# Linear chemical dose controller Summer 2011 final research report

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**Abstract**

Accurate chemical dosing in water treatment plants is imperative to ensure optimal efficiency during flocculation, sedimentation, filtration and disinfection. AguaClara designed the linear chemical dose controller (LCDC) and linear flow controller (LFC) systems to allow plant operators to reliably set and maintain a desired dose of coagulant and disinfectant. A linear relationship between head loss and chemical flow is created by using the major head loss through a small diameter tube to control the flow. To maintain this linear relationship, the systems have been designed to eliminate sources of minor head loss. Our team is actively working to minimize minor head losses through the systems, reduce the systems' maximum percent error and standardize the components and calibration techniques to be used to fabricate the systems in the field.

## Introduction to LCDC and LFC theory

The linear chemical dose controller (LCDC) and linear flow controller (LFC) use major head loss to regulate chemical flow. The relationship between major head loss and the chemical flow rate is given by the Hagen-Poiseuille equation. The chemical flow rate ($Q_C$) is a function of major head loss ($h_f$), the diameter of the small diameter tube ($D_{Tube}$) that connects the constant head tank (CHT) and the drop tube, the kinematic viscosity of the chemical solution ($\nu$) and the length of the small diameter tube ($L_{Tube}$).

$$Q_C = \frac{h_f g \pi D_{Tube}^4}{128 \nu L_{Tube}} \tag{1}$$

The Hagen-Poiseuille equation assumes that the chemical flow is laminar (see Spring 2011 Final Report "Introduction to Current Research" section for explanation on how laminar flow is ensured), viscous and incompressible, as well as that the flow passes through a tube with a constant circular cross-section that is significantly longer than its diameter. When one rearranges the Hagen-Poiseuille equation, one can see that major head loss ($h_f$) increases as the length of the small diameter tube ($L_{Tube}$) is increased.

$$h_f = \frac{128 Q_C \nu L_{Tube}}{g \pi D_{Tube}^4} \quad (2)$$

In past LCDC and LFC designs, AguaClara assumed that the length of the small diameter tube was sufficient to ensure that major head losses dominated and that the linear relationship between the chemical flow rate and the major head loss, as seen in the Hagen-Poiseuille equation above, would be maintained. However, during the Spring 2011 semester, the LCDC team observed quadratic tendencies in the relationship between head loss and chemical flow (see Spring 2011 Final Report "Initial Laboratory Results" section for an analysis of the experiments that gave these results). Minor head losses result from flow expansions through the system and are proportional to the square of the chemical flow rate. Upon observation of significant minor head losses, the Spring 2011 LCDC team designed a method to model the magnitude of the minor head losses and sought to eliminate their sources.

## Minor head loss modeling

To determine the magnitude of minor head losses through the LCDC or LFC systems, one can calculate the minor head loss coefficient, $k_e$. The minor head loss coefficient ($k_e$) is a function of the minor head loss ($h_e$), the diameter of the small diameter tube ($D_{Tube}$) and the chemical flow rate ($Q_C$).

$$k_e = \frac{h_e g \pi^2 D_{Tube}^4}{8 Q_C^2} \quad (3)$$

After collecting data from many experimental setups (see Spring 2011 "Experimental Design" section for a depiction of the group's experimental apparatus), the team applied Mathcad's genfit function to each experiment's data. The genfit function was given an equation developed from the fact that the total head loss through the system ($H_{Total}$) is the sum of the major ($h_f$) and minor ($h_e$) head losses.

$$H_{Total} = h_f + h_e \quad (4)$$

The equation for major head loss is given above as equation (2). By rearranging equation (3), one sees that minor head loss ($h_e$) is a function of the diameter of the tube ($D_{Tube}$), the chemical flow rate ($Q_C$) and the minor loss coefficient ($k_e$).

$$h_e = \frac{8 Q_C^2 k_e}{g \pi^2 D_{Tube}^4} \quad (5)$$

Therefore, equation (4) can be represented as

$$H_{Total} = \frac{128 Q_C \nu L_{Tube}}{g \pi D_{Tube}^4} + \frac{8 Q_C^2 k_e}{g \pi^2 D_{Tube}^4} \quad (6)$$

Equation (6) was input into Mathcad's genfit function. Genfit is given an array of observed flow rate data for the given experimental setup, an array with total head loss values, and guesses for both kinematic viscosity and the minor head loss coefficient. It then calculates a value for kinematic viscosity and the minor loss coefficient which fits the inputted experimental data. Because there are two terms in Equation (6), one with a linear relationship between head loss and chemical flow rate, the other non-linear, the genfit function allows the group to separate the non-linear influence and quantify its effects.

## Impact of the experimental apparatus' structure

The result of applying Mathcad's genfit function to the group's experimental data is a measure of the minor loss coefficient value, which represents the magnitude of minor head losses which are present in the system, for each experiment performed. In this way, the LCDC team is able to perform experiments under different conditions and see which circumstances minimize minor head losses.

The Spring 2011 team indicated that there were several primary sources of minor head loss that were known. From their experimental results, they identified that there is significant minor head loss as (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 down into the drop tube. Yet the analysis of experimental results indicated additional sources of minor head loss somewhere in the LCDC system.

In the Spring 2011 final research report, the team suggested two possible additional sources: (1) the entrance region, the area in the tube within which the parabolic velocity profile has yet to fully develop and (2) the curvature of the small diameter tube. The entrance region was investigated by the Spring 2011 team and the conclusion was that although additional head loss is likely through the entrance region, the entrance regions are present in every tube, and thus do not explain fluctuations in minor loss coefficients when the tube length is changed (see Spring 2011 "Minor loss modeling" section for more detailed explanation).

The summer 2011 team began its analysis by testing the other suspected source, the curvature of the small diameter tube. They did so by altering the experimental apparatus. Rather than mountaing the stock tank, CHT and lever arm on the 80x20 frame, as was done during the Spring 2011 semester, the LCDC system was moved outside of the lab and set up so that the CHT could be far from the drop tube. This would allow the small diameter tube(s) to be straight rather than curved. Figure 1 depicts the new experimental setup designed to straighten the small diameter tube(s) (see Spring 2011 "Experimental design" for more details about the components of the LCDC system).

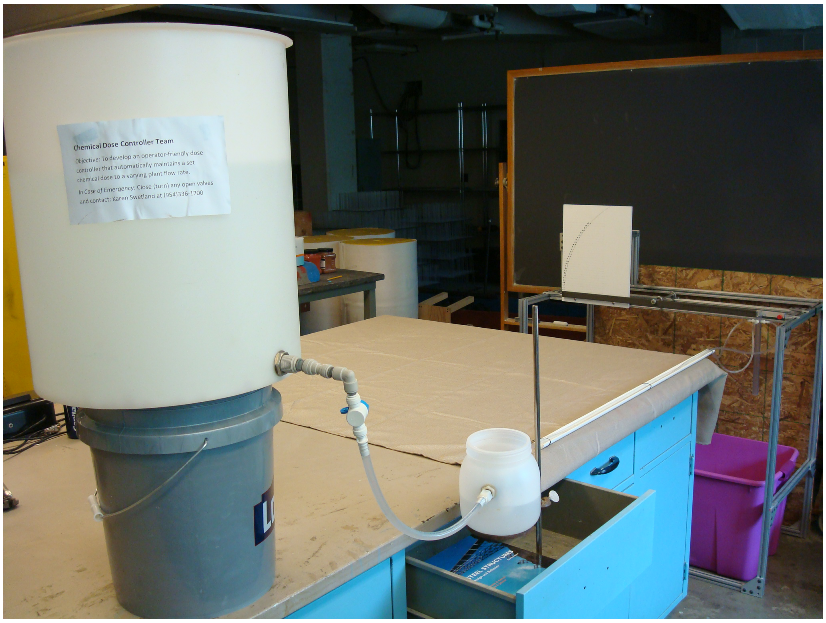


Figure 1: Summer 2011 experimental apparatus. Note the small diameter tubes between the CHT and the drop tube are straight within the white trough.

Furthermore, the summer 2011 team initiated the development of a new method to connect multiple parallel small diameter tubes to the drop tube. In the past, with less than 4 parallel small diameter tubes needed, the tubes would be connected directly to the drop tube. This arrangement can be viewed below in Figure 2.

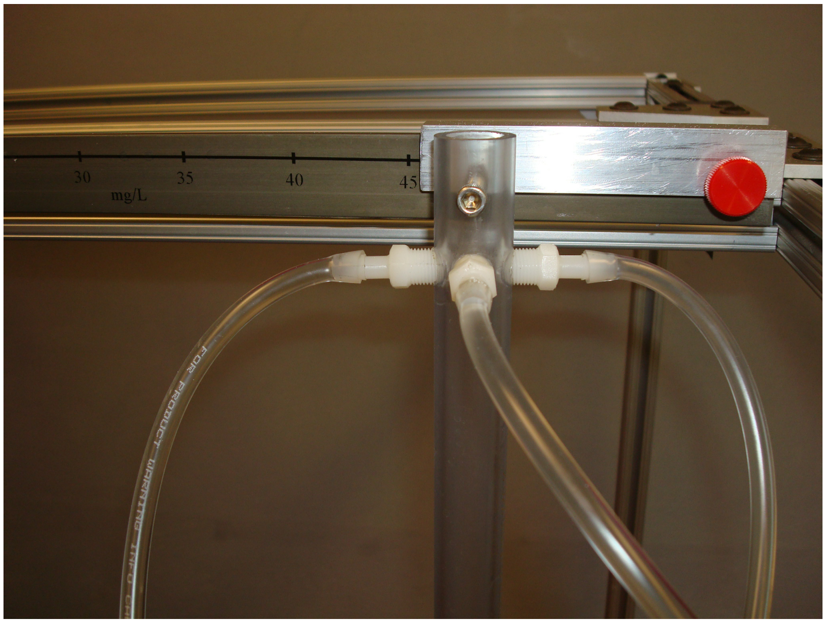


Figure 2: Detailed image of three small diameter tubes connected directly to the drop tube

Alternatively, if between 4 and 9 parallel small diameter tubes were to be connected to the drop tube, a reducer would be added to the top of the drop tube to allow a larger space to which to attach parallel small diameter tubes. A drop tube with a reducer is pictured in Figure 3.

Figure 3: Detailed image of reducer with nine small diameter tubes connected

The problem with the designs presented in Figure 2 and Figure 3 is that for the small diameter tubes to connect to the barbed fittings which are at a 90 degree angle from the constant head tank, they must curve sharply just before their connection with the barbed fitting. This sharp curvature increases minor head loss through the system. Therefore, the summer 2011 team designed a tee piece which would allow each small diameter tube to be connected straight to the drop tube, eliminating the need for sharp curvature just before the connection. This new design is presented in Figure 4.

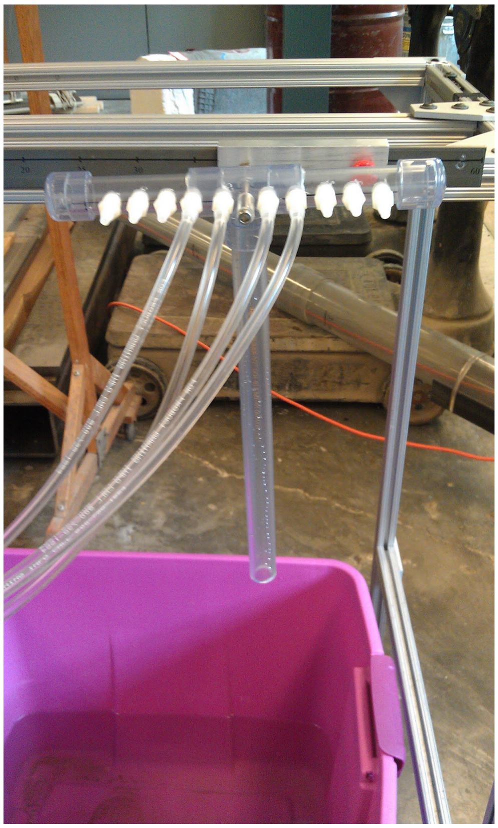

Figure 4: Detailed image of novel tee connector with 4 small diameter tubes connected

With the new experimental setup in place, experiments were conducted to analyze the effect of straightening the small diameter tube(s). Figure 5 shows the results of the Spring and Summer 2011 teams' experiments with different barbed fittings and different experimental setups.

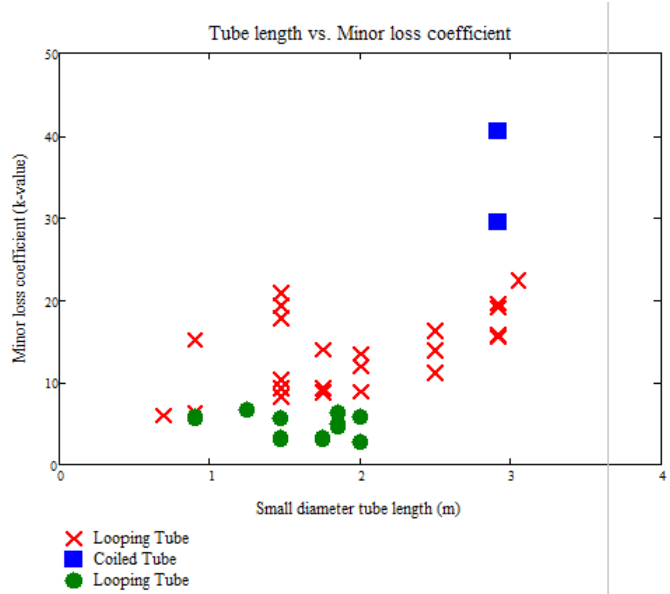


Figure 5: Minor loss coefficients as a function of tube length

One can make several conclusions from Figure 5. First, coiling the small diameter tube produced the two highest minor loss coefficients in the data and is therefore unadvisable. Second, each experiment performed with the CHT and drop tube far from each other to straighten the small diameter tube(s) yielded a lower minor loss coefficient than prior experiments with a curved small diameter tube. This conclusion indicates that AguaClara's LCDCs and LFCs, which have to this point been designed and installed with curved small diameter tubes, must instead have a straight small diameter tube.

# Calibration

In the past, AguaClara engineers have set the zero flow point by ensuring that the LCDC's lever arm is horizontal and there is zero chemical flow at the same point where there is zero flow through the plant. Then, the expected flow rate at the maximum chemical flow point, where total head loss equals 20 cm, is calculated using Equation (1). One or more small diameter tubes are connected in parallel and shortened until the expected flow rate is achieved. With this style of calibration, because the calibration occurs at the maximum chemical flow point, the LCDC system is guaranteed to be able to produce the plant's maximum desired chemical dose.

During the Spring 2011 semester, the team realized that if calibration occured at the point where total head loss is equal to 10 cm, rather than 20 cm, the system's maximum absolute percent error at any point would decrease (for more details, see Spring 2011 "Calibration technique results"). The drawback to this method is that the LCDC system can no longer deliver the maximum desired chemical dose. The summer 2011 team believes that achieving the maximum desired chemical dose is of the utmost importance and therefore, calibration must occur at the maximum chemical flow point, where total head loss equals 20 cm.

With regards to calibration, the reason a high minor loss coefficient is undesirable is that as the minor loss coefficient increases, the maximum absolute percent error through the system also increases due to the non-linearities present. Consequently, experimental arrangements are evaluated based upon the maximum absolute percent error present at the maximum chemical flow point after calibration. Figure 6 shows the maximum absolute percent errors at the maximum chemical flow point as a function of tube length.

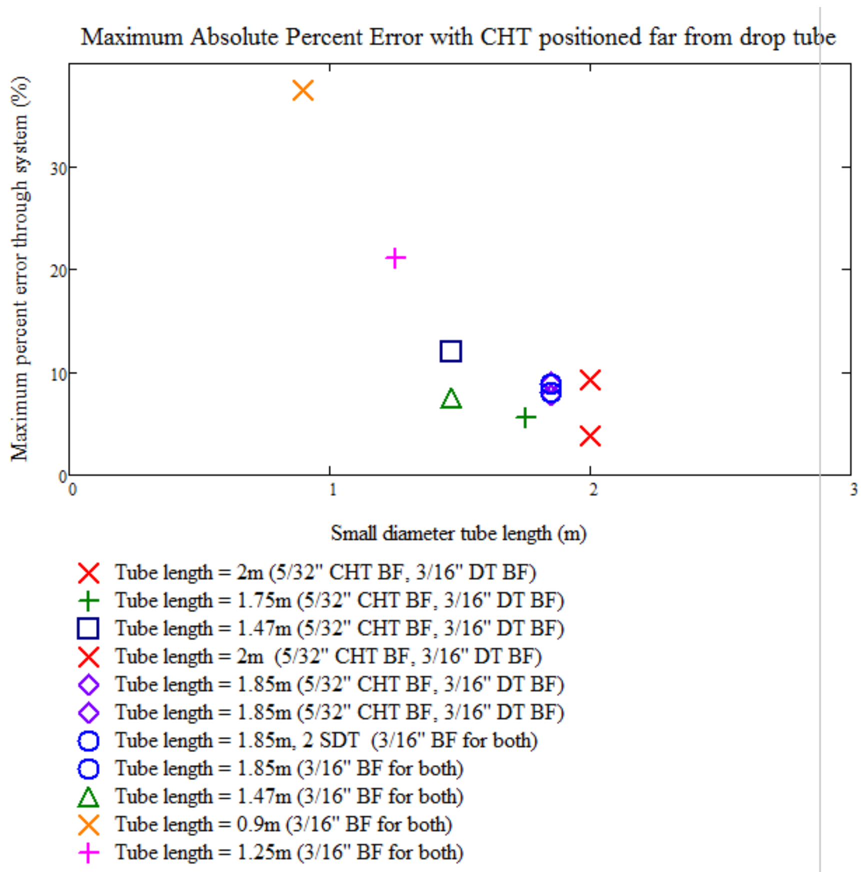


Figure 6: Maximum absolute percent error at the max chemical flow point as a function of tube length

All of the experiments in Figure 6 were performed with the same experimental setup as seen in Figure 1. The only changes made were the tube lengths and the type of barbed fitting used. There is a clear trend that as the tubing is lengthened, the maximum absolute percent error decreases. The goal with the LCDC system has been to reduce the maximum absolute percent error to below 10%. Figure 6 shows that this goal has been achieved when using tubes above 1.47 m in length and calibrating at the maximum chemical flow point.

# Design implications

Summer 2011 research demonstrates that the small diameter tubes must be maintained straight rather than curved and that they must be at least roughly 1.5 m in length to maintain a maximum absolute percent error below 10%. With these new design restrictions, it may not be possible to design LCDCs and LFCs for any given desired chemical flow rate. Consequently, the team is now designing a system which, with kinematic viscosity assumed to be equal to that of water (1 $mm^2/s$), will deliver 2.5 mL/s per small diameter tube. The length of the tube will be approximately 1.85 m and the maximum absolute percent error will be roughly 8% if the kinematic viscosity of the stock solution is near 1 $mm^2/s$. (Kinematic viscosity is inversely proportional to the chemical flow rate, as seen in Equation (1).) Three parallel small diameter tubes can currently be attached to a single drop tube and therefore deliver a total maximum chemical flow of 7.5 mL/s. During the Spring 2011 semester, the team fabricated a reducer to which up to 9 parallel small diameter tubes could be attached. However, new research indicates that the tight curvature of the tube that would be needed to attach several of the tubes to the perpendicularly-oriented barbed fittings adds minor head loss and therefore is not ideal. The development of a new attachment to the drop tube should allow for many more than 3 small diameter tubes to be connected in parallel and thus provide larger maximum attainable chemical flow rates. Additionally, if the LCDC flow rate per tube is standardized to 2.5 mL/s, plant operators would simply alter the stock tank concentration so that they can achieve their maximum desired chemical dose. (See "Kinematic viscosity testing" below for a discussion of the kinematic viscosity of a range of stock concentrations) This degree of freedom should allow AguaClara to standardize the flow rate per small diameter tube and still have the flexibility to serve an entire range of plant sizes with the LCDC.

## The LCDC parts list

After the most recent advances, the design which minimizes percent error and is easy to fabricate and operate has begun to clarify. Minimizing the number of components used in the design is an omnipresent goal for each semester's LCDC team. Nonetheless, the components used are very specific and the research conducted with these parts is very detailed. For example, to understand the minor head loss coefficient analysis, one must be clear which barbed fittings were used during the experiment. The new LCDC team during the fall 2011 semester will have zero members who have worked on the LCDC team during the spring or summer 2011 semesters. Therefore, for the new team to understand previous teams' research with specific components, a detailed, up-to-date, comprehensive parts list is mandatory. This list is complete for all parts necessary downstream of the constant head tank to fabricate the LCDC in the lab. The list is in the third tab of the Excel file "HondurasDoserParts2011" and is posted as an attachment on the LCDC wiki. The total cost of these parts is under 40 USD.

## Current research

### Method to connect multiple parallel dosing tubes

After the new tee piece (seen in Figure 4) was fabricated, it was immediately tested in the laboratory. Flow rate measurements were taken with two and with four parallel dosing tubes, each 1.85 meters in length (Note: with the current tee prototype, only an even number of dosing tubes can be connected so as to maintain symmetry. This can be overcome by placing a barbed fitting at the center of the tee and moving the screw's position higher.). By connecting multiple dosing tubes in parallel, one assumes that each dosing tube will be able to deliver the same maximum chemical flow rate. In previous experiments, one 1.85 meter tube was able to deliver a chemical flow of 2.5 mL/s at the maximum total head loss setting of 20 centimeters. However, during the trials with two and four 1.85 meter dosing tubes connected in parallel, the cumulative chemical flow rates were smaller than the expected 5 mL/s and 10 mL/s, respectively. One hypothesis is that the additional tube curvature necessary when attaching more than one dosing tube decreasing the flow rate through that tube, decreasing the realizable cumulative chemical flow rates of the entire system. This matter is being investigated and the tee piece prototype will likely be adjusted to address this problem.

### Kinematic viscosity testing

In the past, the LCDC team assumed that the kinematic viscosity of the coagulant solutions being used in AguaClara plants was roughly equal to the kinematic viscosity of water, 1 $mm^2/s$. Additionally, the kinematic viscosity was believed not to be a pressing matter because the coagulant stock concentrations being used in operating AguaClara plants were all well below 300 gm/L. These assumptions were based upon the published results of a Russian paper which presented the graph in 7.

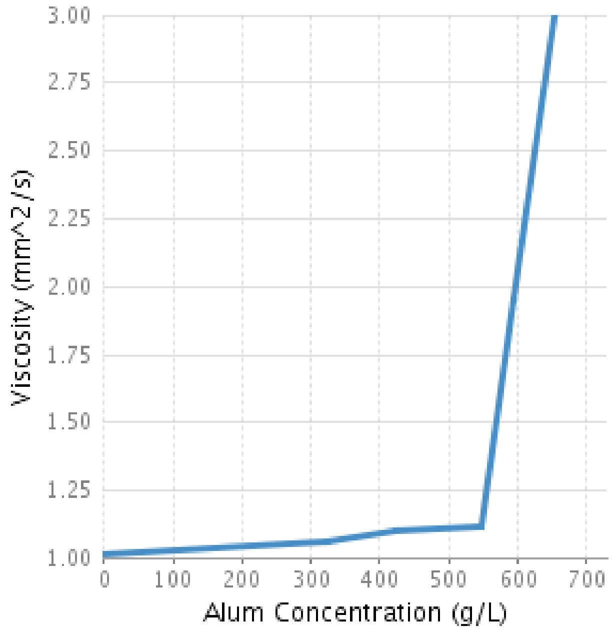


Figure 7: Kinematic viscosity of alum solutions from Russian paper

The summer 2011 LCDC team investigated the chemical flow limits of the LCDC system to see the range of plant sizes within which the LCDC could be used. The initial belief was that, for plants with higher plant flow rates, the coagulant stock concentration could be increased so that the same dose could be delivered into the plant's water without necessitating a higher chemical flow rate through the LCDC system.

With thoughts of using higher coagulant stock concentrations, it was necessary to verify the kinematic viscosity data presented in 7. Therefore, the team used the Vibro Viscometer in the Nanobiotechnology Center (NBTC) in Duffield Hall to directly measure the kinematic viscosity of alum and PACl solutions with concentrations ranging from 10 gm/L to 600 gm/L. The results are presented in 8.

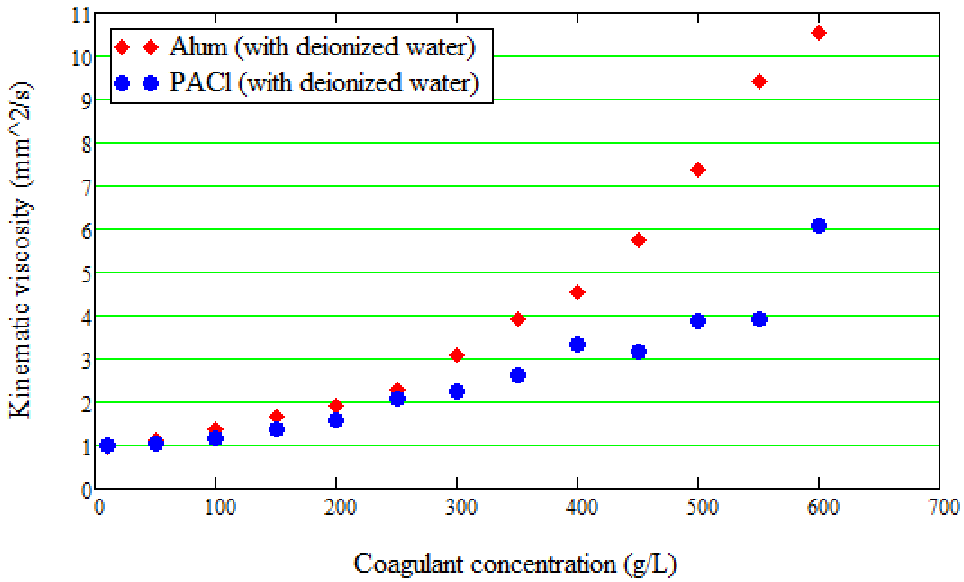


Figure 8: Kinematic viscosity of alum and PACl solutions

The results indicate that for coagulant concentrations above 100 gm/L, the kinematic viscosity cannot be assumed to be approximately equal to that of water. Kinematic viscosity must be taken into account when predicting chemical flow rates through the LCDC system.

## Marcala El Chiflador 2 LCDC retrofit

The most recent LCDC design was fabricated and tested after the Marcala El Chiflador 2 plant was in operation. Therefore, the plant currently has the old LCDC design with three parallel dosing tubes each 60 centimeters long. These three dosing tubes are curved because the constant head tank is located close to the drop tube. The setup is shown in Figure 9.

Figure 9: Current (as of July 2011) LCDC installed at the Marcala El Chiflador 2 AguaClara plant

This system was designed to deliver a maximum coagulant dose of 60 mg/L. Nonetheless, data collected at the plant in June 2011 determined that the maximum attainable coagulant dose using this system was 51 mg/L, due to lower than expected coagulant flow rates. A maximum coagulant dose of 51 mg/L with a coagulant stock concentration of 133 g/L indicates a total coagulant flow rate (the cumulative coagulant flow rate of the three dosing tubes) of 8.5 mL/s. The total coagulant flow rate ($Q_C$) is, via Equation (7), a function of the plant flow rate ($Q_P$), the coagulant stock concentration ($C_C$) and the maximum coagulant dose ($C_P$).

$$Q_C = \frac{Q_P C_P}{C_C} \tag{7}$$

Due to the discrepancy between the desired maximum coagulant dose and the maximum coagulant dose the current LCDC system was able to deliver, a retrofit was attempted. The newest LCDC design, with multiple 1.85 meter, straight dosing tubes was desired. However, due to the physical layout of the plant, the retrofit was not accomplished. In Figure 9, one notices that the constant head tank is in fact mounted on a pillar rather than a wall. This pillar is surrounded by walkways. Therefore, there was no wall along which to run the straightened 1.85 meter dosing tubes. Dosing tubes of length 1.85 meters were installed, but the constant head tank's and the drop tube's positions were unchanged, yielding extreme tube curvature. Due to this tube curvature, the maximum coagulant dose was measured to be 24 mg/L. This was the first major realization that physically retrofitting the most recent LCDC design may not be as simple as previously thought.

In addition, retrofitting is likely to be accompanied by an alteration of the coagulant stock concentration. The Marcala El Chiflador 2 plant is using alum as their coagulant, with a stock concentration of 133 gm/L (as of August 2011). Judging from the results presented in 8, the kinematic viscosity of their stock solution may be significantly higher than that of water, to which the stock solution's kinematic viscosity is assumed to be equal. Along with the tube curvature, this is likely responsible for reducing the chemical flow rate and thus reducing the maximum attainable coagulant dose to be 24 mg/L. When a retrofit is performed, the coagulant stock solution's kinematic viscosity must also be taken into account.

Retrofitting strategies will likely have to be carried out on a case-by-case basis with innovative strategies for positioning the system to ensure that the 1.85 meter dosing tubes can be straight.

## Rigid tubing

Due to the retrofitting difficulties experienced in the Marcala El Chiflador 2 AguaClara plant, a new experiment has begun. To relieve ourselves of the necessity of maintaining roughly 1.85 meters between the constant head tank and the drop tube within which to place the dosing tubes, would it be possible to use two sections of rigid tubing, placed horizontally one above the other with a flexible tube in a U-shape connecting them? This way, it may be possible to reduce the horizontal space necessary for the dosing tubes by one half while maintaining two lengthy sections of straight tubing. This idea will be explored experimentally in the coming weeks.

## Float attachment and counterweight design

The AguaClara LCDC team must improve the method by which it attaches the float to the non-dosing side of the lever arm. In the past, it has been accomplished by means of fishing line or a chain. However, this attachment could be improved to aid during calibration. Figure 10 depicts a prototype float attachment.

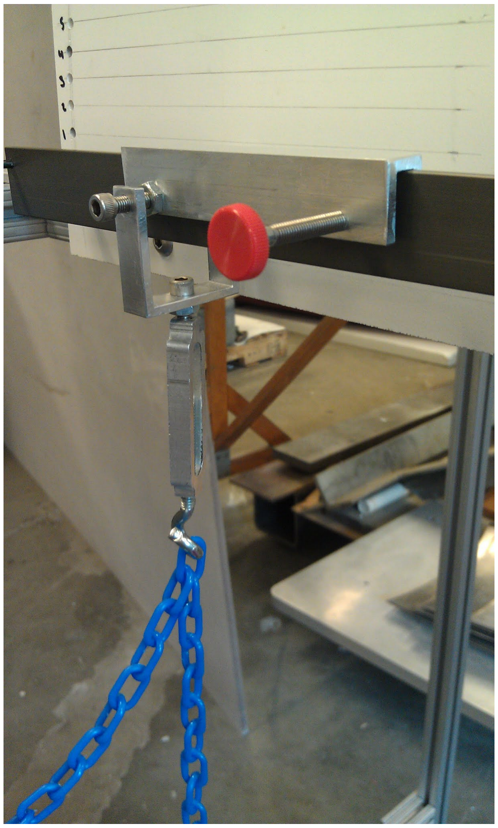

Figure 10: Improved float attachment prototype

As seen in Figure 10, the new float attachment design uses a slider and two screws, just as the drop tube is attached on the other side of the lever arm. It attaches the float to the slider with a chain and a turnbuckle. The turnbuckle is included to make precise corrections when setting the zero chemical flow point during calibration. The slider is included so that the position of the float may be altered during calibration to ensure that each small diameter tube is able to achieve a maximum flow rate of 2.5 mL/s. The method of attaching the turnbuckle has been improved by the addition of an upside-down aluminum U-channel. One end of the turnbuckle has a stud which screws directly into the upside-down aluminum U-channel while the other has a hook which connects to a link of the chain. Additionally, a counterweight has been designed to provide tension through the chain. The design was arbitrarily based upon raising the level of the float in the water by 1 cm. After preliminary testing, the team believes that additional tension may be preferable once an easy method to attach the counterweight is designed.

### Evaluation of the LCDC design's physical strength

Since the beginning of the spring 2011 semester, the LCDC design has increasingly added stress to the lever arm. The drop tube is now heavier because of the new tee piece and the possibility of connecting many small diameter tubes in parallel. The float attachment, which has never been tested in the lab and was previously just a chain or fishing line tied through a hole in the lever arm, now consists not only of a chain but also of a slider, three screws, an aluminum U-channel and a turnbuckle. Finally, a counterweight will soon be added to the design and connected directly to the lever arm.

These new additions to the LCDC design specifically increase the stress placed upon the lever arm and the sliders. A thicker lever arm and thicker sliders could be fabricated and tested to examine the point at which they will replace the currently-used components.

## Future work

My detailed task list has been slightly altered as it was originally written for two people and now there is only one person working with the LCDC/LFC system for the summer.

Nonetheless, immediate future work includes helping AguaClara engineer Sarah Long design 3 flow controllers and 1 dose controller for two Aguas de Siguatepeque plants in Honduras. The LFC must be redesigned as it is usually a very compact system with the CHT very close to the outlet of the small diameter tubes, but will now have to have to CHT positioned far from the outlet of the small diameters tubes to maintain straight tubes. This design will likely be developed with Sarah over the next few weeks. I am brainstorming methods to attach the counterweight so that it will not interfere with the drop tube's slider. It is likely that the counterweight will be rectangular and attached directly to the lever arm rather than connected via a chain.

Additional work from our detailed task list that will be addressed includes:

1. Perform experiments to see, with stock concentrations with high kinematic viscosity, if we can maintain $<10\%$ maximum percent error with shorter tube lengths.

2. Investigate the maximum chlorine concentration in the chlorine stock tank to avoid losing chlorine as a gas. Finding this upper limit will allow us to use a higher chlorine concentration in the stock tank and therefore have lower chemical flow rates necessary for adequate disinfection.

3. Design an easy way for the plant operator to measure the real-time plant flow rate. Is the LFOM the best location for a scale or would a scale somewhere on the LCDC or elsewhere in the entrance tank be better? Is there a way to put a plant flow rate scale on the LCDC's lever?

4. Order all parts necessary to fabricate a new flow controller in the lab. Do this to practice how it would be done in an AguaClara plant in Honduras.

5. Work with the design team to devise an automated method to generate the LCDC chemical flow rate labels and plant flow rate labels to be included in the design files.

## Advice to future team members

1. Jump right in to this project by reading previous teams' resports and, more importantly, playing with the LCDC apparatus. The more time you spend using it and thinking about it, the quicker the concepts and the system will make sense.

2. All research files from the summer 2011 LCDC team are posted as attachments on the LCDC wiki. Learn how to log into the wiki and review what's there.

3. Ask for help from the people around you in the lab. Both Andrew Hart and Karen Swetland have worked on the LCDC team in the past and always have comments and insight that are useful to help the team's progress. Also, as soon as possible introduce yourself to Paul Charles and Tim Brock in the machine shop. Their ideas and help in fabricating our apparatus are invaluable to our team.

4. Be flexible and proactive with fellow team members. It is not easy being new to this team, but efficient communication and honesty will help the team function optimally.

5. Take very detailed notes about each experiment that is performed. The details are very easy to forget if not written down. Which barbed fittings were used? What length and inner diameter tubing was used? If I'm using multiple parallel small diameter tubes, is there enough head from the constant head tank to supply the float valve's orifice with enough flow to support the chemical flow rate?

6. Set up weekly meetings with Monroe and with your research team leader to stay in constant communication and awareness about the goals you're working towards.