Linear Chemical Dose Controller Fall 2011 Research Report

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Abstract

Continuous and accurate chemical dosing in water treatment plants is required for optimal efficiency during flocculation, sedimentation, filtration and disinfection. AguaClara designed the linear chemical dose controller (LCDC) and the linear flow controller (LFC) systems to allow plant operators in Honduras to easily set and maintain the dose of coagulant and disinfectant through one system. A linear relationship between the head loss and chemical flow is created by using only major head loss, where the flow is controlled by a small diameter tube. To continue using this linear relationship, the current experimental system has been designed with the goal of eliminating minor head loss. Our team is actively working towards the continuation of this work, decreasing the minor head losses throughout the systems, reducing the systems maximum percent error under 10%, and standardizing the components and calibration techniques that will be used to fabricate this system in the field.

Literature Review

Chemical feed and control systems are of vital importance to the longevity and efficiency of any drinking water treatment plant. This is required due to the numerous factors that a chemical feed can control, ranging from coagulant addition to incoming water supplies to disinfection and pH moderation after the water has gone through primary stages of the plant. Ranging in complexity from simple systems based off using a float to control the dosing flow to fully automated controls that have an exact amount of dose being performed, AguaClara is searching for a system that is both sustainable and has an accurate dose rate. The aforementioned systems, though useful, have flaws that hinder them in applications to AguaClara plants.

In the current market, more and more chemical dosing systems are relying on complex computers and large hydraulic tanks to control the amount of disinfectant and coagulant being entered into the plant. The chemical dosing rate is automatically changed with the plant inflow, due to the copious amount of sensors and computer parts present. A major downfall of the complex system is the amount of upkeep required, and the fact that because they are “closed” systems, often including large tanks and piping, a problem cannot be noticed before it has escalated to a much bigger problem. These systems, though highly accurate in their dosing of chemicals when working, are prone to mechanical failure, which in turn leads to incorrect dosing or abandonment of the water treatment plant due to specialists required to fix the problem being unavailable.

On the other hand, simple systems, the idea that AguaClara is based off, are prone to having their own problems that must be dealt with accordingly. A requirement of a chemical doser is a stable free surface which serves as a baseline for the head loss calibration in the system, often performed by a float on the surface of the chemical head tank. This is often ignored, removed, or simplified to a “hole in a bucket” system. Though the dosing is relatively steady for a small period of time, as the head in the chemical tank drops, so does the pressure, thus reducing the amount of chemical added to the plant inflow. These simplified systems also have a problem with changing the rate of chemical being added if there is variable inflow, varying from low to high values, due to the manual adjustment of the chemical dose being needed.

It is the purpose of AguaClara to create a sustainable water treatment plant, which required a chemical doser that does not rely on machines or electricity to control its actions. The design that has been implemented in numerous AguaClara plants involves using a lever and float that allows a direct relationship between the plant flow and chemical dose to be formed. This allows the chemical dosing to change with different plant flow rates, the float controlling the vertical position of the lever which is attached to a chemical feed tube, and because the system is simple in design it can be easily fixed if an error is discovered, or if extra chemical feed tubes are required to increase the flow rate of chemical.

Background

The linear chemical dose controller (LCDC) and the linear flow controller (LFC) use major head loss to regulate chemical flow to the water treatment plant. This 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 the major head loss (h_f), the diameter of the small diameter tube (D_{Tube}), which connects the constant head tank (CHT) to the drop tube, the kinematic viscosity of the solution being used (ν) 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 used is laminar (see Spring 2011 Final Report, “Introduction to Current Research” section for an explanation on how this laminar flow is ensured), viscous and incompressible. This Equation also assumes that the flow in the tube passes through a constant, circular cross-section that is significantly longer than its given diameter.

When the Hagen-Poiseuille is rearranged in regards to the major head loss (h_f), one can see that this variable increases proportionally as the length of the small diameter tube (L_{Tube}) is increased.

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

Past LCDC and LFC designs assumed that the length of the small diameter tube was sufficient enough to ensure that the major head losses dominated the Equation. These designs also believed that the linear relationship between the chemical flow rate and the major head loss would be maintained, as shown in the Hagen-Poiseuille Equation (1).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. When the Spring 2011 LCDC team observed these results, they designed a method to model the magnitude of the minor head losses and sought to eliminate their sources.

The Summer 2011 LCDC team discovered that a large percentage of the minor losses originated from the curvature of the small diameter tube. To reduce this minor loss, the small diameter tube was straightened by using a PVC trough, which was done by moving the stock tank and CHT from being mounted on the 80x20 apparatus frame and placed it at a further distance away. Another method developed to minimize minor losses, which originate from expansions and curves, was to use smaller barbed connectors than necessary for the inner diameter of the used small diameter tubing. This greatly reduced the minor loss through the system, though there is still a large enough value in the system to require further analysis of the experimental apparatus.

To determine the magnitude of minor head losses though the LCDC or LFC systems, the minor head loss coefficient (k_e) can be calculated. 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).

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

After collecting data from numerous 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 set. 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.

$$H_{Total} = h_f + h_e \tag{4}$$

The Equation used to calculate major head loss is given above as Equation (2). By rearranging Equation (3) according to minor head loss, one can see that the 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).

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

Therefore, by substituting Equations (2) and (5), Equation (4) can be represented as:

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

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

Methods

The result of applying Mathcad's genfit function to the Summer 2011 team's experimental data is a measure of the minor loss coefficient value, which influences the magnitude of minor head losses that are present in the system, for each experiment that was performed. In this way, the LCDC team is able to perform experiments under different conditions, such as varying small diameter tube length and using different stock concentrations,. These variables affect the flow rate required to get the max dose, the small tube by its varying length and the viscosity of the chosen stock concentration, both of which are impacted by minor 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 there is significant minor head loss found as (1) entrance losses as flow entered the barbed fittings from the CHT, (2) expansion losses when the 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, despite these numerous choices, the results found in this previous group indicated that there were still additional sources of minor head loss somewhere in the LCDC system.

In the Spring 2011 final research report, the team suggested two additional sources where minor head loss could be found: (1) the entrance region, the area in the tube within which the parabolic velocity has yet to fully develop and (2) the curvature of the small diameter tube. The entrance region was investigated

Figure 1: Summer 2011 experimental apparatus. Small diameter tube(s) between the CHT and drop tube are straight in the white trough. This setup will be continued to be used for the preliminary experiments to test the validity of the viscosity tests and data evaluated by the Summer 2011 team.

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 a more detailed explanation.)

The summer team began its analysis by testing the other suspected source, which was the curvature of the small diameter tube. This was accomplished by altering the experimental apparatus. Rather than continuing to use the setup from the Spring 2011, the Summer 2011 team created the experimental setup designed to straighten the small diameter tube(s) being used as shown in Figure (1) (see Spring 2011 "Experimental design" for more details on components of the LCDC system). With this new setup, experiments were conducted to analyze the effect of straightening the small diameter tube(s) instead of allowing excessive coiling/bending.

The Summer 2011 research demonstrates that the small diameter tube(s) must be maintained straight rather than curved and that they must be at least 1.85m in length to maintain a maximum absolute percent error below 10%. The only possible error with the data that they developed and used was that they designed a system that was based in using a liquid that had an assumed kinematic viscosity equal to water (1 mm^2/s). Kinematic viscosity is inversely proportional to the chemical flow rate, as seen in Equation (1). This was due to the past LCDC teams assuming that the kinematic viscosity was not a pressing matter because the coagulant stock concentration being used in operating

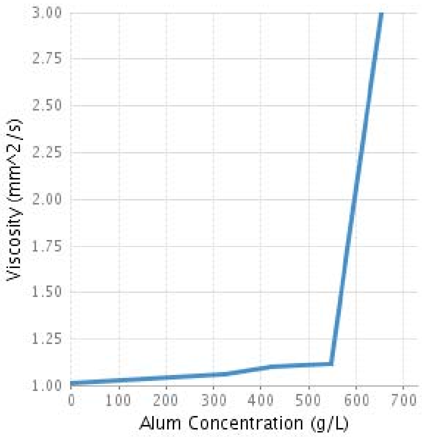

Figure 2: Kinematic viscosity of alum solution from a Russian paper. At lower concentrations it is shown to have a similar viscosity to water.

AguaClara plants were all well below 300 gm/L. These assumptions were based upon the published results of a Russian paper, which is presented in Figure (2).

The Summer 2011 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 of the Spring and Summer 2011 LCDC teams was that, for plants with higher flow rates, the coagulant stock concentration could be increased so that the same dose could be delivered into the water of the plant without necessitating a higher chemical flow rate through the LCDC system.

The Summer 2011 team directly measured the kinematic viscosity of both alum and PACl solutions with concentrations ranging from 10 gm/L to 600 gm/L to see if it followed a similar trend to the Russian data. The results are presented in Figure (3).

The results found by the Summer 2011 team 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 flows rates through the LCDC system. The data found in Figure (3) was vital to changes in the LCDC system, and allowed a Mathcad file to be developed by Monroe Weber-Shirk to account for the kinematic viscosity values and for selecting an appropriate tube length. This MathCad file can be found under the AguaClara source code website, and the MathCad file containing the Summer 2011 viscosity data can be found on the AguaClara Linear Chemical Dose Control specific website. As the concentration

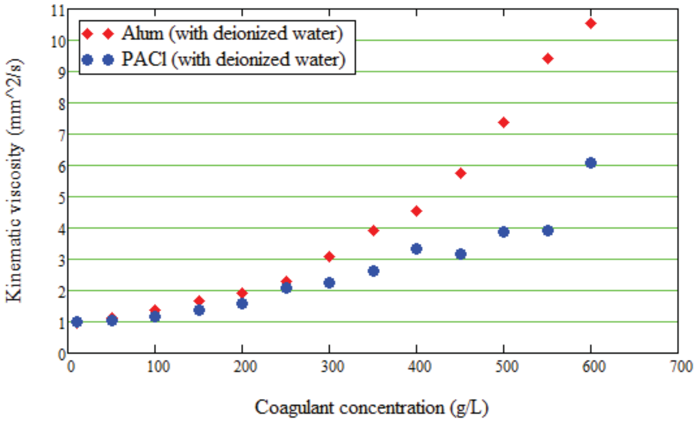

Figure 3: Kinematic viscosity of alum and PACl solutions taken by using the Vibro Viscometer in the Nanobiotechnology Center (NBTC) in Duffield Hall on Cornell Campus.

of the coagulant increases so did the viscosity of both Alum and PACl, which means that it flowed slower through the 1.85m length tube. This requires future designs and experiments to use a shorter tube length to deliver the same flow rate found by water in previous testing for comparison.

The current experiments will measure the flow rate of water and coagulant, using Alum or PACl, through shorter tube lengths and also through a new apparatus setup. The previous experimental design requires a perfectly straight tube, in a trough, to reduce minor loss, as seen in Figure (1). This design, though reducing a large percentage of minor loss, is not highly practical for use in the field because of the need for a perfectly straight tube that takes up a large amount of horizontal area.

Therefore, the Fall 2011 team with be experimenting with reducing horizontal length and how this affects the flow of chemical dosing. Instead of simply moving the CHT closer to the drop tube, allowing the tube to hang free, there will be various different experimental setups to see which will give the lowest value for the minor loss coefficient, K. There will be three separate setups that will be tested along with addition or exclusion of a minor weight, less than 100 grams as shown in Figure (4) and using a new barbed fitting for a $\frac{1}{2}$in ID tube that will be connected to the smaller ID tube (Figure 5). If it is shown that the addition of the weight, and a particular setup, give a better k-value than the purely horizontal setup, this will be experimented with further by either increasing the weight or moving it along the tubing.

The first of these new setups will be to move the CHT closer to the drop tube with the dosing tube coming from the base with a push-to-connect, instead

Figure 4: Weight that will be used in testing. Small size, less than 100 grams. Will be "hung" on the tube to reduce the length of curved tube.

Figure 5: Two fittings that will be used in following experimental setups. The picture on the left is the drop tube with the previously tested barbed fitting. The picture on the right is the new, larger, 1/2" barbed fitting for the larger ID tube that will be connected to the smaller ID tubing.

Figure 6: Fall 2011 preliminary lab setup. The single, small diameter tube is attached to the CHT by a push-to-connect at the base instead of a barbed fitting on the side. This dosing tube is then connected directly to the dose tube using a previously tested barbed fitting. The picture on the right shows the addition of a weight to reduce curvature to a single point.

of from the side with a barbed fitting. This dosing tube will still be attached directly to the drop tube using barbed fittings that, in the past, were shown to greatly reduce the minor loss coefficient. As shown in Figure (6), there is curvature in the tube when this setup is used. The addition of a small weight centralizes the curve to a smaller portion of the tubing, resulting in a longer section of straight tubing.

The next experimental setup is similar to the first in that it continues to use one single tube that is connected to the base of the CHT. Instead of attaching straight to the drop tube, the smaller diameter tubing will be attached to a larger, $\frac{1}{2}$in ID tube. To facilitate this, there will be a small (5cm or less) section of rigid, $\frac{1}{4}$in ID tube that will act as an transition in sizing for the two drastically different tube sizes. These tubes, according to Equation (5), will not contribute significant minor losses due to their large diameter. Again, as shown in Figure (7), this setup will require testing with and without a minor weight. The curvature is again centralized when the weight is attached, leading to a fairly straight smaller diameter tube coming from the push-to-connect and connecting to the larger ID dose tube.

In order to decrease the horizontal distance, keep the tubes fairly straight, and use the tested tube lengths, a purely vertical design has been created, as shown in Figure (8). The length of the smaller diameter tube is a calculated

Figure 7: Fall 2011 preliminary lab setup. The single, small diameter tube is attached to the CHT by a push-to-connect at the base instead of a barbed fitting on the side. This dosing tube is then connected to a $\frac{1}{2}$in ID tube by using a small section of $\frac{3}{8}$in ID rigid tubing. The picture on the right shows the addition of a weight to reduce curvature to a single point.

Figure 8: Fall 2011 preliminary lab setup. The single, small diameter tube is split into two, uneven sections. One longer section is attached to the CHT by a push-to-connect at the base instead of a barbed fitting on the side. This dosing tube is then connected to a $\frac{1}{2}$in ID tube by using a small section of $\frac{3}{8}$in ID rigid tubing, which is then curved to complete the 180-degree turn. The shorter segment of small diameter tube is connected to this and then connected to the $\frac{1}{2}$in dosing tube. The picture to the far right shows how the addition of a weight reduces curvature in both tube segments.

value using both the viscosity and expected flow, which was confirmed by both experimentation and theory.The total length of tube used in the vertical tests must equal the total length of tube used in the horizontal experiments. These tubing lengths were found using the LCDC Design Mathcad file, giving the tubing lengths of 1.32m for Alum and 1.42m for PACl. Because this setup includes two separate segments of tubing, there is slight curvature from the larger ID tube pushing out. The addition of the weight reduces curvature in both tube segments, thus making an almost straight tube for both tube segments.

The procedure for measuring the flow through the system is the same no matter what apparatus setup is being tested. Starting with an empty CHT, and the valve between the stock tank and the CHT turned off, decide which apparatus setup is being used. For a single tube test, attach either end of the tubing to the push-to-connect and make sure to firmly push it into the connect point so that there will be no accidental leaking. If this test is using the 100gm weight, slip it over the tubing, making sure that it is resting on the point of tubing that is closest to the ground. Attach the tube either directly to the drop tube, to the smaller barbed fitting, or insert it into the larger $\frac{1}{2}$in tubing. This larger diameter tubing, that is directly connected to the drop tube using a larger barbed fitting, should be at a minimum 60cm long. This ensures the tubing will be able to be used at all head loss settings, up to 30cm, and will be able to slide along the lever without causing unnecessary bending.

For split tube experiments, first create your segment of $\frac{1}{2}$in tubing that will curve between the two segments, where a length of 25cm creates a curve that is not too sharp to create unnecessary pressure in the tube, but is still short enough to allow the tubes to be fairly near to the CHT and parallel. A short piece of $\frac{1}{4}$in rigid tubing will be inserted into each end of this tubing, to allow a smooth transition between the small diameter tubing to the large. It may be required for the tape to be wrapped around this short, 5cm, segment to make the outer diameter a tad larger, creating a snug, leak-proof connection between the two tubing sizes. Taking the longer of the two pieces of cut tube, 71cm for Alum tests and 76cm for PACl, insert one end into the push-to-connect and the other into one end of the created $\frac{1}{2}$in curved piece. Insert the other piece of tubing, 61cm for Alum and 66cm for PACl, into the other end of this piece of curved tubing. In split tube experiments, it is not possible for the small diameter tube to go directly to the drop tube, so the other end of the shorter length tube must always be connected to the 60cm dosing tube.

After these initial tests, supplemental experiments are required to test certain variables besides the addition of a weight. Instead of using the $\frac{1}{2}$in tubing setup, which could allow minor losses from the transition from $\frac{1}{8}$in ID to $\frac{1}{2}$in ID, replacing this setup with only the $\frac{1}{4}$in ID tubing should still have a positive reduction in the k-value. This experiment can be performed by simply inserting the smaller ID tubing into the larger, or by using a double ended barbed reduction fitting for a $\frac{3}{16}$in ID to a $\frac{1}{4}$in ID tubing. The reduction fitting is a more stable connection, rather than inserting tubes into each other, which is vital for use in the field, where higher flows may blow out less than acceptable tube connections.

Before any experiments are started, the apparatus must be calibrated. This is done when the stock tank valve is open, the CHT has reached a constant level, and the lever is at the “zero” head loss setting.The goal is to have zero chemical flow at the same point when the zero flow through the plant. To make sure that the zero point is accurate, raise the CHT slightly to see if an increase in height causes an immediate response in flow to the dosing tube. When the apparatus is correctly calibrated, the tubing that is connected to the dose tube should have water all the way up to the barbed fitting. This can be checked by raising the lever to “one” head loss setting, seeing if there is flow, and then returning the lever to “zero” setting to make sure the flow does actually stop at this point.

Weigh the container that will catch the flow in 60sec intervals. This is important because it will allow you to zero out the scale after each use, ensuring accurate weights. Though a flow can be taken at all head loss setting, the range that will give the most accurate flow data is: 4cm, 8cm, 12cm, 16cm, 20cm. After setting the lever to this head loss, wait a moment for the flow to become uniform in nature. Collect this flow in the container for 60sec, timed with a stop watch for accuracy. Remove the container, weigh the container and flow captured, record, then recycle this volume by pouring it directly into the stock tank. For later experiments using Alum and PACl, this will keep the volume of available chemical fairly consistent. During this period of time, the lever can remain in its test setting with the water/chemical flowing. Make sure to completely dry the container before doing another 60sec trial.

After three trials are recorded for a setting, to create an average that can account for any collection errors , return the lever to "zero" setting. This allows the CHT to reach its original level again, and also ensures that the "zero" level of the apparatus is still the correct "zero" level. Repeat for each head loss setting, making sure that the lever is parallel to the rig to limit errors in flow quantity.

Enter the data into the Mathcad file, subtracting the weight of the container and dividing by the density of the liquid being used. This will be the volume of flow, and multiplying by the 60sec interval will give the flow rate at each head loss setting. Thus the flow rate of the experimental setup can be compared with the Hagen-Poiseuille flow rate, and the k-value of the apparatus can be estimated.

The first experiments will continue to use the original setup that was implemented in Summer 2011, see Figure (1), using a PVC trough to stabilize and straighten the flexible tubing used. Water was used throughout these experiments as a control, with both tubing lengths used, which will be 1.32m for Alum and 1.42m for PACl. These experiments will be used with varying concentrations of Alum and PACl later in testing, and should confirm the experimental data discovered by the Summer 2011 team. These distances were found using the viscosity data from the Summer team, and calculating an appropriate length using Mathcad and the tube ID currently available to the team. It is required to use this setup to confirm the data that was created and analyzed in previous team's work.

Analysis

The first split tube experiment required taking a tube that was 1.32m in length, and cutting it into two equal sized pieces of 0.66m in length. One piece of this tubing came directly from the base of the CHT, where the push-to-connect valve has been fitted for tubes with an outer diameter (OD) of $\frac{1}{4}$in. This length of tubing will hang from the base and is connected to a much larger ID flexible tube. This tube is curved, but because it has a much larger ID in comparison to the $\frac{1}{8}$in ID straight tube, there will be minimal major and minor losses. The larger diameter flexible tubing will be curved to complete a 180-degree turn, which was connected to the other portion of small ID tube, pointing straight back up. The smaller diameter tube is connected to another section of large ID tube, approximately 60cm in length, which makes a 90-degree turn to attach to the drop tube.

During this initial design, it was assumed that the two lengths of the small diameter tube could be equal, or semi-equal with a few cm difference. While as-

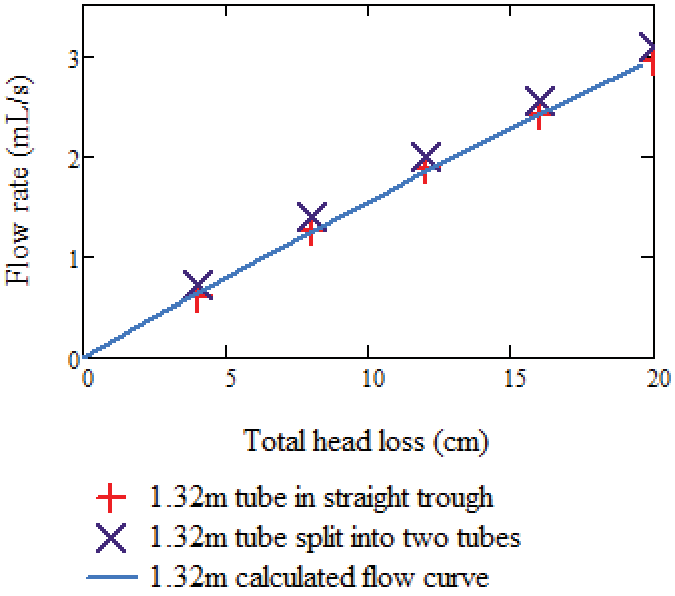

Figure 9: Preliminary data collection using new design of split tubes, 0.71m and 0.61m respectively. Compared to the straight 1.32m tube, and the calculated flow curve, the split tube design has a marginally higher flow rate in comparison.

sembling the new experimental apparatus, it became apparent that two different lengths of small diameter tube, with length differences of 10cm or more depending on how severe the larger ID tube would be curved. The decided lengths of tubing to use in the 1.32m design for testing was a 0.71m tube to come from the base of the CHT, and 0.61m to be the connecting section. Note that the two equal length tubes were previously tested. A small weight, approximately 100gm in mass, is also hung on this larger ID connector to force the smaller ID tubes, which control the flow, to hang straight instead of slightly bent/curved.

As shown from Figure (9), there was a slight increase in the flow rate using the new apparatus setup. A cause of this has not be determined, though it was narrowed down to the new additions to the apparatus: the small ID tubes themselves, the large ID at the bottom, the hanging weight, or the large ID connected to the drop tube. The length of the small ID tubes is not in question, since it is shown, on Figure (9) that the flow rate in a perfectly straight test resulted in the calculated flow rates.

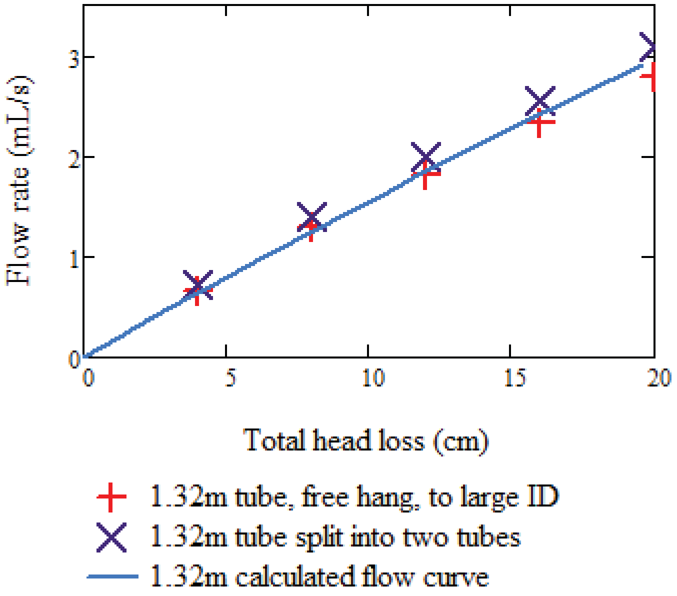

Figure 10: Graph showing a comparison between the free hang flow rate, and the flow rate when using two tubes of different length. The free hang tube is fairly consistent with the calculated flow rate for the tube length.

It was determined that testing the large ID tube to the drop tube as a factor would be easiest, and another experiment was run using a free-hang tube from the base of the CHT connecting straight to the $\frac{1}{2}$in tube connected to the drop tube. The free hang tube data showed that it had a similar flow rate to the flow rate function at that tube length, except for a decrease when total head loss was equal to 20cm, as shown in Figure (10). In past experiments by other teams, it was determined that loose "coiled" tubing creates more minor head loss. The information found by the last experiment seems to suggest that the minor loss is greatly reduced when the tube is connected directly to the base of the CHT, most likely due to the small ID tube being fairly straight from the push-to-connect.

After completing experiments using the four different setups, and the addition of the small weight, it is possible to create a table that shows how the k-value changes with each changed variable. Figure (11) shows the results of the fifteen experiments, with most k-values being under 10. In the Spring 2011, the lowest k-value was 2.748 with a large majority of the k-values over 10. The Fall 2011 experiments have results that are, at a maximum, 10% higher than 10, with the lowest k-value being 2.418.

From this data, it was apparent that adding a weight significantly drove k-values lower, so experiments that do not implement this new design should no longer be needed. Since testing was done for only two different tube lengths, 1.32m and 1.42m, it is required to use more testing lengths to see if there is a trend in the k-value. A k-value that is slightly higher, but consistent, over different tube lengths is an easier variable to deal with than a k-value that varies wildly over each different length. The design will be easier to implement if it is known that the k-value is the same no matter what length of tubing is cut.

Additional experiments were performed at more lengths of tubing to see the variability of the k-value. This includes the single, straight tube in PVC, with and without the addition of the 60cm $\frac{1}{2}$in ID tubing to the drop tube, a single tube with a weight to the $\frac{1}{2}$in ID, and a single tube with a weight to the $\frac{1}{4}$in ID tubing segment using new barbed fittings. The last two designs are assuming that the use of a $\frac{1}{4}$in ID is comparable to a $\frac{1}{2}$in ID, since the minor losses in a $\frac{1}{4}$in ID tube will be reduced by a factor of 16, which should be enough satisfy the design.

The highest value of these k-values is found in the single tube with a weight that is connected straight to the $\frac{1}{4}$in, without the use of a barbed fitting. This k-value was 5.9, much lower than the values found in the Summer 2011 values. The lowest, consistent, k-values were again found by using a single, straight tube, that was coming from the side of the CHT. The k-values for the straight tube with the 60cm $\frac{1}{2}$in ID tube attached were slightly higher, most likely due

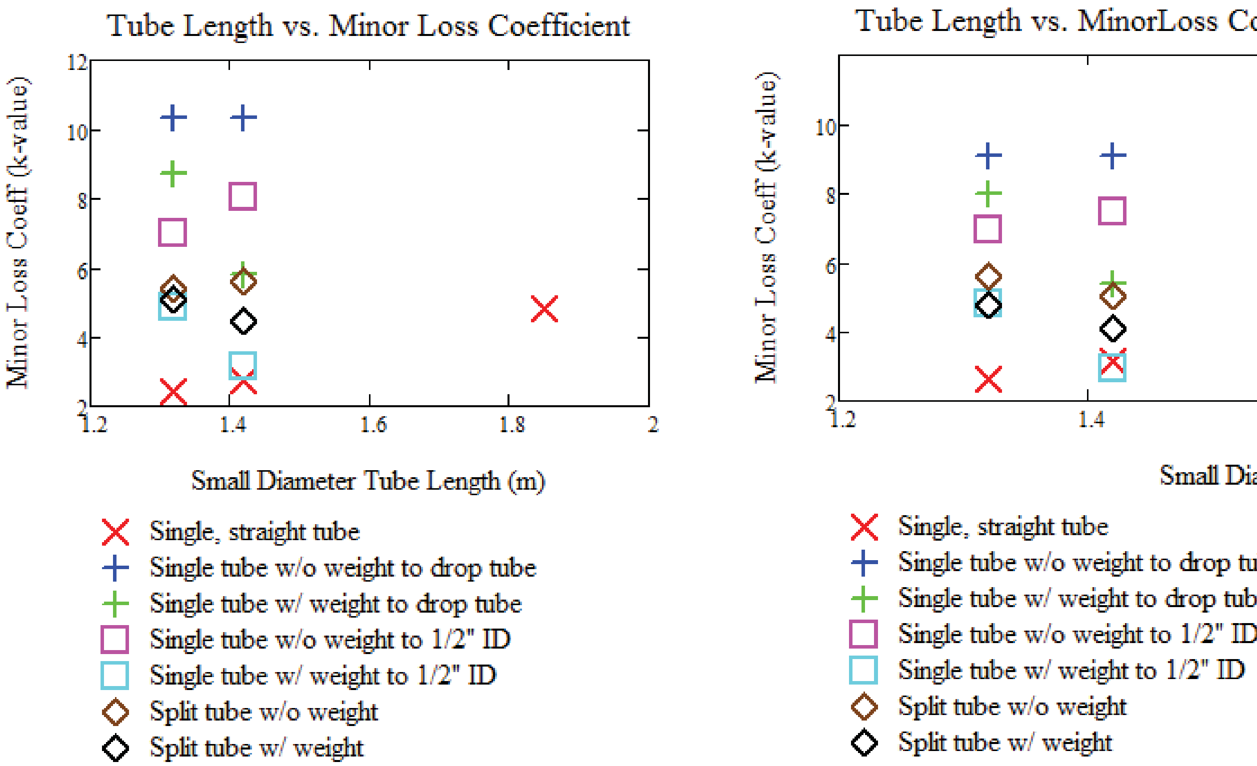

Figure 11: Minor loss coefficients as a function of tube length using different experiment setups. The addition of weight to the tube has a marked decrease in the minor loss coefficient, which will require further testing in an attempt to decrease the k-value further.

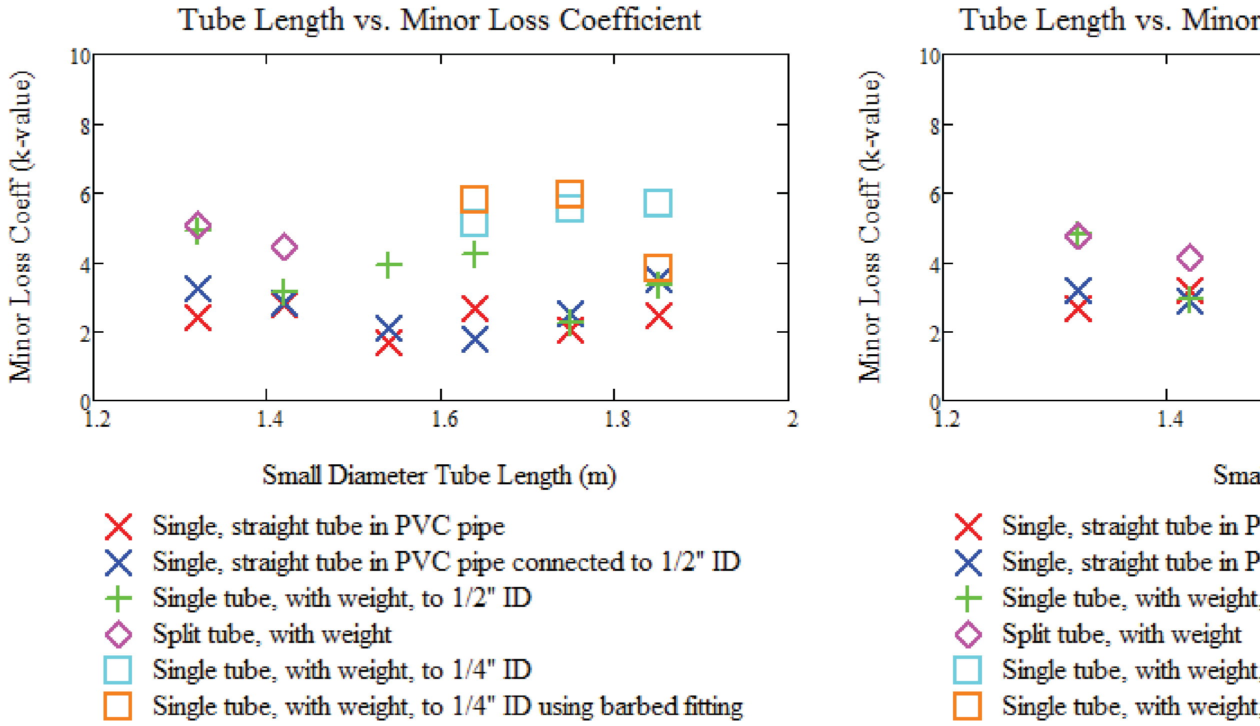

Figure 12: Minor loss coefficients as a function of tube length with different experimental setups. The minor losses should be reduced by a factor of 16 when using a 1/4" ID tubing instead of 1/2" ID, which should be substantial enough to require only one type of tubing to be used as a connection between the smaller diameter tubing instead of two.

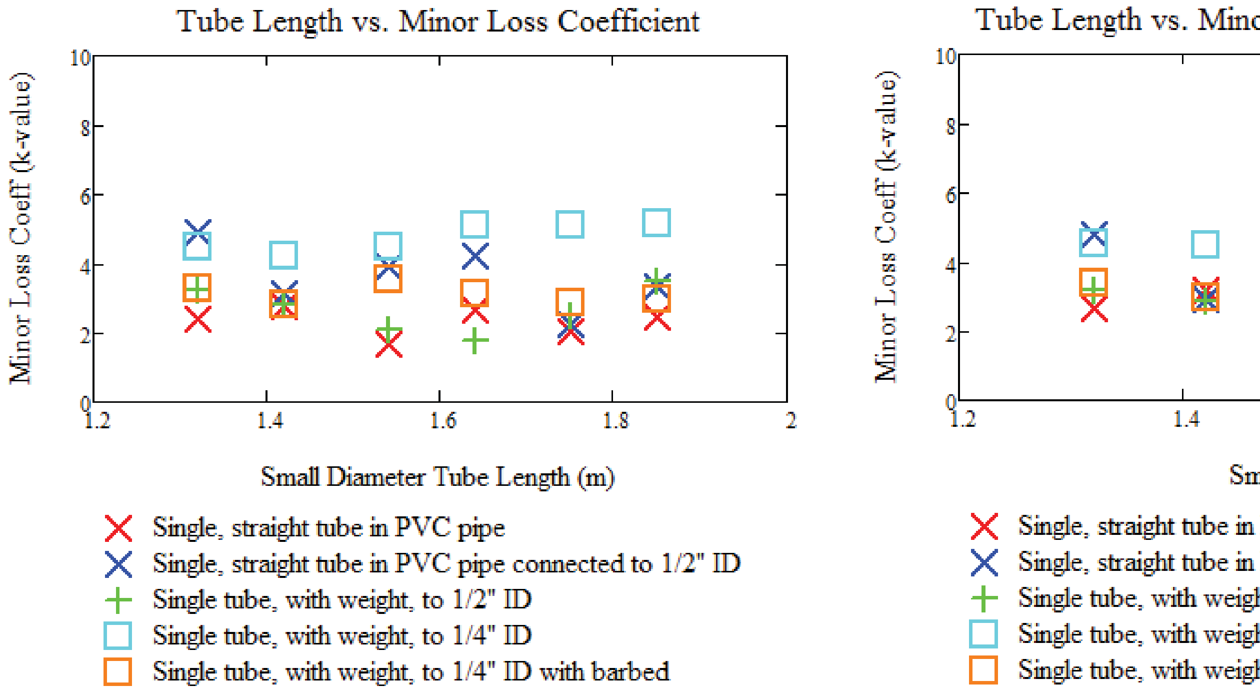

Figure 13: Minor loss coefficients as a function of tube length with different experimental setups. Though the minor loss k-value is reduced by using 1/4" ID fittings, the 1/2" ID setup and straight tube in a PVC pipe have the lowest calculated k-values.

to the length of tube being so long that sections were no longer in the PVC pipe and were not completely straight.

As a result of increased variability in the experimental observations, it was required for the $\frac{1}{4}$in ID experimental setup to be re-run to ensure accuracy. When duplicated, the k-values of the experiments were more consistent, as shown in Figure (13). All k-values calculated from the observed flow were beneath 6.000 , with the largest value created by the single tube that was connected to the $\frac{1}{4}$in ID tubing without use of a barbed fitting. Figure (14) shows a simpler view of the experiments excluding the known lowest k-value setups that required the straight tube in a PVC pipe.

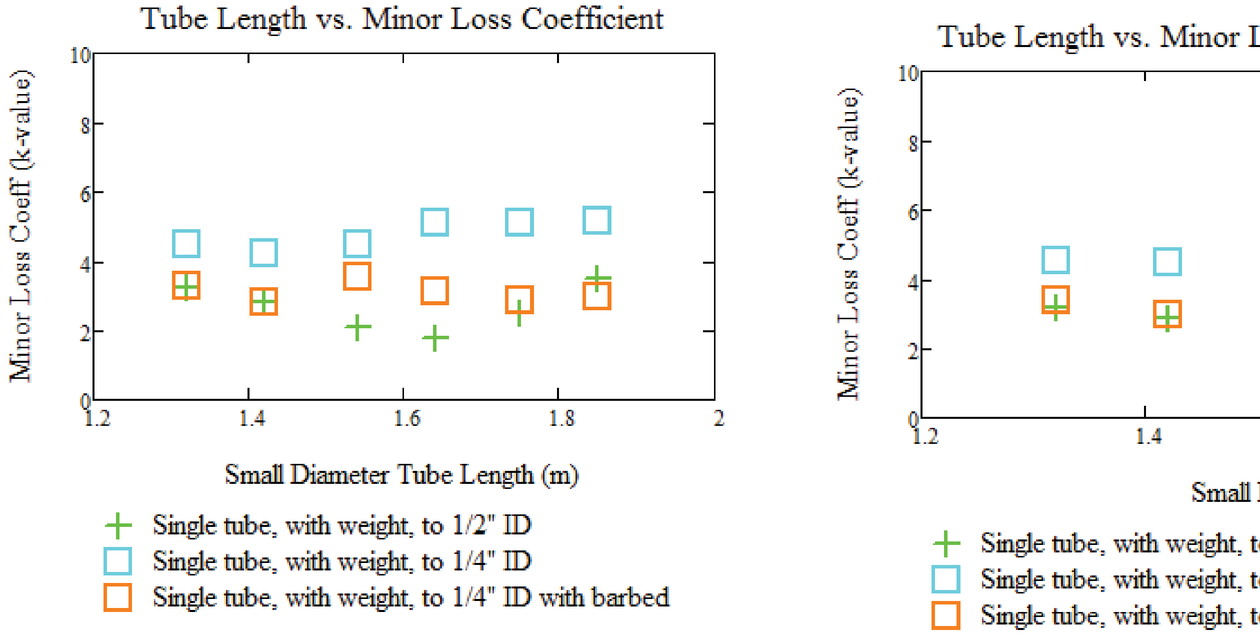

Figure 14: Minor loss coefficients as a function of tube length with three experiment setups. Simplified view of Figure (13), removing experiments that would not be plausible to use in Honduran water treatment plants.

Conclusions

The group first starting the experiment thought that splitting the smaller ID would result in higher minor losses due to the tubes being connected at four points instead of two in previous setups. In previous experiments, the tube was connected at two barbed fittings, of a larger size to reduce minor losses. The current setup has the tube connected to the CHT base with the push-to-connect, which does not put a large amount of force on the tube, but the the flexible $\frac{1}{8}$in ID tube is then forced into a $\frac{1}{4}$in ID, which is then connected to the large $\frac{1}{2}$in ID tubing. This unique connection, requiring an intermediate tube to allow the smaller ID tube to flow into the largest ID tube, is used twice on the other portion of tubing.

Instead of causing a decrease in flow rate, which is the case when there is sizable minor losses, it seems like the addition of the large ID has slightly increased the flow rate. As shown by the Hagen-Poiseuille Equation (1), which is based off laminar flow, the flow is proportional to $\frac{D^4}{L_{Tube}}$. The value of the proportion for the larger ID tube is over 550. The flow of the system should only be controlled by the length and diameter of the small tube, but this addition of larger tube can reduce the loss created from the expansion and curvature of the small, inner diameter tube..

The length of the large ID tube connected to the drop tube fitting will remain constant in future experiments, with this length staying constant at 60cm in each experiment. If the flow is only increased when the large tube is present at the drop tube, and not when present as a curve connector between two split tubes, this would be because of the minor loss coefficient being minor, because the larger diameter tube is performing all expansions and curving.

From the new k-value data, it has been confirmed that the large tube as a connection to the drop tube will greatly reduced the minor loss coefficient by approximately 35% in value. This is substantial because it brings even the highest of these k-values to 4.8, already performing at a level equal to or better than most plants in Honduras. The hypothesis at the beginning of these experiments was that a split tube should have a similar flow and k-value to a single tube of the same length. From the experiments it should be noted that the k-value of the split tube, though not changing as much with the addition of the weight, had a much smaller initial k-value than the other experimental apparatus, barring the straight tube apparatus.

The addition of the weight reduced the k-value for all experiments. For the single tube that was connected to the $\frac{1}{2}$in tube, the decrease in k-value was 30-60% in value. The split tube had the smallest k-value decrease with the addition of the weight, only decreased by 6-21%, but it is still a reduction of the k-value. This is in agreement with the hypothesis that the addition of a weight will reduce the curvature and will keep the small diameter tube straighter than if allowed to hang free.

The smallest k-value obtained was obtained using the straight apparatus setup, but there is a wide range in the 1.32m, 1.42m and 1.85m k-values from 2.748 to 4.832. A k-value that is fairly uniform with the increase of tube length is key, because the change in flow can be easily estimated. Also, a trend in the k-value with an increase/decrease in length could be found with more data points on the k-value graph.

It seems as if the straight tube setup is optimal, but the goal of the Fall 2011 team is to both reduce the k-value and the horizontal distance needed by the apparatus. The current system of using a short section of rigid tubing may be a source of minor loss, since it allows the liquid to expand before reaching the large diameter tubing. To avoid this possible cause of increased k-value, the apparatus for both the split tube and $\frac{1}{2}$in dosing tube could be changed at this one connection. Instead of simply inserting the small diameter tube, and allowing it to end halfway through the rigid section, it should be pushed through the entire rigid section and have the ends of the the two tubes equal. This will allow the water flow to go directly from a $\frac{1}{8}$in ID to a $\frac{1}{2}$in ID without intermediate expansion.

The straight tube is considered the "best" setup available, giving a close to linear chemical flow and also having the smallest k-value present. This setup was performed without using a section of large diameter tube connecting to the dose tube, which has now been shown to make a substantial difference in lowering the k-value. It is likely that the addition of the large tube at the end of the straight setup will reduce the k-value even more since it will eliminate the bending of the small diameter tubing when the lever changes the head loss.

All setups have only been performed with two different tube lengths (1.32m and 1.42m), or three with the initial straight/horizontal (including 1.85m). It has been confirmed that the addition of a weight makes a substantial difference, so the two setups that will be further tested are the split tube and the single tube to the large diameter because they both had the lowest k-values. They will be tested with longer segments/sections of tubing to see if the k-value varies widely with each tube length increase. Again, this will show a trend in k-value increase or decrease.

After testing it has been shown that, after re-doing the 1.85m tube setup, that the straight setup is again the best out of the tested setups. The average k-value was 2.325, with a maximum value of 2.744, and the k-values across different lengths of tube was very consistent. The other straight tube setup, which included the connection to the $\frac{1}{2}$in ID tube, had a slightly higher k-value because the length was so long that it was no longer contained in the PVC tube, and thus curvature was present in some points of the tube despite trying to keep perfectly straight.

The single tube from the base of the CHT, with a weight, is the next best system after the two perfectly straight setups. After runs in each tube length, the minimum k-value is 2.232 and the max value was 4.871. The average of all experiments was a fairly impressive 3.615. This system has been the easiest to setup, and the simplest to fix when air bubbles are present in the tubing. This will be important if this setup is implemented in existing plants.

It was theorized that the $\frac{1}{4}$in ID tubing would decrease the minor losses by a factor of 16, from the equation (5) , which should be enough for the system to function at a similar k-value as the $\frac{1}{2}$in ID tubing. From the results, it is shown that the k-value for these are low, they are not as low as the $\frac{1}{2}$in ID experiments. The use of the barbed fitting did bring the average k-value present down by 5%, from 5.442 to 5.167. Compared to the previous experiments, this decrease is not as significant as before. There is a large degree of variability in the capture of flow for the double-barbed fitting experiments, with a range of values of 2.119. Experiments may need to be re-run, due to improper calibration, and the rest of the small diameter tube lengths must be run.

Due to the variability found in the single tube setup that implemented the $\frac{1}{4}$in ID tubing only, these experiments were repeated to test the validity of the k-values. With the setup being calibrated to a higher degree of precision than previously, the average of the barbed fitting k-value decreased to 3.107 compared to the k-value average of 4.756 without the barbed fitting. This is a decrease in the k-value average of 35%, which is more consistent with the theory that a barbed fitting will substantially reduce the minor loss coefficient found in the system.

The new double barbed fitting, which are optimum for a change in ID from $\frac{3}{16}$in ID to a $\frac{1}{4}$in ID, should have little to no minor loss due to it being a bigger fitting than necessary for the smaller ID tubing. It is possible that there is minor loss from the fitting located in the $\frac{1}{4}$in ID, since that end is an exact fit to the tubing and is not a slightly larger barb like that for the smaller ID. There is no conversion barbed fitting that would go from $\frac{3}{16}$in ID to $\frac{5}{16}$in that can be found in McMaster, so it is necessary to go to an outside manufacturer to find a fitting that would accomplish this. If the barbed fitting is too specialized, expensive, or difficult to obtain, it should not be used in lab settings. Even if this barbed fitting can be found, the difficulty of finding it and its cost may limit its use in Honduras.

Currently the single tube with a weight connected to a $\frac{1}{2}$in ID tube is showing the lowest, and most consistent, k-value that could be implemented easily into Honduran water treatment plants. Unlike the split tube, which may have similar k-values, there is only one "main" tube being used. The split tube with lower k-values, is not practical for plant-use due the abundance of tubing that much be switched, changed, or clamped due to the numerous connect points. To decrease the amount of reduction connections, and the minor losses, the $\frac{1}{4}$in ID tubing should be used instead of a combination of $\frac{1}{4}$in ID and $\frac{1}{2}$in ID.

The single tube setup is slightly more implausible to be used safely, simply because there is no reducer currently on the market that has a barbed fitting with both a $\frac{1}{2}$in diameter barbed fitting and $\frac{3}{16}$in diameter barbed fitting for the smaller diameter tubing. So if this apparatus were to be used the tubes would not have a stable connection due to lack of fittings, thus relying only on the snugness of fit between the smaller inner diameter tube that is inserted into the larger ID tube. Thus, the experimental setup that had the lowest k-value currently tested is a single, $\frac{1}{8}$in ID tube that is connected to a $\frac{1}{4}$in ID tube using a double ended barbed reducer, a weight to have longer sections of straight tubing, and a $\frac{1}{4}$in barbed fitting on the drop tube.

Final Thoughts

There has a been a marked reduction in the k-value from the Summer 2011 Team results, creating consistent k-values below a value of 6.000. The setups portrayed in Figure (14) are the three setups tested by the Fall 2011 team that would make the largest positive difference if used in non-laboratory settings. Though the straight PVC tube experiment has the lowest k-values, it is not plausible to have such a large amount of horizontal space dedicated to one part of the plant when similar results can be found with a simpler and more space-friendly design. These experimental setups do not require an excess of materials, such as the PVC or split tube setups, and can be easier assembled without multiple parts, which would again be required for the complicated split tube apparatus.

The task list that was drafted before the experiments started was not consistent with the work done, though the results are of vital importance to the current designs. The task list was created with the idea that the k-value would change with different viscosities, which is incorrect, and focused solely on the stock concentrations. It was only after a few weeks that it was apparent that lowering the k-value of the entire system would solve many of the problems. Since the k-value is independent of viscosity, the flow of different stock concentrations could be calculated from the data created by the Summer 2011 team. Also the task list was not as detailed and project-oriented as it could have been.

From the original task list, the tasks finished that did not deal with review of MathCad or the previous apparatus were those dealing with the creation of a new experimental design, using and creating a new up-to-date component list due to the new setups, and writing an article for submission to Journal of Environmental Engineering that explains past work on the chemical doser. An updated task list will be created to document the tasks that were completed by the team throughout the semester and posted to the LCDC wiki page.

The components required for the doser have been edited slightly, using a different barbed fitting for the drop tube and requiring a reducing barbed fitting when using a dual-tube apparatus setup. This has been updated in the excel file that documents all the parts used in the system, which will need to be edited further for future use due to the abundance of parts listed that are no long required for the present system.

Overall, the Fall 2011 team accomplished its goal to create a chemical doser that has a greater linear relationship than previous designs. Its simplicity, ease of use, and higher accuracy in flow will make it easy to install in future plants and, if required, it should not be difficult to retrofit LCDC's in previously built plans.

Future Work

Future teams will need to continue testing the horizontal setup. Instead of using a push-to-connect from the base of the CHT, which is not a fitting that is used in Honduran plants due to a high error associated with them, the base connection should be one of the tested barbed fittings. Also a proper weight will need to be researched that can be ordered and used in the field, equal to or less than 100 grams in weight but able to be clipped on or slipped over a tube while in use.

The Fall 2011 team was unable to do any in-depth testing with different coagulant, which should be a large part of the work done by the Spring 2012 team. This will confirm or deny the viscosity data that was created by the Summer 2011 team. Also, a point that was broached by Antonio Elvir during his visit was the build up of deposits in the float valve orifice in the field. It is possible that this can be controlled by having the float valve submerged in the solution in the CHT, but this should be tested in the lab for further confirmation.

Though the k-value has been reduced greatly, there is still minor loss present in the system. It will be the work of the future teams to see if this value can be reduced further, if possible, and to see if a design can be created using multiple tubes that will still have a k-value that is sufficiently low.