Theoretical Modeling of Aeration Method

Phenomenon of Floating Floc

Abstract

Some water treatment plants have a problem with particles rising to the surface of the water instead of settling out in the sedimentation tank. These floating particulates then contaminate the effluent water. This problem likely stems from the supersaturated condition of the water as it enters the facility. As the gas goes out of the solution the bubbles can get attached to sediment particles and bring them to the surface instead of letting the particulate matter settle to the bottom of the sedimentation tank. This problem can be alleviated by increasing the rate of gas transfer so that the solution can equilibrate in the grit chamber so there will not be many bubbles still forming once the water reaches the sedimentation tank. One way to increase the gas transfer rate is to add even more air bubbles to the solution to increase the area of air/water interface, a property on which the gas transfer rate is defined. The water can be aerated by making small holes around the influent pipes. The difference in pressure will cause the air to be sucked into the water pipe at a rate dependent on factors such as the velocity of the water, the size and number of holes and how far above the end of the pipe the holes are made. A program was written to calculate the flow rate of the air into the orifice as a function of the water flow rate, pipe size, location of the holes and total area of orifice. The program is used to find the optimum set up for a given water flow rate.

Introduction and Objectives

A major concern at the Tamara water treatment plant in Honduras is the phenomenon of floating floc particles. The floating particulates then leave the plant with the cleaned effluent thus polluting it again. The other AguaClara treatment facilities also have problems with rising sludge, but to a much lesser degree. This project was made to devise a way to keep the solid particulates from rising to the surface of the sedimentation tank in adherence to AguaClara's mission of sustainable water treatment. Since the solution can not require any electricity, the fundamentals of fluid dynamics were utilized. Aeration is used in the lab in order to equilibrate solutions rapidly but these systems use air pumps which in turn use electricity. This project had the task of constructing a sustainable method of pumping large quantities of air into flowing water. The set up could then be used for any treatment plant that has problems with floating floc particles.

Procedure

Several fundamental properties of fluid dynamics were used in order to devise a solution to the problem of floating floc particles. The concept of aeration was employed to prevent the solids in the solution from rising up the water column in the sedimentation tank. Infusing the water with many air bubbles increases the area of air/water interface thus increasing the gas transfer rate. This means that the gasses infused into the supersaturated water will form into bubbles and leave the solution faster. The goal is for all of the excess gas to have left the water by the time the solution gets to the sedimentation tank. Once the water has equilibrated with the atmosphere all the excess gas will have been removed so there will no longer be gas bubbles forming and bringing floc particles up to the water surface. Without the influence of gas bubbles the particles will settle to the bottom of the sedimentation tank. The rapid influx of air bubbles will also cause more turbulence in the water, helping dislodge any gas pockets that have attached to the suspended solids.

Vertical, full free flowing water pipes have below atmospheric pressure on the inside thus when there is a hole in the side of the pipe exposing it to air at atmospheric pressure a vacuum will form as the air enters the orifice since molecules move from areas of high pressure to those of low pressure. Once the pressure inside the pipe equals that of outside the pipe there will no longer be any mass transfer. Another constraint on the amount of air that will be sucked into the pipe is that of head loss. As the flow of air combines with that of the influent water the total flow rate, density and viscosity of the solution changes increasing the amount of head loss. The amount of head loss incurred between the orifice and the open end of the pipe can not exceed the actual distance between said orifice and pipe exit. Once either condition is met the system will be at equilibrium and there will be no net change in flow rate.

Calculating the flow of air through the orifice can be done via an iterative process. For any given influent flow rate, influent pipe diameter, orifice diameter and distance of the orifice from the outlet the flow rate of air through the hole can be projected. The value can not be solved for directly because there are too many dependent variables throughout the equations. This dependence can be seen in the list of equations used to model a vertical pipe full of free falling solution that has a hole in the side that is open to the atmosphere. Thus an iterative "guess and check" algorithm was made to solve the system of equations. There are two variations of this MathCAD program. One calculates the flow rate of air entering the pipe for many different orifice areas until the total orifice area allows so much air in that the pressure inside the pipe equals that of outside the pipe. The other version varies the distance between the outlet of the pipe and the location of the holes until the headloss through that section of pipe equals the distance between the hole and the outlet. This second program takes the orifice size as an input. Both programs can be downloaded here:
*Calculation of Qa through various numbers and sizes of holes
*Calculation of Qa for various pipe lengths

Principals used:
Orifice flow
Friction
Reynolds number
Blended density
Blended viscosity
Flow rate
Headloss
Static pressure
Bernoulli's principal

Equations:

Basic Equations

$$Q_{.a} := K_{.or} \cdot \frac{\pi \cdot d_{.hole}^{2}}{4} \cdot \left[\frac{2 \cdot (-P1)}{\rho_{.a}}\right]^{\frac{1}{2}}$$

$$h_{.1} := f_{.p} \cdot \frac{L_{.pipe}}{D_{.pipe}} \cdot \frac{v_{.1}^{2}}{2 \cdot g}$$

$$P1 := (\rho_{.wa} \cdot g) \cdot \left(\frac{v_{.2}^{2}}{2 \cdot g} + \frac{P2}{\rho_{.wa} \cdot g} + h_{.1} - z - \frac{v_{.1}^{2}}{2 \cdot g}\right)$$

$$v_{.1} := \frac{Q_{.a} + Q_{.w}}{.25 \cdot \pi \cdot D_{.pipe}^{2}}$$

$$Re_{.p} := \frac{\rho_{.wa} \cdot v_{.1} \cdot D_{.pipe}}{\mu_{.wa}}$$

$$f_{.p} := \frac{0.25}{\log\left(\frac{\varepsilon_{.pipe}}{3.7 \cdot D_{.pipe}} + \frac{5.74}{Re_{.p}^{0.9}}\right)^{2}}$$

$$v_{.2} := v_{.1}$$

$$P2 := g \cdot h_{.under} \cdot \rho_{.wa}$$

The above equations are fundamental equations of fluid dynamics. They solve for flow through an orifice, headloss through a pipe, pressure at a point in a water column solved for using Bernoulli's equation, velocity as a function of flow rate, Reynolds number, friction through a pipe, and the pressure due to the weight of water above.

Fluid Mixture Properties

$$\rho_{wa} := \frac{Q_a \cdot \rho_a + Q_w \cdot \rho_w}{Q_a + Q_w}$$

$$x_a := \frac{Q_a \cdot \rho_a}{Q_a \cdot \rho_a + Q_w \cdot \rho_w}$$

$$x_w := 1 - x_a$$

$$VBN_w := 14.534 \cdot \ln\left(\ln\left(\frac{\mu_w}{\rho_w} + 0.8\right)\right) + 10.975$$

$$VBN_{wa} := x_a \cdot VBN_a + x_w \cdot VBN_w$$

$$\mu_{wa} := \rho_{wa} \cdot \left(\left(e^{\frac{VBN_{wa} - 10.975}{14.534}} - 0.8\right)\right)$$

The viscosity of the mixture was calculated using Refutas equation. This method for calculating the viscosity of a liquid that is made of several different substances is three part. The first step is to calculate the Viscosity Blending Number (VBN) for all of the substances based on their individual density and viscosity (1). Then a combined VBN is calculated using the sum of component multiplied by its mass fraction in the solution (2). Finally a kinematic viscosity of the blended sumstance can be calculated through equations (3).

The density of the mixture of air and water can be calculated based on the total mass over the total volume. The program measures the flow rate of each substance (air and water) and so the density is calculated in reference to this unit of measurement. The blended density can be calculated by first multiplying the individual flow rate of each component by its original density then dividing this value by the final total flow rate. This will provide an equation with the units (mass/time)/(volume/time) and cancel out to the units of density.

The dynamic viscosity is simply the combined kinematic viscosity multiplied by the combined density.

Performance Index

$$PI := \left(\frac{g \cdot h_{.1}}{\theta_{.pipe}}\right)^{\frac{1}{3}} \cdot \theta_{.pipe} \cdot \phi_{.air} \cdot d_{.hole}^{\frac{-2}{3}}$$

$$\theta_{.pipe} := \frac{L_{.pipe}}{Q_{.a} + Q_{.w}} \cdot \frac{\pi \cdot D_{.pipe}^{2}}{4}$$

$$\phi_{.air} := \frac{Q_{.a}}{Q_{.a} + Q_{.w}}$$

The Performance Index (PI) can be broken down into three parts: volume fraction or air, retention time in the pipe and then the actual PI value. These equations are further explored in the Results and Discussion section.

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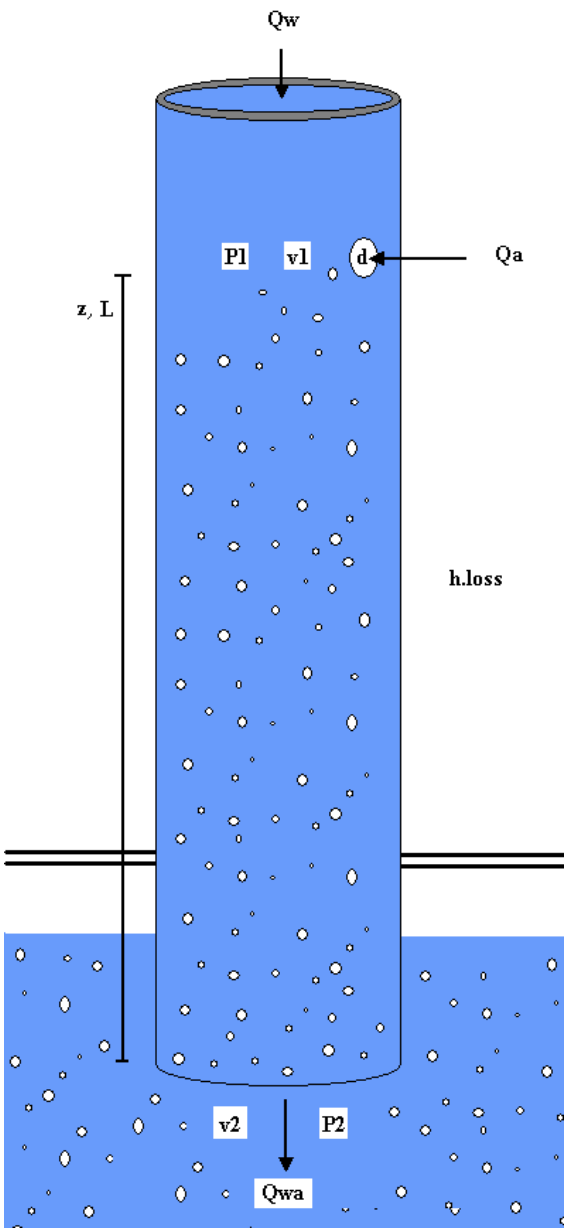


Subscript x:
a = air
w = water
wa = air water mix

Variables:
Q.x = Flow rate of x
K.or = Orifice coefficient
d.hole = Orifice diameter
D.pipe = Pipe diameter
L.pipe = Distance between the orifice and the outlet
P1 = Pressure at orifice
P2 = Pressure at outlet
V1 = Velocity of mix at orifice
V2 = Velocity of mix at outlet
h.l = Headloss
f.p = Friction factor in pipe
Re.p = Reynolds number
h.under = Outlet's depth below the surface
.x = Density of x
.x = Dynamic Viscosity of x
x.x = Mass fraction
VBN.x = Viscosity blending number
.x = Kinematic viscosity
PI = Performance index
g = Gravity

Results and Discussion

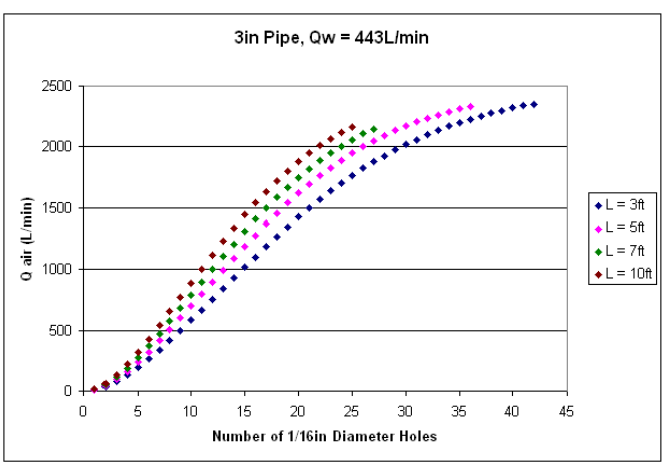
The data presented below was calculated using the two MathCAD programs discussed previously. The following values are the constants used in the calculations.

$$\rho_w := 1\,\frac{gm}{cm^3} \qquad \mu_w = 1.003 \times 10^{-3}\,\frac{kg}{s \cdot m}$$

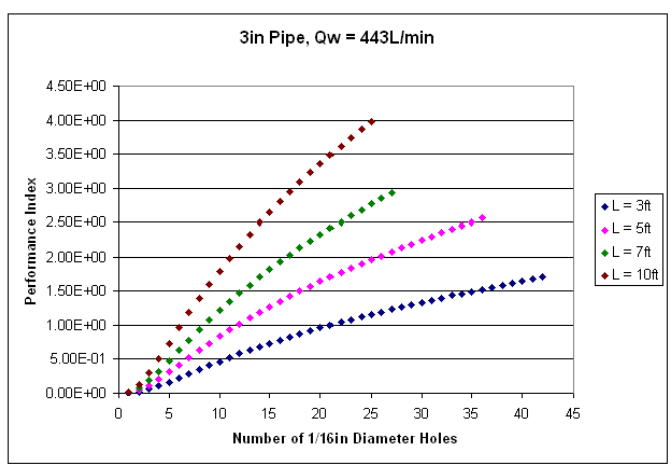
$$\rho_a := .001\,\frac{gm}{cm^3} \qquad \mu_a := 1.983 \cdot 10^{-5} \cdot \frac{kg}{m \cdot s}$$

The different configurations of this improvised aerator can be evaluated two different ways. One selection method would be based on the amount of air that is pulled into the pipe. Another is to choose the set up which provides the greatest Performance Index value.

Graph 1 demonstrates both the dependence of air flow on the number of holes as well as the length of the pipe. For any given number of holes the flow rate of air into the orifices increases with increasing length of pipe. As the orifice area reaches its maximum possible size, determined by the difference in pressure and headloss in the pipe that was discussed previously, the rate of increase in air flow rate as a function of the number and size of holes decreases and begins to level off. Though longer pipes have a greater flow rate of air for any given number of holes, the shorter pipes can have a greater total orifice area before it reaches the breaking conditions. Graph 3 shows the explicit relationship between pipe length and flow rate of air for two different hole configurations. One set up has 10 1/8in diameter holes while the other has 10 1/16in diameter holes. The configuration with greater diameter holes has an exponentially greater amount of air flowing through them.

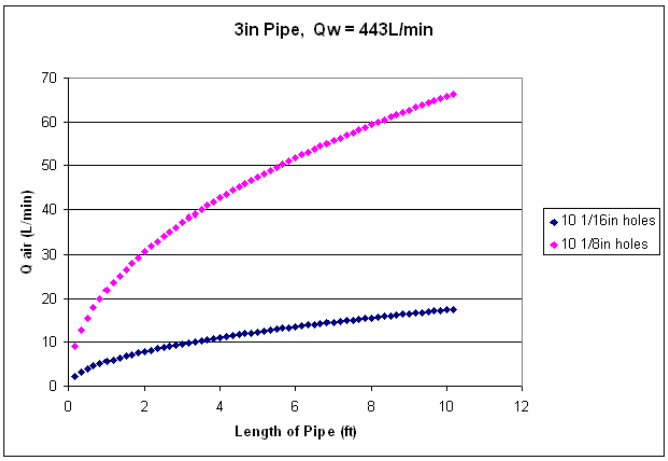


Graph 1

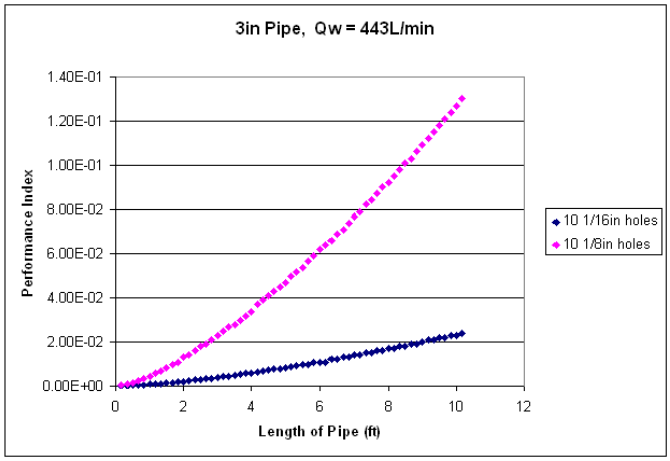


Graph 2

The Performance Index (PI) is a unitless value which indicates the ability of the bubbles to interact with the entire solution and remove the supersaturated gasses. It is based on the length of time that the mixed solution is in the pipe, the estimated bubble size, the amount of headloss and the amount of air in the solution based on volume fraction. The longer the mixture is in the pipe the more time there is for the bubbles to interact with the water. This means that situations with a longer distance between the orifice and the pipe opening or a larger diameter pipe will have a greater PI as shown in Graphs 2 and 4. However, the pipe can not be made infinitely long or with a very large diameter without impacting the amount of air that enters the pipe. The bubble size is estimated to be about the size of the orifice thus the smaller the hole, the smaller the bubble, the greater the PI for a given total orifice area. This being the case, the program increases the orifice area by increasing the number of holes in the pipe; the individual hole sizes are given by the user.



Graph 3



Graph 4

Conclusion

This research shows that it is possible to draw a significant amount of air into a vertical pipe with water flowing very fast. The next step in this research is to look closely at the data for different configurations (hole size, number of holes, location of holes, diameter of pipe) and decide on the optimum set up. This design will then be forwarded to the Cornell Engineers in Honduras so that they can try to implement the design in Tamara. The easiest way to test this design will be to make the holes in a PVC pipe then switch out part of the existing pipe with this PVC section. If the apparatus does not perform as theory would dictate the pipe can then be swapped out for a new one which either has a different hole configuration or no holes at all.