Chemical Dose Controller Final Report

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AguaClara Final Report

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Date Submitted: 02/08/10

Date Revised: 22/08/2010

Abstract

The Summer 2010 Chemical Dose Controller (CDC) Team has spent the summer exploring the challenges associated with manufacturing precise orifices. The team has run a series of tests measuring flow rate on orifices created from Legris polyamide, flare cap fittings, refrigerator caps, and carburetor jets to determine their precision and accuracy. The orifices manufactured from polyamide were deemed inadequate, which caused the team to consider in-house and off-the-shelf manufactured orifices created from brass, which showed much lower deviations from the expected flow rate. This report describes

the results of the team's experiments on four different types of orifices and endeavors to set future goals for next semester's CDC Team.

Introduction

By far, the biggest hurdle in the development of AguaClara chemical dosing technology has been devising a method for accurately and precisely administering chemicals while adhering to the fundamental AguaClara design constraint: creating solutions which do not rely on electricity and are easy to implement and understand by the plant operator. Modern water treatment plants have highly dependent technology consisting of automated control systems and precise metering pumps. An AguaClara engineer’s challenge is to design accurate metering of chemicals without use of highly dependent technologies.

The primary process chemical administered through the doser is alum. Alum is a chemical flocculant that allows particles to stick together and become large enough to settle and be removed. Thus, accurate alum dosing is vital for plant operation as it has a great impact on the effectiveness of flocculation and sedimentation.

To that end, AguaClara engineers have been developing a Chemical Dose Controller (CDC) which utilizes principles such as differences in elevation head, and major and minor losses in pipes to predictably meter process chemicals. The first CDC developed by AguaClara engineers was the Linear Dose Controller (LDC) so named because of the linear relationship that exists between flow and the major head-loss that occurs as fluid flows through a pipe. This design utilized the predictable major head loss that occurs in a small diameter pipe to meter the flow, and therefore the chemicals, administered to the plant. The linear relation between plant flow and major head loss holds that Q is proportional to hand the relationship is accurately representative under laminar flow conditions. As AguaClara began to design larger plants, this design became limited as chemical delivery flow rates increased enough to enter the turbulent range. In this range, the relation between plant flow and major head loss can be described as the square of the Q value proportional to the height difference shown on the linear bar. Additionally, the linear relationship no longer holds true.

To overcome this difficulty, AguaClara engineers are developing a CDC that utilizes minor head-loss through an orifice (rather than through a pipe) to meter the flow of process chemicals (Equation 1). This is named the *Nonlinear* Dose Controller because the flow rate is now a function of the square-root of the height differential, making the relationship nonlinear.

The nonlinear Chemical Dose Controller's first iteration was designed in the fall of 2008 and has the ability to accurately dose under both laminar and turbulent conditions. This new design uses an orifice to control the flow of alum into the water treatment plant. A float in the entrance tank raises or lowers the lever arm depending on the flow rate, which in turn, controls the elevation head of the dosing tube (Figure 1). For example, an increase in plant flow rate will cause the float to move in the upward direction and the orifice to move in the downward direction, thus increasing the elevation difference between the orifice and the constant head tank and resulting in increasing chemical flow rate. At the moment, a dual scale marked with possible chemical concentrations is attached to the lever arm. The plant operator can slide the dosing tube along this scale in order to obtain the required amount of alum.

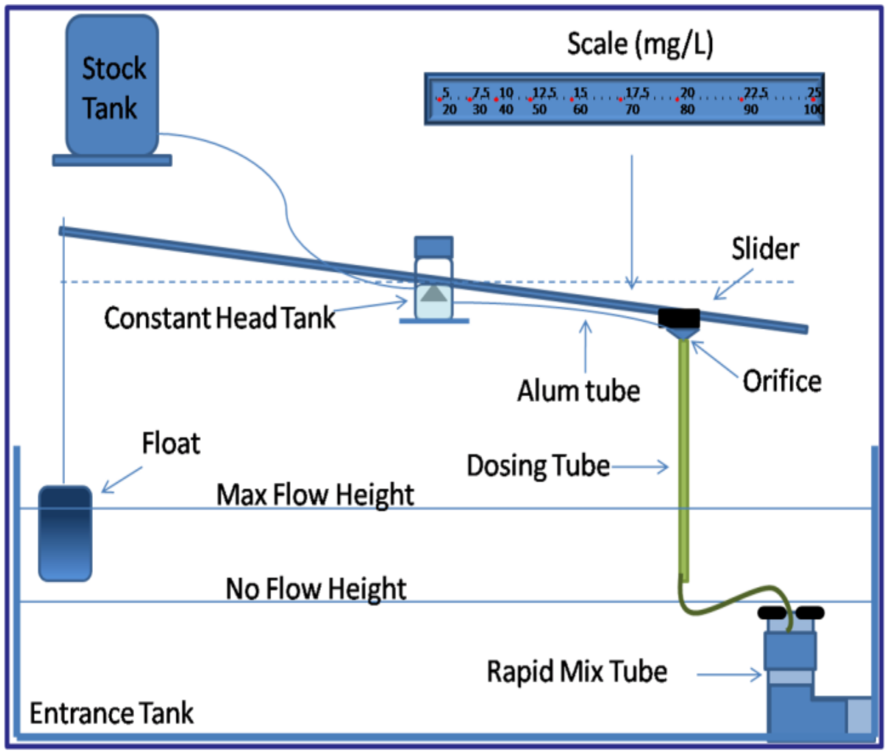


Figure 1: Schematic of the Nonlinear Chemical Dose Controller

The theory behind the nonlinear CDC is based on the flow rate of the incoming water and the available head in the tank (Equation 1):

$$Q = K_{Orifice} * (2gh)^{1/2} \qquad (1)$$

Where: Q is the flow rate of the alum, $K_{Orifice}$ is a coefficient related to entrance and exit losses, and h is the available head. This relationship holds true for both laminar and turbulent flow.

There have been several design modifications that have been accomplished over the past few semesters: ensuring that minor head losses predominantly accounted for energy loss in the chemical dosing system, reducing surface foam, and improving the accuracy by which the orifices dose chemicals. Experimental data gathered in the lab shows that major losses account for roughly 2% of the total head loss. Therefore most energy loss in the plants can be accounted for by minor losses through the orifice. This greatly simplifies the calculation of theoretical flow rates. At very low plant flow rates, there were additional hydraulic constraints. The team found that when trying to maintain flow at values of head below 4 cm, the surface tension at the orifice from the alum solution and major head-loss effects of friction in the dosing tube was limiting flow.

Surface foam was observed to be created in the flocculator and rapid mix sections of full-scale plant and hypothesized to be a result of the presence of surfactants in the water from natural organic matter (NOM) and the hydraulic jump of dosing the alum above the water intake. As a preventive measure, the entry point of the dosing tube was redesigned to be submerged in the entrance tank.

The Summer 2010 CDC Team sought to conduct a series of experimental validation tests that investigated the level of precision that could be expected from the dosing orifices. The team considered several types of orifices and analyzed the data collected from these tests to find the optimal combination of orifice diameter, material and manufacturing method. In addition to tests of precision, the team considered the level of accuracy, i.e. similarity to calculated values, the orifices could provide. The orifice equation that relates chemical flow rate to available head is straightforward, but non-ideal effects that occur at the entrance and exit regions of the orifices cannot be calculated theoretically. These non-ideal effects include the dependence of vena contracta at the entrance region on the shape of the inlet faces and the effects of head loss at the orifice exits as a result of swirling flow and turbulent motion. Once the data has been collected, empirical determination of an orifice discharge coefficient can be used to correct for these non-ideal effects.

Experimental Design

In order to eliminate as many sources of error as possible, the lever arm and float that connected to the 'entrance tank' were removed from the experiment setup. Instead, the dosing tube was connected directly from the constant head tank to a linear bar marked from 0 to 40 cm (Figure 2).

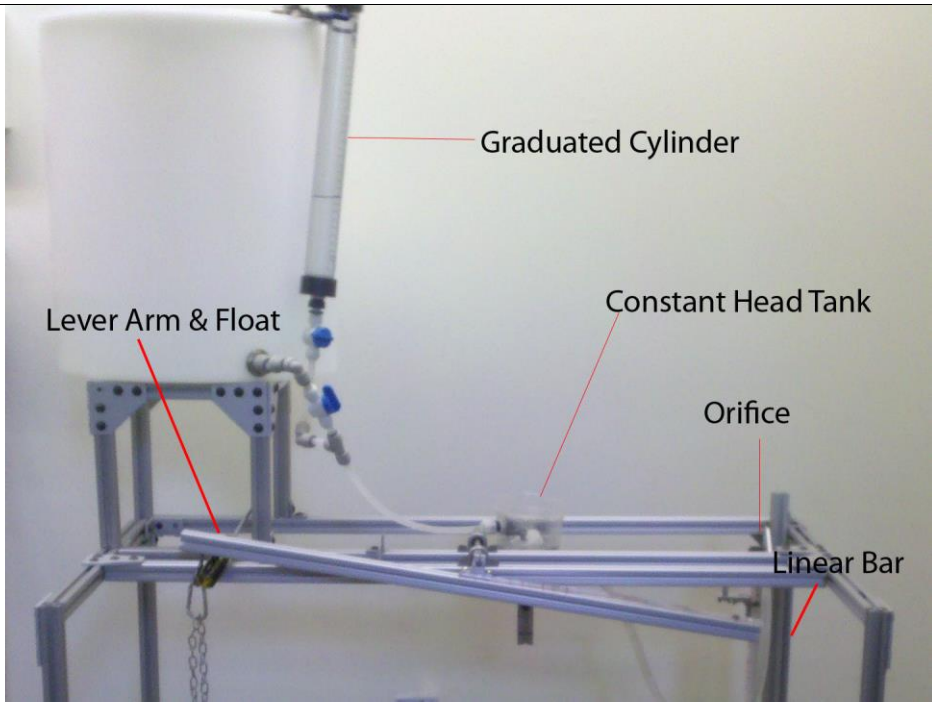


Figure 2: Experimental Design Setup

The orifices were tested throughout this range and the experimenters recorded the flow rate values in mL/min at each value of elevation head. The original test consisted of drilling the orifices in the direction of flow, as drilling in this direction was thought to lessen the effects of drill bit breakthrough. The test was then run five times on each orifice with a range of 0 to 40cm on the linear bar.

This data was entered into a spreadsheet that calculated the variance and standard deviation of these flow rate values, indications of the level of precision that could be expected from the dosing orifices. The spreadsheet also calculated upper and lower limits for a 95% confidence interval that was used to compare the measured flow rate with a theoretically calculated value. This calculated value came from inputting the orifice diameter into Equation 1. The information gathered from the experiments was utilized to determine the level of accuracy that could be expected from the orifices and assisted in the derivation of an orifice discharge coefficient to correct for non-ideal effects as described in the Introduction.

The first data set (collected from Legris polyamide orifices of 1 and 2mm in diameter) demonstrated wide variance within each orifice indicating that our testing apparatus and/or testing procedure was unreliable. To rectify this error, the team modified the setup of the experiment in a few ways as described in the Results and Discussion section.

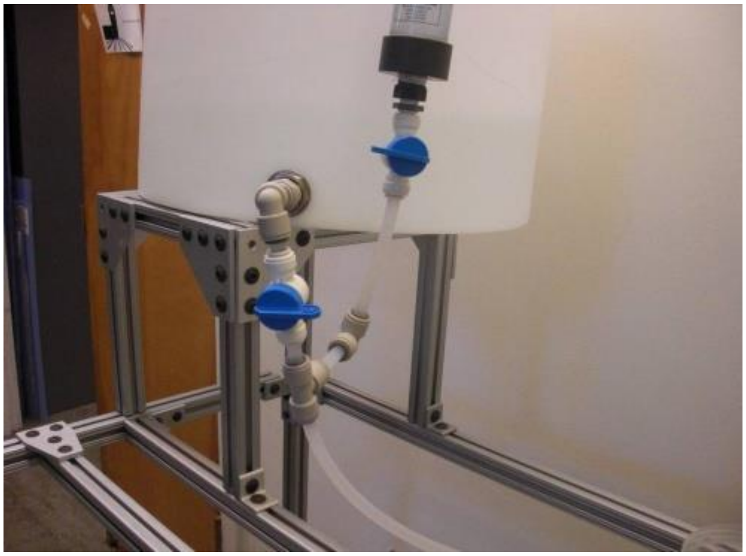


Figure 3: New Tubing (3/8" inner diameter)

However, the unsuitability of Legris Polyamide caps led the team to consider manufacturing orifices out of more machinable materials.

Two types of brass caps were thus chosen for validation: Refrigerator Tubing caps and SAE Flare caps. Two caps of each type were drilled with 2mm diameter orifices in the direction of flow. The results of this test, which shall be discussed in greater detail in the next section of this report, showed large inconsistencies between different orifices. The team's first solution to this problem was to remove the copper ferrules and rubber grommets from the caps thus creating more consistent entrance regions. However, this proved to have no effect whatsoever on the data. The team then determined that the inconsistencies could be attributed to the centering bit creating a different shaped entrance region, and thus a different vena contracta coefficient, in each cap. Since drilled brass does not create significant burrs at drill-bit break-through, the next round of tests was conducted on caps drilled against the direction of flow. This design was based on the assumption that the bevel created by the centering bit would only occur at the exit region thus keeping the entrance region consistent between orifices. This theory seems to be validated by the data. For this reason, the team manufactured two more orifices of each type of cap and gathered data on these as well. This increased the amount of confidence that could be placed in the results.

The team then decided to investigate the feasibility of using off-the-shelf orifices such as carburetor jets. Four brass carburetor jets of 0.040in (approximately 1mm) diameter were tested in the same way as the refrigerator and flare caps. These proved to be the most precise metering orifices tested thus far by the CDC team.

Results and Discussion

Legris End Caps

Figure 4: Legris End Cap

Data from our first series of experiments showed considerable variance *within* each orifice for both the 1 and 2mm diameter orifices (Figure 5,6). Ranges exceeding 28 mL/min were noted to have standard deviations exceeding 15 mL/min and a relative standard error of 69.6%. It was noted that at heights 0-4 cm, no flow or little flow was actually seen coming from the administering tube due the surface tension of the water. Additionally, during the 2 mm orifices tests, the level in the head tank dropped when testing in the 36 - 40 cm range on the linear bar. The team theorized that this was because the diameter of the float valve orifice on the constant head tank was 2.29mm and the orifice being tested was very similar in size. The orifice in the head tank thus had difficulties keeping up with the tested orifice at these high flow rates.

Due to these issues, the team chose to eliminate the very low and very high values of head from the testing range. The range of 8-24 cm, with five increments between these values, was chosen for the next tests as this distance had shown the least amount of variance and only an average standard deviation of 5mL/min in the previous tests.

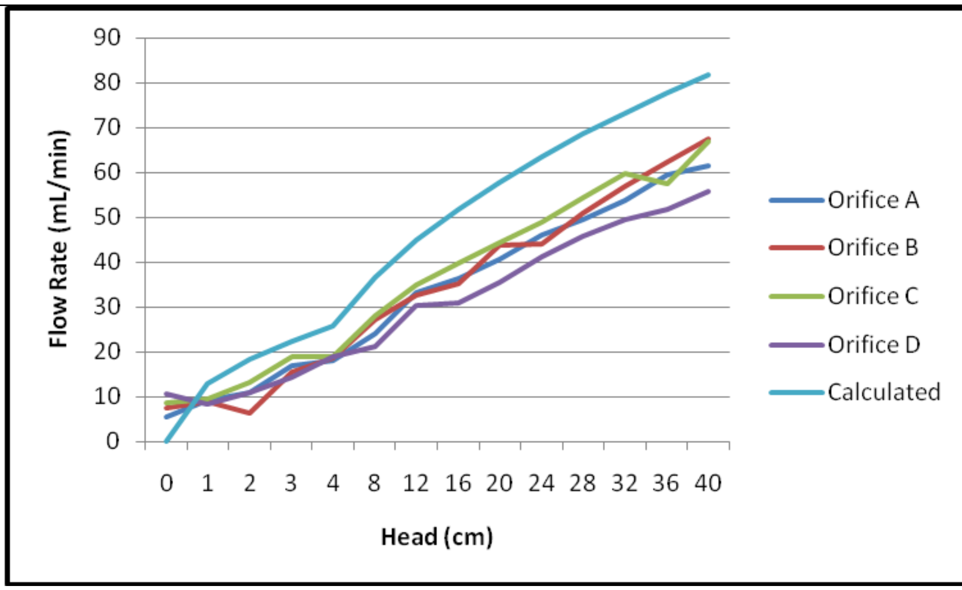
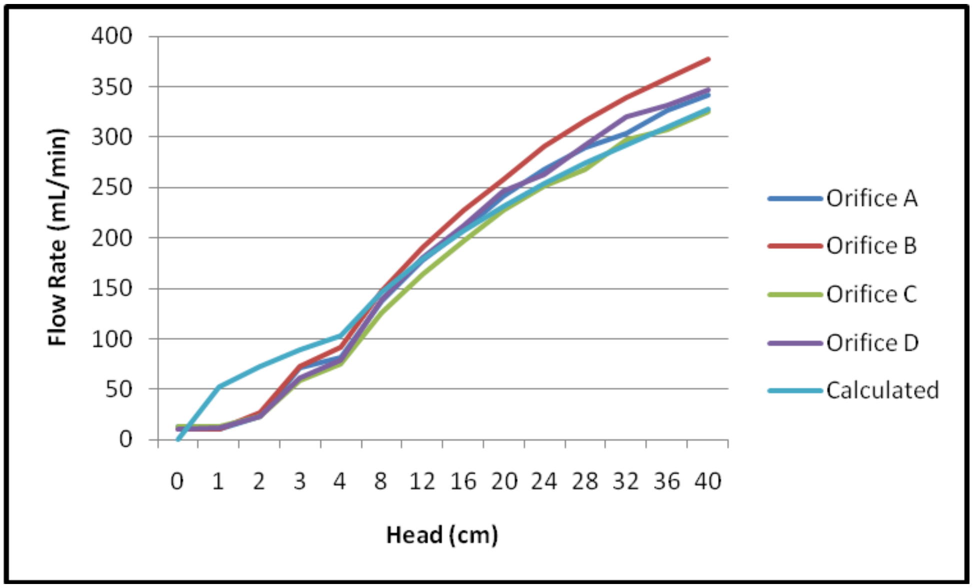


Figure 5: Legris Caps, 1mm, drilled in direction of flow - Version 1



Figures 6. Legris Caps, 2mm, drilled in direction of flow – version 1

Due to the wide variance shown *within* an individual orifice, the team decided to modify the testing apparatus as well as described in the Experimental Design section of this report. These design modifications resulted in each individual orifice showing an acceptable level of variance within the calculated range. This validated the new testing procedure and allowed the team to continue with the statistical analysis of the data.

However, this analysis revealed that the calculated range *between* orifices was quite high with standard deviations nearing 15 mL/min (Figure 7). The team concludes that this type of material and manufacturing process do not provide reliable and precise orifices.

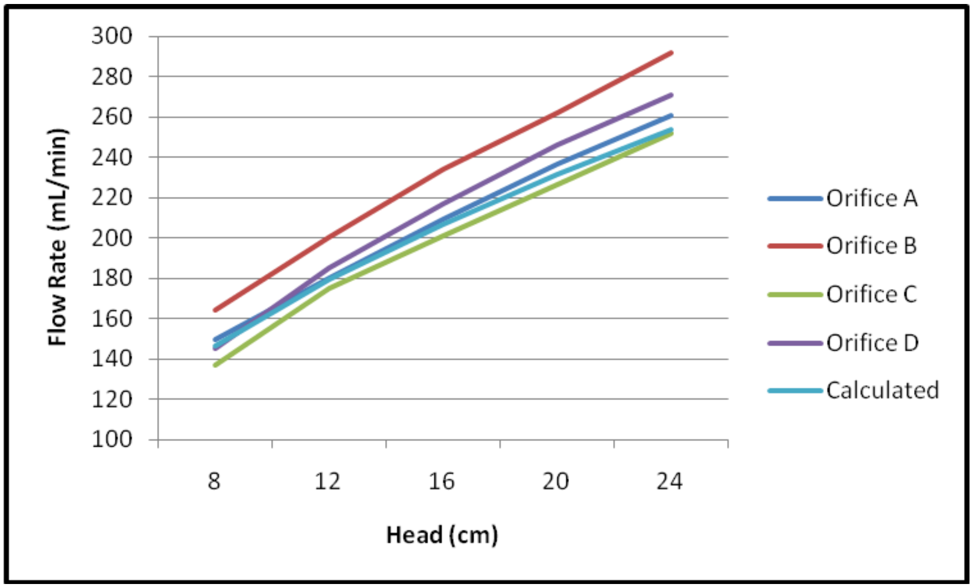


Figure 7. Legris Caps, 2mm, drilled in the direction of flow – version 2

The team hypothesized that the Legris polyamide material heats up and deforms under the stress of the drill bit, causing the orifice holes to not, in reality, be exactly 1mm or 2mm, and that this deformation cannot be controlled. This caused the team to consider testing orifices drilled in-house from brass, as it is easier to machine than polyamide. The team also started to research off-the-shelf precision orifices.

Flare Cap Fittings

The team ordered brass flare cap fittings with a 40 thread count and a brass connector (Figure 8, 9) to use for both the Flare Caps and the Refrigerator Caps. The combination of Teflon tape and a small hose clamp was used to stop any leaking.

Figure 8: SAE Flare Cap

Figure 9: Teflon Tape on Connector

The first version of the flare caps were drilled with a 2mm diameter in the directions of flow and showed up to a standard deviation of 12mL/min and were deemed unacceptable (Figure 10).

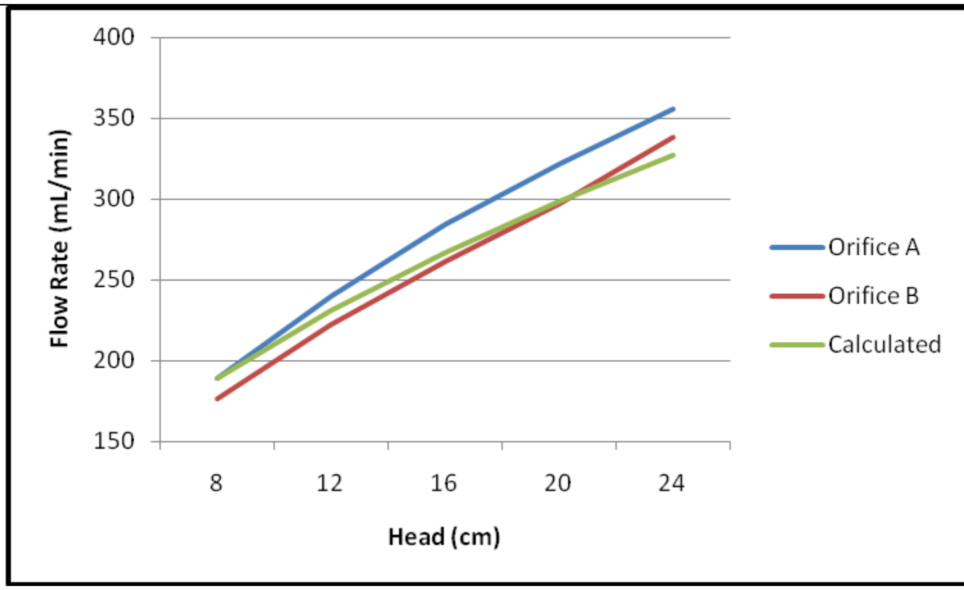


Figure 10: Flare Cap, 2mm, drilled in direction of flow

The second version of the flare caps was drilled against the direction of flow. This was done since it was difficult for the machinist to drill holes with exactly similar entrance regions. Since brass is very machinable, the team hoped that drill-bit breakthrough would not be as critical a problem with the flare caps. The standard deviation of these tests did not exceed 4mL/min. However, the team could not find a K_{vc} value that would fit the entire range of data (Figure 11).

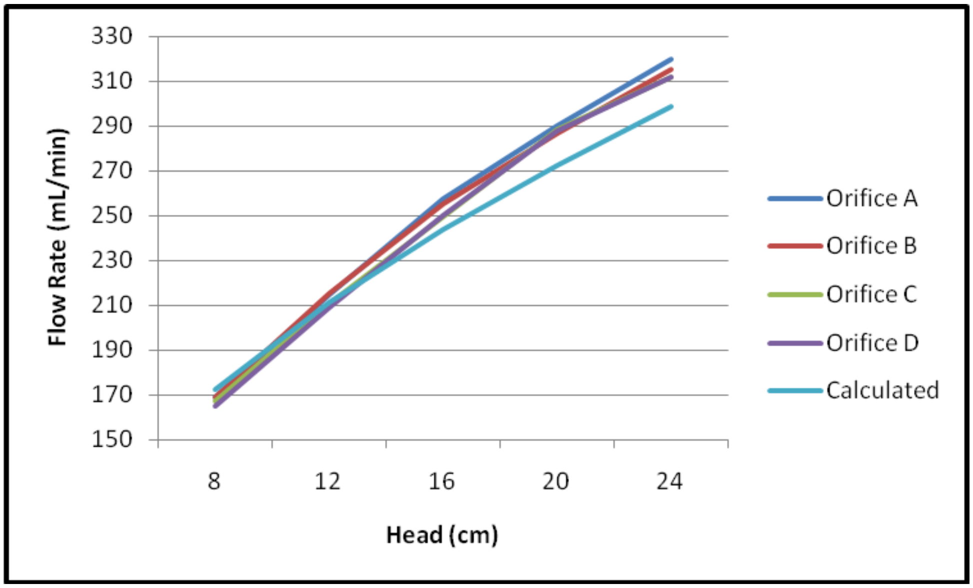


Figure 11: Flare Cap, 2mm, drilled against direction of flow, best fit $K_{vc} = 0.75$

Refrigerator End Caps

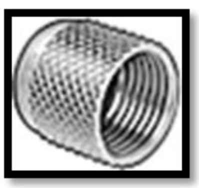


Figure 12: Refrigerator End Cap

The first trial of refrigerator caps (Figure 12) drilled in the direction of flow showed a large standard deviation of 9mL/min (Figure 13).

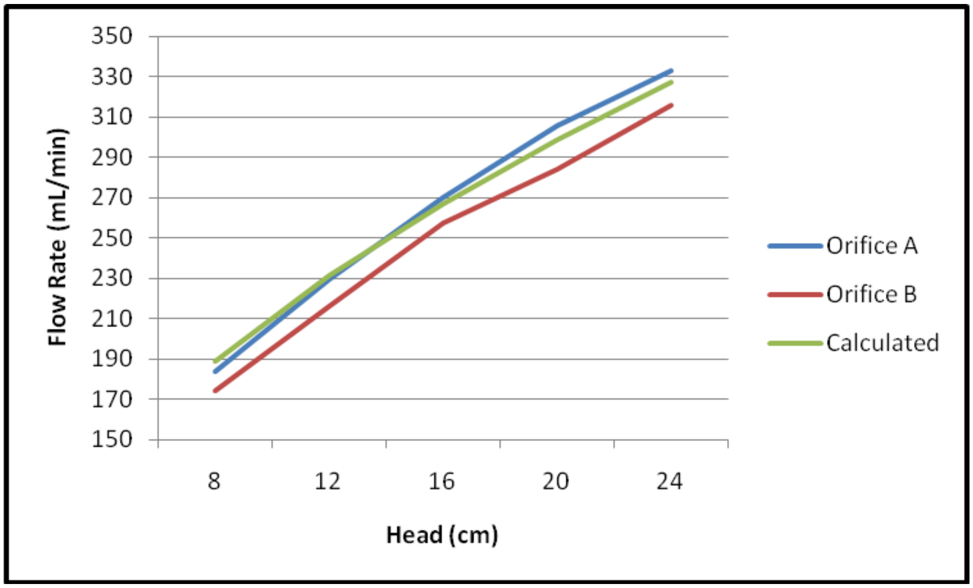


Figure 13: Refrigerator Cap, 2mm, drilled in direction of flow

The results of the second trial of refrigerator caps, drilled in the opposite direction of flow, showed less than 5% variation between orifices (Figure 14), which was lower than the team's benchmark. Furthermore, a K_{vc} value of 0.8 was found to fit the entire data set.

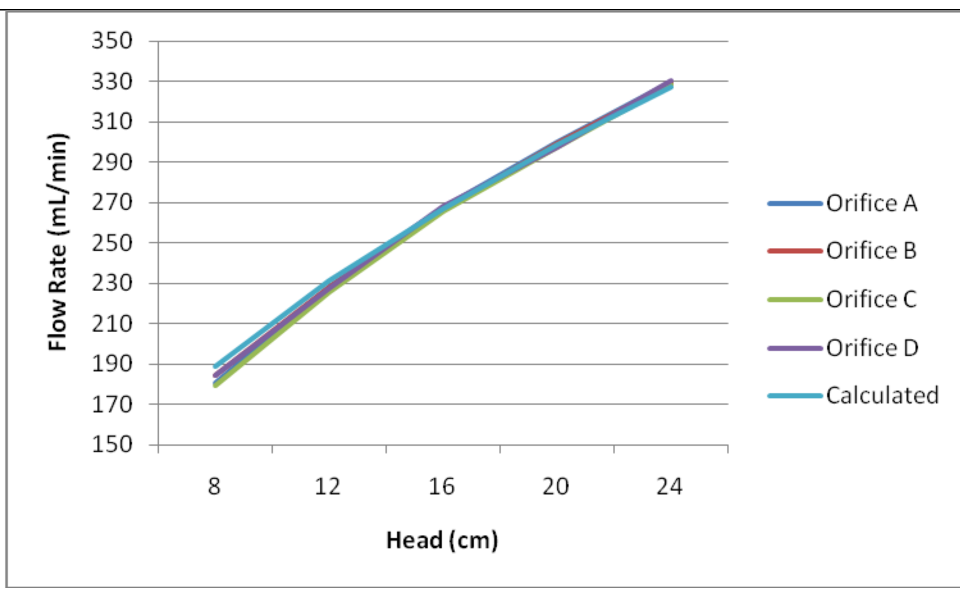


Figure 14: Refrigerator Cap, 2mm, drilled against direction of flow, best fit K_{vc} = 0.8

Carburetor Jets

Lastly, the CDC Team tested off-the-shelf carburetor jets (Figure 15). The carburetor jets were much smaller than originally expected. To create an adequate connector, the team drilled through a piece of PVC to create the needed thread count to connect the carburetor jets to the soft tubing, which worked perfectly (Figure 16).


Figure 15: Carburetor Jet

Figure 16: Carburetor Connector Manufactured from PVC

The carburetor jet orifices showed a percentage variation of less than 5% between orifices and were the most precise metering orifices tested by the team throughout the summer (Figure 17).

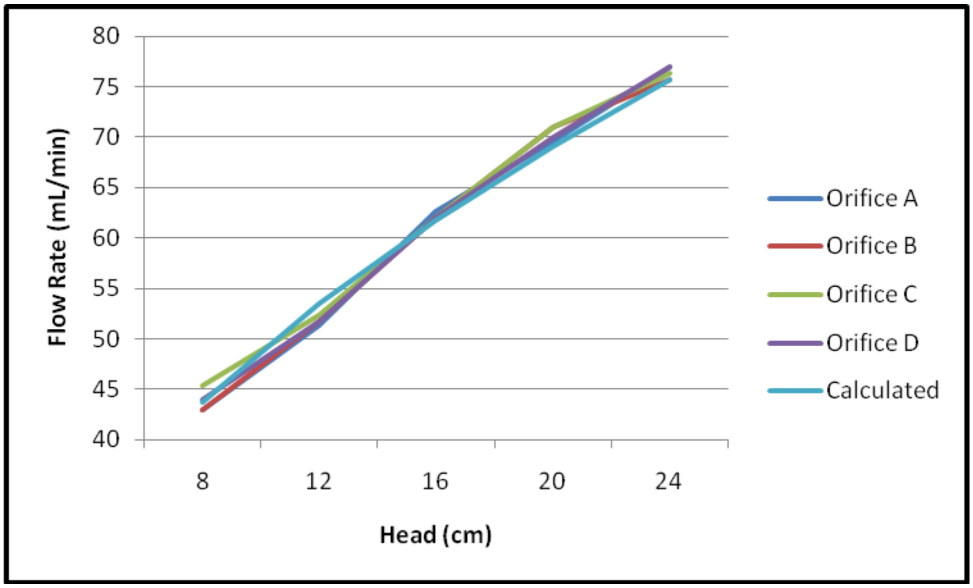


Figure 17: Carburetor Jet, 1mm, best fit K_{vc} = 0.74

Problems

Finally, there were several problems the Team ran into while running these flow rate tests on the different orifices. The first problem the team encountered was the inability of the constant head tank to maintain constant water level at high plant and dosing flow rates, in this case, large values of elevation head between 28 and 40 cm. The water level in the tank would steadily decrease as the tests were being conducted thus establishing a constantly changing and erroneous zero level. To correct for this fault, the team decided to disassemble the existing tubing (¼” ID) from the water source to the constant head tank and replace it with tubing of a larger diameter ($^3/_8$” ID). The larger diameter of this new tubing would be able to match the flow rate from the orifice at large values of head.

The second problem faced by the team was the difficulty in determining an accurate zero level for the linear bar marking head levels. The method initially used to accomplish this involved keeping the slider fixed at zero centimeters of head and moving the linear bar up and down until the orifice started to drip. This proved to be an unreliable approach as it could not take into account the effect of surface tension (a phenomenon that prevents liquid from flowing through the orifice at small values of head). This problem was resolved by moving the bar closer to the constant head tank. The head tank has the zero level marked on it and the team was able to line up the zero levels of the tank and the bar, thus establishing a more reliable basis for the remainder of the experiment. Lastly, as the orifices were extremely unreliable at low values of head (below 8 cm) due to issues caused by surface tension, the testing range was abbreviated to include only the most reliable data range of 8-24 cm of head with five distinct data points equally spaced in this range. A second series of tests was run on the 2mm diameter Legris orifices to determine if the changes made to the testing procedure would have any impact on the data. The modified experimental setup and procedure provided consistent and satisfactory results. For this reason, the team saw no need to change the experimental design for the subsequent rounds of testing.

Conclusion

The results of these three rounds of tests show that it is possible to machine reliable orifices from brass though slightly better results can be obtained from off-the-shelf brass orifices. However, since both the in-house and off-the-shelf orifices satisfy the criterion for less than 5% percent variation set by the team, the final decision on which would be more applicable in an AguaClara plant must be made after considering the local availability and ease of replacement of each of these types of orifices.

Future Work

These tests have proven that it is possible to manufacture precise and reliable orifices from brass. However, the chemical compatibility of brass with alum, chlorine and saturated sodium carbonate is suspect. For this reason, the future CDC Team should conduct some material research in order to gain a better understanding of the chemical compatibility of brass and its applicability in water service applications. If this research shows that brass is extremely incompatible with chlorine, the team must find a material that possesses desirable machinability characteristics as well as chemical compatibility. A possible material that may satisfy these needs is polyvinyl chloride (PVC). While the materials research is being conducted by one part of the team, it would be advisable to have a different section of the team testing orifices drilled out of PVC. Once a suitable material has been found, the CDC team should devote its attention to analyzing the reliability of the orifices throughout the entire 4-40 cm range of head.

A revision of this system that would relocate the dose controller to a more convenient central location in the plant is being considered. After conducting the validation tests on these orifices, the future CDC team should thoroughly consider all options for this redesigned chemical dose controller. At the final stage of the design process, communication with the Design Team regarding integrating the CDC into the design tool is vital.