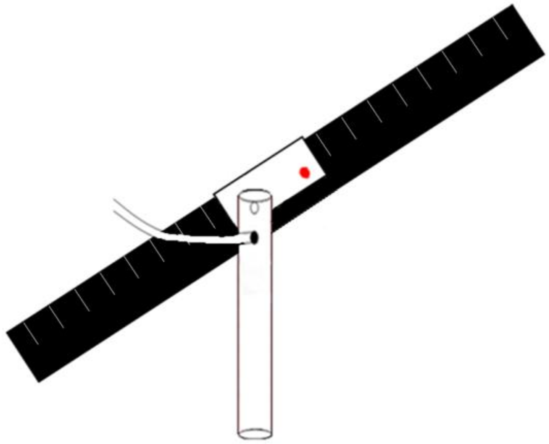

Figure 15: Angled flow controller

If this angled design still does not allow the plant operator to reliably set the chemical flow, a third design could be constructed. This design (Figure 16) has holes drilled at elevations along the lever which correspond to different chemical flow rates.

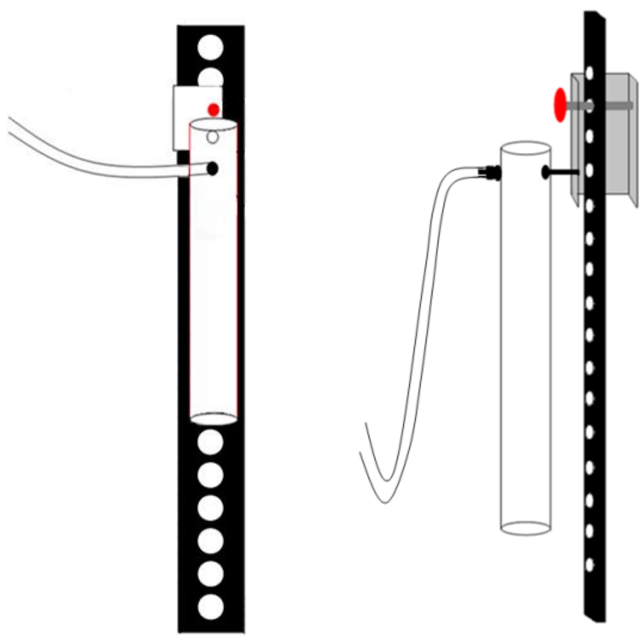

Figure 16: Flow controller with holes (front and profile views)

The plant operator would use the screw to hang the slider on one of the drilled holes. This design minimizes the possibility of the slider changing position because the slider is hanging through a hole. Also, this design would make it very easy for the operator to accurately set the drop tube at a certain elevation time and again. However, of the three designs presented here (Figure 14, Figure 15 and Figure 16), the design with holes is the most difficult to fabricate in the field.

Reducer Proof of Concept

The team fabricated a new drop tube using a reducer as seen in Figure 17. The two and a half to half-inch reducer will allow the operator to connect up to nine small diameter tubes in parallel to deliver chemical flow into the entrance tank via the drop tube. The barbed fittings are all at the same elevation in the reducer. The reducer fits securely over the drop tube and does not have any adhesives attaching it to the drop down tube. In a functioning plant, it is advised that adhesives be used to ensure a secure attachment between the reducer and the drop tube. Although this is a new design, it will adhere to the same principles employed by a CDC system which does not use a reducer, namely, equations (1), (2) and (3). Ultimately, the team believes that this design will allow for linear dosing of up to 25 mL/s to 30 mL/s.

Figure 17: Image of reducer with 9 small diameter tubes attached

Linear flow orifice meter algorithm

Basic design

The new LFOM algorithm uses recursion to minimize the mean squared error of water flow measured between each row of orifices. The flow through one orifice ($Q_{Orifice}$) is a function of the difference in water level to the center of the orifice (H_{diff}), the radius of the orifice (r), multiplied by a constant which describes the vena contracta effect ($Pi_{VenaContractaOrifice}$ = 0.63) (Equation 12).

$$Q_{Orifice}\left(H_{diff}\right) = \sqrt{2gH_{diff}}\pi r^2 \pi_{VCOrifice} \tag{12}$$

From Equation 12, one can calculate the current flow given the depth of the water in the entrance tank. Then, one can subtract the result from the ideal flow to find the additional flow needed. By rounding

$$OrificesInRow = floor\left(\frac{Additional\ Flow}{Q_{SingleOrifice}}\right) \tag{13}$$

both up and down, where the variable named additional flow is the additional flow needed to achieve optimal linear flow and $Q_{singleOrifice}$ is the flow out of a single orifice when the water right at the top of the orifice. One of these numbers will be the best approximation, so we then run the recursion with each of them. Once each row has a number of orifices designated to it, the mean squared error is calculated

$$Mean\ Squared\ Error = \sum_{each\ row}(Flow\ Out - Ideal\ Flow)^2 \tag{14}$$

where the ideal flow, the ratio of rows submerged multiplied by the total flow rate, is subtracted from the flow out, the calculated actual flow through the orifices (Equation 14). A modified algorithm has been written and designed for high flow rates, which replaces the first to rows with a row of orifices of twice the diameter to reduce the number of orifices that are required to be drilled.

New algorithm's results

The figures presented below are the output from the old LFOM algorithm (Figure 18) and the output from the newly-designed algorithm (Figure 19).

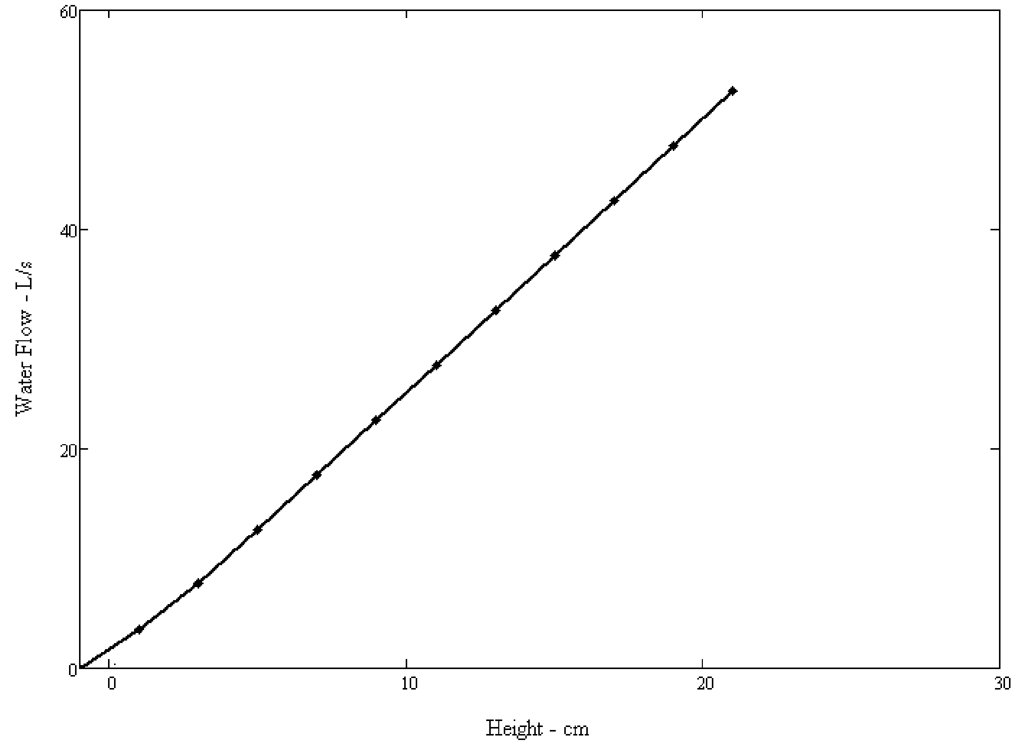

Figure 18: Old LFOM algorithm’s output

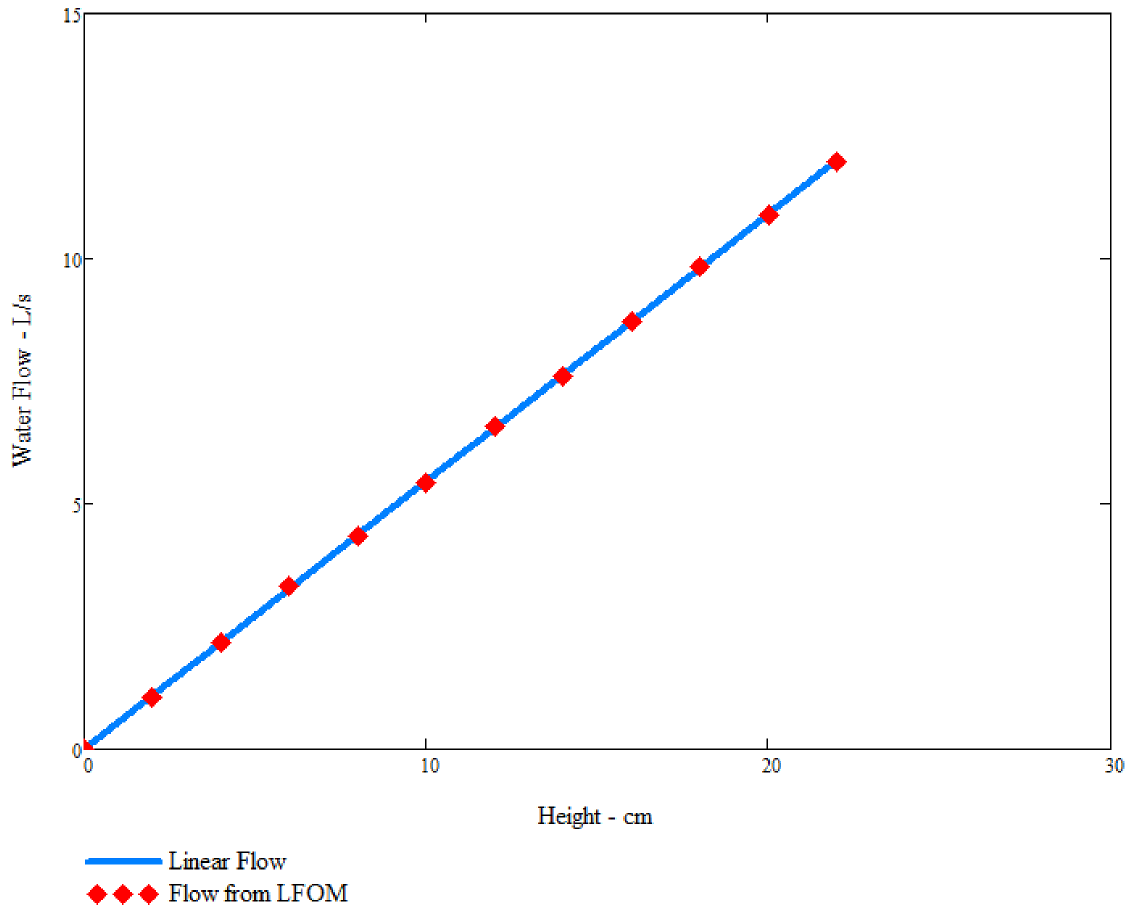

Figure 19: New LFOM algorithm's output

Although a linear relationship between water flow and water height in the entrance tank is maintained in each graph, the previous method (Figure 18) presents a clear problem. The zero-flow point is below the zero elevation level causing the graph to have a positive y-intercept. The newly-designed algorithm's output (Figure 19) allows the zero-flow point to coincide exactly with the zero-elevation point. This is a clear improvement with the goal of optimizing flow through the LFOM in AguaClara plants and allowing the flow rate through the LFOM to be more easily predicted and modeled.

Current Research: Linear flow orifice meter

Algorithm adaptation

For low plant flow rates, one concern is that large orifices would result in significant error, because as total flow decreases and flow through individual orifices used to model linear flow remains constant, percent error will increase. Because the orifices are an approximation of linear flow, perhaps a decrease in orifice diameter would increase the LFOM's precision by allowing a closer approximation at each row. However, the algorithm remains at or below the 5% error level above the first row, for all plant flow rates greater than 1.5 L/s (AguaClara wiki, Project sites, accessed from <https://confluence.cornell.edu/display/AGUACLARA/Project+Sites>). As this is far below the range of current AguaClara plants (the smallest plants have a flow rate of 6 L/s), the team has decided that reducing orifice diameter would is not necessary.

Additionally, the algorithm was updated to calculate LFOM pipe diameter. The constraint that governs the diameter of the LFOM is the average velocity of the water as it falls. The cross-sectional area of the pipe must be sufficiently large such that the water does not back up and cause the water level to rise above the orifices of the LFOM. If this were allowed to happen, the linear relationship between flow rate through the LFOM and water height is lost. Therefore, the average velocity of the water which flows through the LFOM's orifices into the pipe ($V_{AvgThruLFOM}$) must be greater than the minimum velocity needed to clear the pipe, as determined by plant flow rate (Q_{Plant}) and the cross-sectional area of the pipe (A_{Pipe}).

$$V_{AvgThruLFOM} > \frac{Q_{Plant}}{A_{Pipe}} \qquad (15)$$

Based upon the average velocity ($V_{AvgThruLFOM}$) from Equation 15, Equation 16 is used to calculate the necessary pipe diameter (D_{Pipe}). Note that in Equation 16, a safety factor of 2 is used to ensure that the pipe diameter is of sufficient size.

$$D_{Pipe} = 2\sqrt{\frac{\pi_{Safety} * A_{Pipe}}{\pi}} \qquad (16)$$

This constraint calculation must only be carried out for 100% of flow capacity at a height equal to 0 inside the LFOM. The calculation is performed at maximum LFOM capacity because for lower levels of flow, average velocity can be much lower and one can assume that water will not back up. Additionally, the location in the pipe immediately below the LFOM is the most constricting because at this height, maximum flow is considered and at this location in the pipe, the water has the least amount of time to accelerate.

To calculate the average velocity above ($V_{AvgThruLFOM}$), the LFOM must be modeled as a proportional weir. The old algorithm used the Sutro Weir, a shape which is rectangular near its base but begins to curve at a certain height (Figure 20).

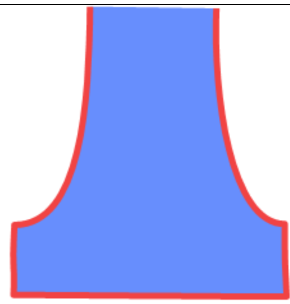

Figure 20: General sutro weir shape

However, the formula representing the sutro weir's relationship between its width and its height is much more complicated than necessary because it constrains the width of the weir. Instead, if the width of the weir is allowed to be infinite at height zero, one finds a theoretical weir shape that is much easier to use in the LFOM algorithm. The Stout Weir, which gives a linear relationship for all heights, employs this equation (Montes, J.S. "Numerical solution to the inverse weir problem." Journal of Hydraulic Research 30.4 (1992): 453-465.):

$$Width = \frac{\alpha}{\sqrt{Height}} \tag{17}$$

First we must calculate alpha, the coefficient which affects the slope to allow for different flow rate changes as height (h) is altered, by solving this equation for alpha:

$$MaxFlow = \int_{0cm}^{20cm} \sqrt{20cm - h} * \frac{\alpha}{\sqrt{h}} dh \tag{18}$$

We can then compute the average velocity ($V_{AvgThruLFOM}$) by weighing the speed the water gains when falling from each height by the volume of water that flows from that height. To do this, one takes the integral of velocity (FallVelocity) multiplied by the flow (FlowRate), which are both functions of height, and divides by the total flow of the plant (Q_{Plant}):

$$V_{AvgThruLFOM} = \frac{\int_0^{H_{max}} V_{Fall}(h)*Q(h)*Width\,dh}{Q_{Plant}} \quad (19)$$

Where, $Q(h)$ is the flow at height h, and V_{Fall} is the freefall velocity at the bottom row of the LFOM:

$$V_{Fall} = \sqrt{2*g*(H_{max} - h)} \quad (20)$$

$$Q(h) = \pi_{VenaContracta}\sqrt{2*g*h} \quad (21)$$

and Width*dh is the area for FlowRate.

Because the Q_{Plant} cancels out the Q_{Plant} from the alpha in width, we find that the average velocity depends only on the maximum height of the LFOM. We find that at 20cm, the velocity is:

$$2*g*\frac{\pi_{VenaContracta}}{Q_{Plant}}\int_{0cm}^{20cm}\sqrt{h(20cm - h)}*\frac{\alpha}{\sqrt{h}}dh = 0.841*m/s$$

These stout weir calculations allow the algorithm to calculate the optimal LFOM pipe diameter. Accurately finding this pipe diameter is important because it constrains the number of orifices that can be drilled in one row of the LFOM.

The only concern is that the LFOM algorithm has as $2^{\text{total number of rows}}$ iterations, so one additional constraint on the number of rows in the LFOM should be the time needed to perform these iterations in the ADT.

Integration into the design tool

The LFOM file has been fully and successfully integrated into the design tool, with all needed variables defined within in the input files. The flow calculations have been double checked, and the file has been commented for easier understanding and future editing.

Concluding Recommendations

The linear chemical dose controller system is not perfect. It is inherently based upon a series of hydraulic tradeoffs which must be balanced when designing the system:

- Tubes with a larger diameter allow for higher chemical flow (while maintaining laminar flow), but require longer small diameter tubes.
- Shorter small diameter tubes give higher chemical flow rates but have higher percent error from linear flow rates.
- Longer small diameter tubes give lower chemical flow rates but are less prone to significant percent error from the desired linear chemical flow rates.

The majority of this semester has been spent examining the minor losses from various components of the CDC system. While the aforementioned tradeoffs are known, the details concerning minor losses are not yet completely understood. It has been established that there are significant minor head loss components in the following places: (1) entrance losses as flow enters the barbed fittings from the CHT, (2) expansion losses when flow exits the CHT's barbed fittings and enters the small diameter tube and (3) exit losses as flow exits the barbed fittings and flows into the drop tube.

However, none of these losses explain why the minor loss coefficient changes as the length of the small diameter tube changes. Possible additional sources of minor head loss include (1) minor head loss through the entrance region (which changes length depending upon the Reynolds number of the flow and the diameter of the tube) and (2) the radius of curvature of the small diameter tube between the CHT and the drop tube. One way to test the minor head loss through the entrance region is to situate the CHT and the drop tube closer together on the 80 X 20 so that the team could take flow measurements with shorter tube lengths (ie. between 10 cm and 40 cm). At the higher end of flow rates with these tubes, the parabolic velocity profile may never fully-develop if the entrance region comprises the entire length of the tube. All possible sources of additional minor head loss must be more fully investigated if the minor losses through the system are to be fully understood. The long-term goal is to completely understand and theoretically explain the minor losses throughout the entire system given the components used.

A second suggestion, that components for the system be chosen that have extremely low potential to cause minor head losses, confronts a trade-off between the system's appearance and its functionality. The barbed fittings employed on the CHT and the drop tube improve the system's appearance, but clearly add minor head losses. A barbed fitting which does not cause any additional minor head loss would be optimal.

Throughout the semester, the goal was to design a system which operated with a maximum percent error under 10%. For small diameter tubes with lengths above 1 meter, using the improved calibration methods described in this report, this goal has been achieved (see Table 4). With this knowledge, the geometric layout of the plant could be drawn with the condition that a small diameter tube with length above 1 meter must be able to fit, without dramatically decreasing its radius of curvature, between the CDC system's CHT and the drop tube. Because the CHT and the lever apparatus are typically simply drilled into walls near the entrance tank, the team believes the plant's design has the freedom to include this condition.

Future Work

We believe that the LFOM task list has been completed.

The minor losses through the CDC system must be analyzed further, specifically the losses through the entrance region before the parabolic velocity distribution has developed and the losses due to the curvature of the small diameter tube between the CHT and the drop tube.

Additionally, the team's data collection and analysis must be transferred from Excel to Mathcad. This is a task that the team hopes to complete after the submission of this final report, but before the end of the semester.

The components to used for the CDC system and the flow controller system must be standardized. Several new components were tested in the lab for the first time this semester (new size of barbed fittings, new reducer and a new screw for use with the reducer)

From the original detailed task list, there are two goals the team failed to address this semester: (1) designing an easy way for the operator to measure plant flow rate and (2) examining the sensitivity of the CDC system's float to currents in the entrance tank. The team suspects that, with the new entrance tank design, currents will no longer have a significant effect on the float's position; however, this is speculatory and was not thoroughly researched.

Team Reflections

The meetings with Matt Hurst and Professor Weber-Shirk have been extremely helpful this semester. Especially because all three full-time members of our team were knew the AguaClara research, these meetings helped us generate ideas and guided our research. New AguaClara research team members should really be encouraged to communicate with their team leaders and with Professor Weber-Shirk.

The minor loss modeling has really been a challenge for the team. Under normal circumstances, the minor loss coefficient should not depend on length nor flow rate. However, both of these variables are having an effect. We think these complicated challenges have really initiated some thoughtful discussion about the CDC and we think we are moving closer to understanding the system's losses.

There has also been a very nice cooperation with the design team of late. Adam met with May and seamlessly installed the LFOM file into the design tool. Also, Akta has been extremely helpful in discussing and helping to model the minor losses.

Finally, for this research report, we spent much more time making sure the formatting is correct. We felt that it was very important to have the correct formatting for the final research report.