I-063 - AN AUTOMATED DESIGN TOOL FOR SUSTAINABLE, GRAVITY-POWERED WATER TREATMENT PLANTS

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ABSTRACT

Conventional water treatment solutions do not solve the potable water scarcity problem for rural, resource-poor communities. Typical mechanized or package plants are expensive and difficult to both maintain and operate, ultimately leading to abandonment of the plant. AguaClara water treatment plant designs offer a sustainable alternative to mechanical plants. All reactors are open and accessible for the operator to observe and troubleshoot problems; plant components are modular, inexpensive, simple to use, and locally-available for easy replacement; operation does not require hand calculations or highly-skilled labor; and all plants are gravity-powered to eliminate prohibitive electricity costs.
While AguaClara addresses ease of operation and local material availability to ensure successful long-term operation of its plants, the capital cost is optimized as well using parametric design equations. Algorithms are based on fundamental physics, allowing current designs to be scaled over a range of 3 L/s to 100 L/s. AguaClara has developed an Automated Design Tool (ADT) that utilizes these algorithms to produce a detailed 3D AutoCAD drawing of an AguaClara plant specific to a user's request. The ADT is available free of charge on the web, and can produce the full hydraulic design in less than fifteen minutes.

KEY WORDS: Gravity-powered, automated design, sustainable water treatment, local materials.

INTRODUCTION

Installations of conventional mechanized flocculation-sedimentation-filtration-disinfection water treatment systems in resource-poor communities often fail because of limited financial resources, lack of a supply chain or resources for repair of parts and machinery, unpredictable electricity supply, and unreliable performance of mechanized components. Design costs for small facilities can be excessive because the engineering time required for a small facility is similar to the engineering time required for large facilities. We reduce the design costs significantly by providing a free comprehensive design service. In a collaborative effort over the past 6 years we have developed an Automated Design Tool (ADT) – available on the internet at no charge – that creates a custom 3D AutoCAD drawing and a design specifications report for a municipal water treatment plant in response to a client request.

Our goal is to increase access to safe drinking water. The water treatment plant designs we provide are entirely gravity-powered, eliminating both electricity costs and the associated unreliable mechanical components. The facilities are built with the supervision of an implementation partner using local labor and locally-available materials rather than expensive proprietary components. The plant designs are operator-friendly and the treatment processes are easily monitored and enclosed in a building to create a secure and pleasant work environment. Implementation partners provide comprehensive training and technical assistance so that plant operators can troubleshoot any problems that may arise. Facilities can be successfully managed by individuals with a 6th grade education. Communities as small as 1500 people are able to effectively operate and maintain the facilities, and the water boards have sufficient revenue – since community members are willing to pay more for safe water – to make other improvements to the system.

METHODS

The core design algorithms that are coded into Mathcad are scalable parametric equations, making the ADT robust over a wide range of flow rates from 3 L/s to 100 L/s, with this flow range increasing broadly in the near future. The ADT integrates LabVIEW, Mathcad, AutoCAD, and Microsoft Word to produce a hydraulic design and supplementary documentation in less than fifteen minutes. The design server was coded using LabVIEW and is the top level program in the ADT. The user sends a request across the internet from client software (also written using LabVIEW) to the design server. The server then uses ActiveX to run Mathcad, open the top level Mathcad worksheet, and then send client-specified values to that file. The Mathcad worksheet references several other Mathcad worksheets that together calculate all dimensions of the facility using algorithms based on the physics of the treatment process.

As a second step in the design process another set of Mathcad worksheets takes the calculated dimensions and creates the text strings required by AutoCAD to draw each component of the facility. After all calculations are complete, the LabVIEW design server instructs Mathcad to save the worksheet. Then, the design server reads the saved Mathcad worksheet and parses all variable names and values from it, storing them in an array for further use. Next, ActiveX sends to AutoCAD the AutoCAD command scripts generated in Mathcad. AutoCAD processes the commands, draws a 3D model of the water treatment plant such as the one pictured in Figure 1, and saves the file. The 3D rendering is very detailed and includes a gravity-powered chemical dose controller, linear flow orifice meter, hydraulic flocculator, vertical flow sedimentation tanks, and self-backwashing stacked rapid sand filters.

The AutoCAD file provided to users also includes various 2D cross-section views of the plant, which may later be used as figures in construction documents. For example, Figure 2 shows a front cross-section of a

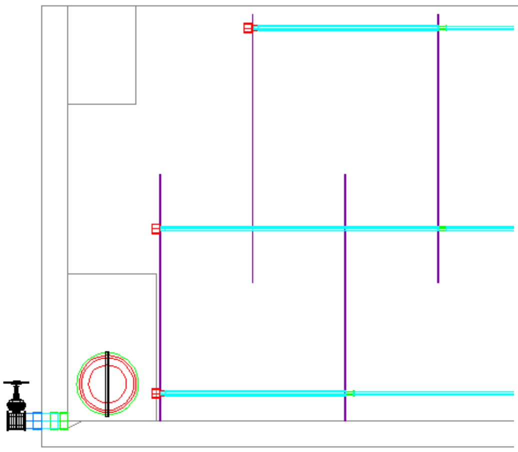

Figure 2. 2D front cross-section of the flocculat
in place for a single channel.

vertical flocculator, allowing the user to see the details of the piping assembly that holds the plastic baffles in place. An engineer will often display relevant dimensions on such a layout and include the drawing in official blueprints for the plant.

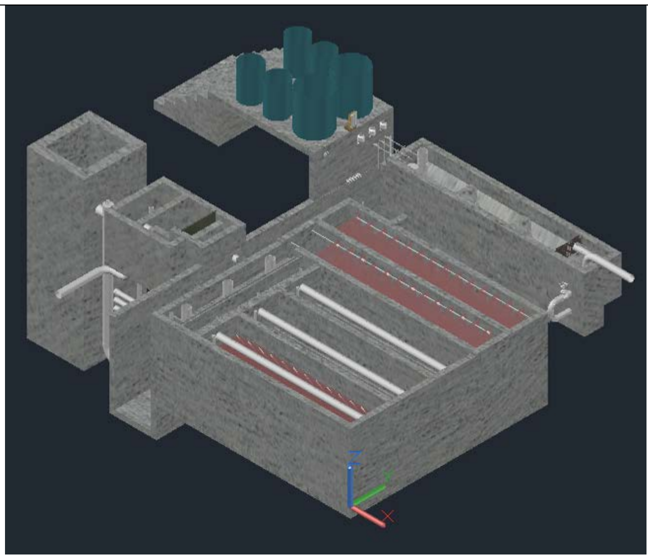

Figure 1. The final 3D AutoCAD model generated by the ADT.

The design server also uses ActiveX to send commands to Microsoft Word. Microsoft Word opens a report template file and then uses the application's "search and replace" function to replace variable names that are included in the report template with the calculated values of those variables. Thus, a customized design specifications document is generated. The document explains the general theory of each reactor as well as the calibration of the chemical dose controller and operation of each unit process. Additionally, the document provides a list of material requirements for each plant reactor, which can be used to make cost estimates for interested stakeholders. Tables 1a and 1b show a portion of a typical materials list table for the entrance tank. The top table (a) is generic, including variable names before the "search and replace" is executed to produce the bottom table (b), which has values specific to a user's request. The table shows both surface areas and volumes of reactor sections so that it is easy to determine either the volume of concrete or the number of bricks required to build any part. The full list would also include quantities of pipe, with associated lengths and nominal diameters, as well as quantities of any other necessary pieces.

Surface area of the entrance tank walls	A.EtWalls
Surface area of the entrance tank floor	A.EtFloor
Total surface area of the ledges between hoppers	A.EtLedge
Volume of the entrance tank walls	Vol.EtWalls
Volume of the entrance tank floor	Vol.EtFloor
Total volume of the ledges between hoppers	Vol.EtLedge
Total volume of the entrance tank hoppers	Vol.EtHoppersTotal

Table 1a. Part of a generic materials list given by the design specifications document for the entrance tank before the "search and replace" function is executed by ActiveX.

Surface area of the entrance tank walls	12.25 m^2
Surface area of the entrance tank floor	7.53 m^2
Total surface area of the ledges between hoppers	7.83 m^2
Volume of the entrance tank walls	1.84 m^3
Volume of the entrance tank floor	1.13 m^3
Total volume of the ledges between hoppers	2.54 m^3
Total volume of the entrance tank hoppers	2.90 m^3

Table 1b. Part of a materials list for a specific request given by the design specifications document for the entrance tank after the "search and replace" function is executed by ActiveX.

Conventional design guidelines such as recommended depths for sedimentation tanks or dimensions for plate settlers are often based on empirical observations from large scale facilities. Many of these design values lack a physical basis and cannot be directly applied to small plants. We have developed physically-based scalable algorithms based on extensive laboratory and full-scale research. Laboratory studies by faculty and students are used to develop fundamental physical relationships that govern water treatment processes while also identifying failure modes. The founding of our algorithms in research ensures that facility designs are robust and scalable while also efficiently utilizing materials.

We specifically depart from empirical design values in the algorithms for rapid mix, flocculation, and flow transitions into the sedimentation tank. The design of these pieces is conventionally based on the turbulent energy dissipation rate rather than the velocity gradient method (Weber-Shirk and Lion, 2010) because the velocity gradient method only applies to laminar flow reactors (Cleasby 1984). As an example, the spacing, S, between the vertical flow hydraulic flocculator baffles for the case of water depth more than 5 times the spacing is given by

$$S = \frac{1}{\Pi_{VCBaffle}\,\varepsilon_{Max}^{\frac{1}{4}}}\left(\frac{\Pi_{Jet}Q}{W}\right)^{\frac{3}{4}} \tag{1}$$

where Q is the flow rate, W is the channel width, $\Pi_{VCBaffle}$ is the *vena contracta* from flow around the baffle (0.41), ε_{Max} is the target maximum energy dissipation rate, and Π_{Jet} is defined below (Baldyga, et al. 1995).

$$\varepsilon_{Max} \cong \frac{\left(\Pi_{Jet} V_{Jet}\right)^3}{S \Pi_{VCBaffle}} \quad (2)$$

where V_{Jet} is the average velocity of the water in the *vena contracta*. The use of such dimensionally correct algorithms makes it possible to design the geometry over a wide range of flow rates.

Rigorous lab research has also enabled us to design a more efficient sedimentation tank that strays from conventional design. Typically, plate settlers are designed to be 5cm apart. The distance is set to prevent floc rollup due to high velocity gradients between the close plates, while keeping the spacing reasonably small to minimize sedimentation tank volume. We have conducted research to see how small the actual spacing between plate settlers can be before the sedimentation tank fails due to floc rollup. Based on lab results, we create our designs assuming a minimum 2.5cm spacing, and we still observe efficient sedimentation at this design value. The savings in tank volume due to the reduction in plate settler spacing is significant. Figure 3 shows a 32 L/s sedimentation tank where in the design pictured at the top (a) uses 2.5cm spacing between plate settlers. In the design pictured at the bottom (b), the conventional 5cm spacing between plate settlers is used, causing the tank to grow more than 30cm in depth. Continued research in sedimentation tank hydraulics shows the promise of being able to grow and maintain a floc blanket at the bottom of the sedimentation tank, allowing for an even shallower dimension than is currently being designed.

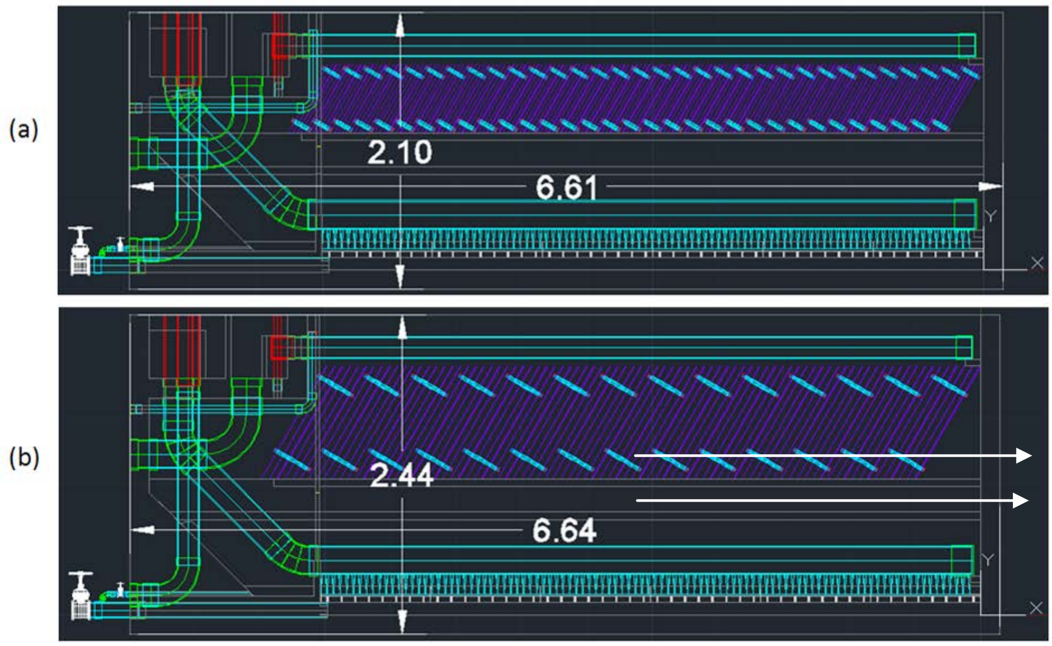

Figure 3. A front view of a 32 L/s sedimentation tank with (a) 2.5cm and (b) 5cm spacing between plate settlers. The sloping section on the left side of the tank is within the floc hopper and allows for efficient draining of sludge.

Designs are created with ease of use, maintainability, and longevity in mind. We continually refine the designs based on feedback from engineers and operators of full-scale plants, ensuring that designs are ergonomic as well as functionally efficient. The resulting algorithms have been proven effective in the field in terms of treatment, and they have been proven to be reliably maintained by local operators. To keep the operation of the plant exoteric, not a single calculation has to be done by the operator at any point. For instance, the flow rate through the plant maintains a linear relationship with the water level in the entrance tank by means of a pipe drilled with orifices in a pattern that mimics a sutro weir. A scale of flow rates corresponding to the water level in the tank is affixed directly to this pipe, informing the operator of the current flow rate without having to make manual measurements. Additionally, the chemical dosing system we employ is hydraulically connected to the entrance tank so that it can automatically deliver the correct amount of chemical, despite changes in flow rate, to ensure a desired reactor concentration at all times. The chemical dosing system includes a sliding scale to adjust the dose based on the influent turbidity of the water, where the scale is labeled with the specific mg/L concentration the operator hopes to maintain in the plant. Thus, even without the assistance of mechanized components, the operator can easily set the chemical dose with little manual labor and without performing a single computation.

To further increase the useful life of the plants, we minimize use of highly specialized parts. Valves, in particular, are expensive and not always locally available. They are they difficult to import to many places, and so replacements must be custom made at high costs. In ADT designs, valves are obviated wherever possible by removable pipes that extend beyond the water level of the tank. Figure 4 shows a typical entrance tank with five such removable pipes in red. Water flows linearly from the right side of the tank over the top of the hoppers, into which large sediment settles before it has the chance to reach the rapid mix pipe shown on the left side. The red pipes are tall enough that water does not flow through them during normal operation. When the operator wishes to drain the individual hoppers, he must remove the pipe and the sediment will flush out of the tank into the drain channel below.

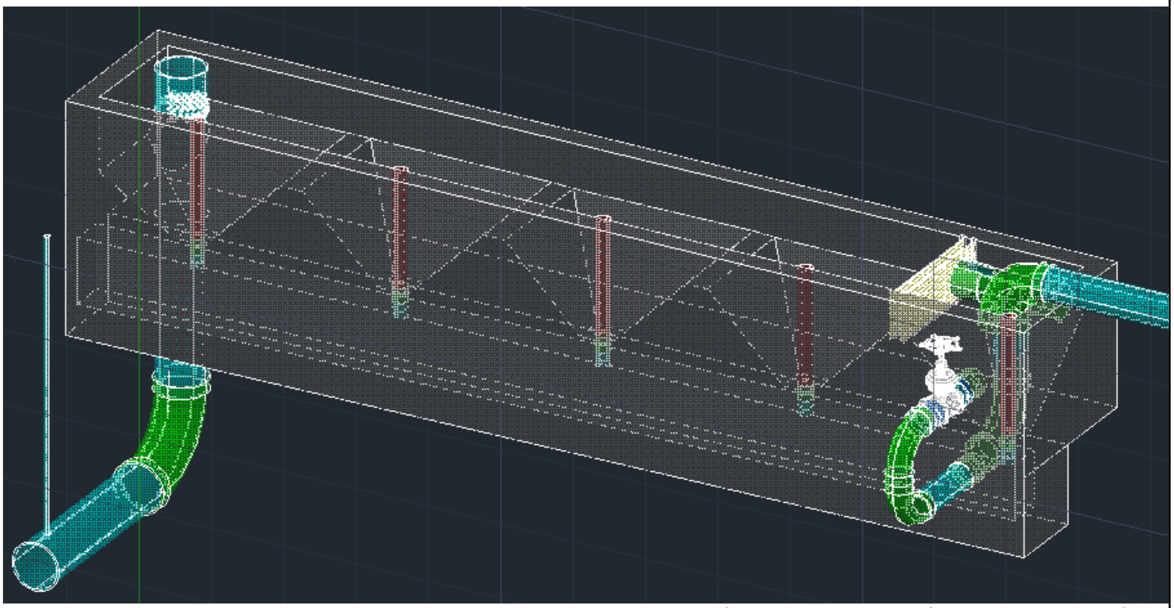

Figure 4. An entrance tank with pipes (red) that can be removed to flush sediment out from the bottom of the hoppers into the drain channel below.

In an effort to reduce maintenance requirements, there are many places in the design where tanks will have sloping sections leading to drain outlets. The hoppers pictured in the entrance tank allow for the sediment to collect right at the edge of the outlet to the drain channel, so that the operator rarely has to physically sweep away sludge. Similarly, there is a floc hopper, which can be seen on the left side of Figure 3, in the sedimentation tank that directs sludge right to the drain.

CONCLUSIONS

Conventional water treatment plant design incurs high costs for the custom design work and the patented technologies used in the plant. When components fail, they cannot be replaced easily or cheaply, and so highly mechanized treatment plants are often abandoned before the end of their useful life. Our sustainable designs on the other hand are built using affordable and locally-available parts. The plant components are easy to maintain, replace, and repair as needed. The plants are inexpensive to maintain since they do not require electricity or highly-skilled labor to operate. Detailed information about the plants including design algorithms is available free-of-charge on our website.

Six gravity powered water treatment plants have been built in Honduras and are currently providing safe drinking water to approximately 25,000 people. The sustained successful operation of these plants attests to the fact that the design addresses obstacles to long-term implementation in communities with limited financial resources. The plants have succeeded in treating water as turbid as 750 nephelometric turbidity units (NTU) to below 5 NTU. The capital cost of the plants is between $15 and $30 per person served – $4000 to $8000 USD/(L/s) of plant capacity – with lower per capita costs achieved for larger-sized communities. The capital investment for ADT designs are approximately 1/3 that of conventional facilities, and maintenance and operation cost approximately $2 to $4 per person per year.

We are committed to continuing to provide a free online design service so that implementation partners can focus on the design, construction, and operation the plants; the training operators for effective implementation; and the transfer knowledge to empower communities to maintain their own water treatment facilities.

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