



Phosphor Removal from Waste Water Using Hydrodynamic Cavitation

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Authors' contributions

This work was carried out in collaboration between both authors. Author MVB wrote the first draft of the manuscript. Author KD wrote the final draft and approved the final manuscript.

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ABSTRACT

Hydrodynamic cavitation principle was applied to phosphate containing water and waste water. A 20% Calcium hydroxide slurry was applied before hydrodynamic cavitation to precipitate calcium phosphate by reacting calcium hydroxide and phosphate in water. A 70% reduction of phosphate in waste water is observed compared to controls runs using orifice plate and jet nozzle designs to produce cavitation. The jet nozzle design showed best results of for phosphate reduction in waste water. After cavitation calcium hydroxide, rich treated waste water was settled and then naturalized with carbon dioxide gas.

Keywords: Hydrodynamic cavitation; phosphor; waste water; water treatment.

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1. INTRODUCTION

Phosphorus abundance in wastewater has negative environmental affects, eutrophication, bacterial growth in drinking water, algal blooms interrupting tourism, and create dead zones in bodies of water resulting in the destruction of valuable fisheries [1]. Along with negative environmental effects the United States Environmental Protection passed regulations to reduce phosphorus in the Chesapeake Bay watershed by 24% by 2025. It is imperative that quick inexpensive ways of phosphorus reduction be examined for various wastewater from municipal, agriculture, manufacturing, recreational, and household sources.

One possibility is hydrodynamic cavitation which is a combination of an increase in flow velocity creating a low-pressure zone over an object or by the motion of an object through that liquid creating a low pressure zone that produces hydrodynamic cavitation [2]. Cavitation is created when the localized area of low pressure falls below that liquids vapor pressure; once the vapor pressure is decreased below this point a vapor filled void is developed [3]. Resulting in what in appearance is a bubble. This localized area contains pressure below the vapor pressure causing the space to have atomized liquid caused by that liquid boiling below the liquids pressure. This vapor filled low pressure void will continue to grow until an unsustainable size is reached. Once this void of vapor reaches an unstable size implosion begins to occur first intrusion of a micro-jet of liquid through the center of void, which than creates momentum to quicken the collapse [4]. This micro-jet carries through and forms a shock wave. This implosion concentrates the energy created by the formation of the cavitation void upon collapse reaching temperatures and pressures approaching of 5000°C, and 2000 atm. [5,6]. Along with pressure and temperature hydrodynamic cavitation increase turbulent flow, Reynolds numbers, and creates an increase in sheer forces from the high velocities of liquid flow involved [7].

Hydrodynamic cavitation can be induced by impellor, a ship's rudder creating a hydrofoil, jets of liquid, and pushing a flow of water through an orifice, which is a plate of smaller openings than that of the pipe diameter the plate is seated in (Rhee and Kim 2008 [8]).

Since movement of liquid or movement of the container is relative, during the creation of liquid

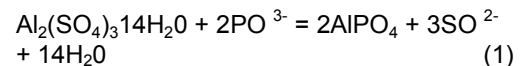
velocity one can move, vibrate or oscillate the container holding a liquid or an object held within that liquid as such is the case with ultra-sonic baths and probes. The high frequency produced from oscillation can create cavitation as the container or probe moves quickly. This is often referred to as acoustic cavitation and is generally associated with acoustic or sono-chemistry [9].

1.1 Types of Phosphate Removal

There are several different and proven methods that are used to remove phosphates from wastewater allowing for the reduction of negative environmental factors cause by excess phosphate. These methods include using biologic, chemical, physio-chemical, crystallization, ion exchange, adsorbents / sorbents, and many other methods that are being developed to alleviate the issue of high phosphate content in wastewater [10].

1.1.1 Aluminum

Aluminum is often used in phosphate removal aluminum sulfate (alum) a widely and commonly available product that is used in many industries which undergoes the following reaction [11].

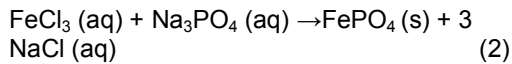


Like all reactions, the dosage of aluminum sulfate depends upon the concentration of soluble phosphate, contaminates and particles within the wastewater. Alum will aid flocculation of solid contamination. The reaction between alum and phosphate is thermodynamically and kinetically favored over aluminum hydroxide formation. This makes aluminum sulfate an attractive and easy to use chemical additive for wastewater treatment. Like many other forms of chemically aided phosphate removal pH is a factor when wastewater is treated. For effective removal, hydroxide ions must be added in some form to buffer the aluminum sulfate with acidic wastewaters. Aluminum phosphate the product of wastewater treatment with alums is not soluble in water but like many phosphate containing salts is acid soluble.

1.1.2 Iron

Iron (III) or iron (II) can be reacted with HCl to produce ferric and ferrous chloride respectively. Ferric chloride and Ferrous Chloride are used in much the same way the calcium is used in the

removal of phosphates. They react with phosphate in wastewater and are then neutralized to precipitate phosphates as iron salts. Chemical factors of wastewater pH, oxygen concentration, catalytic activity and presence of inhibitory substances, e.g. Sulphur all effect the reduction of phosphate in wastewater with the use of ferric chloride. Iron (III) ions form strong complexes with pyrophosphate and tripolyphosphates e.g.. Chemical equation 2, which are then probably removed by adsorption onto iron (III) hydroxy-phosphate surfaces [11,12]. The use of ferric chloride is growing as a water treatment option in the United States and around the world.



1.1.3 Sorbents/ absorbents

Using ion exchange resins nearly 95% of phosphate removal was achieved in controlled lab scale experiments [13]. Although a high amount of phosphates can be removed in this manner the use of sorbents or absorbents can be difficult expensive and may require a high technical knowledge to work with. Also, because this type of phosphate removal may require expensive materials that have a temporary service span, chemicals for cleaning and then must be discarded after their life is over. The viability for municipal use is less likely. With other forms of phosphate removal, it is possible to produce useful and resalable chemicals like calcium phosphate that can be used in farming and gardening. This is not the case in ion exchange chromatography.

1.1.4 Biologic phosphate removal

Using microbes both eukaryote like ameba, yeasts, and protists along with prokaryotes like bacteria in activated sludge operations is a proven and commonly used method to not only remove phosphates in wastewater it is also a proven way to remove ammonia in wastewater. The microorganisms use the phosphate in their cellular functions and cellular structures, they then die settle to the bottom and can be disposed of contain the phosphate formally in waste water. These operations are known as activated sludge operations. Activated sludge operation use anaerobic and aerobic phase to maximize phosphate removal [14]. Under anaerobic conditions phosphates are released from the sludge into solution the two phases grow many

different species of microorganisms' part require and cannot live without oxygen, in the other phase microorganisms are killed by oxygen. Aeration induces the sludge to take up phosphates from the solution more than normal metabolic requirements. Wastewater treatment plants using activated sludge methods for phosphate removal can remove up to 90% of phosphates.

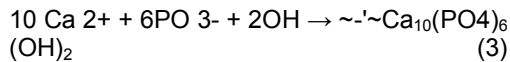
Algae of the species *Cladophora glomerata* and *Vaucheria* can reduce phosphorous in waste water by over 50% if applied to a trickling filter [15].

Another self-sustaining use of biologic phosphate removal and other types of contaminant removal is the use of wetlands and constructed wetlands. Wetlands have been shown to be an extremely effective tool in the removal of phosphates in wastewater. Removal of phosphates in wastewater is on the order of 98-100% removal in wetlands [16]. Wetland uptake of phosphates is found to be the same in both constructed and natural wetlands. The biology in wetlands that metabolizes and removes phosphates is complex and not completely known. What is known is that wetlands are extremely rich and diverse environments where competition for metabolites like phosphates is high. This is what explains the 98-100% rate of phosphate removal between wetland input and output.

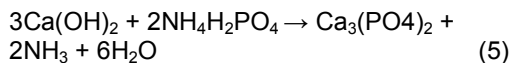
1.1.5 Calcium based removal

Quick lime or calcium oxide are the most common calcium salt used for phosphorus precipitation, this reaction generally forms hydroxyapatite chemical equation 3. Calcium hydroxide and other forms of calcium containing molecules can be modified or chemical reacted with phosphate to precipitate phosphate out of solution. Factors like pH, saturation of the phosphate containing solution with excess calcium, the presence of 'seeds' or super nuclei to create a base for crystal formation all factor into the amount of calcium and phosphate reacting [17]. It has been observed that the lack of hydroxide (OH-) ions inhibit the formation of calcium salts suggested pH range of 7.5 to 11.0 is there for recommended [18,19]. Furthermore, most calcium salts are soluble in acidic solutions starting as low as pH 6.5. When using lime or calcium hydroxide some phosphate will react with the available calcium, however reaction rates and yields are initially low but the rate and yield is aided by supersaturation [18].

Supersaturation allows of settling and the reuse of calcium rich bases like $\text{Ca}(\text{OH})_2$ or lime, and calcium phosphate salts. The reuse of these materials and the salts they produce also allows for super nucleation. Also known as seeding, super nucleation forms the corner stone for the building of crystal lattice structure, as one block is laid and mass grows that super nuclei quickly grows into larger calcium phosphate salts [20]. Carbon dioxide is also important in the removal of phosphates from wastewater De Boice & Thomas calcium is thought first to precipitate calcium carbonate in the presence of high concentrations of hydroxide ions e.g. Chemical equation 4 or in other solutions, bicarbonate, these constituents form from carbon dioxide addition any excess calcium then precipitates phosphate. Other advantages of this include removal of atmospheric CO_2 if outside air is used in the reaction, also the high pH is neutralized and the effluent can be made ready for reintroduction into the environment.



It is possible to reduce the concentration of phosphate in wastewater with the use of calcium hydroxide chemical equation 5. Although simply mixing an amount in of excess amount of $\text{Ca}(\text{OH})_2$ with a sample containing phosphate will generally only yield a fraction calcium phosphate production that the balanced equation shows. This is most likely due to the poor solubility in water, combined with decreasing solubility with increasing temperature—0.189 g/100 mL 0°C, 0.173 g/100 mL 20°C, 0.066 g/100 mL 100°C. Additionally calcium hydroxide is a solid and forms coarse conglomerates when it's dry. There for when put into solution the larger the surface area of the solid the longer it takes to dissolve $\text{Ca}(\text{OH})_2$.



To overcome the issue of low solubility and large surface area hydrodynamic cavitation can be used. Cavitation has been shown to increase the kinetics calcium hydroxide by temporarily increasing temperature of calcium hydroxide in turn increasing dissociation of surface molecules helping to alleviate the problem of poor solubility [21]. Hydrodynamic dynamic cavitation allows for greater dissociation of surface molecules by

causing the violent collapse of vapor filled cavities. These vapors filled cavities expands until an unstable size is reached and upon collapse reaches temperatures and pressures approaching of 5000°C, and 2000 atm [22]. Along with pressure and temperature hydrodynamic cavitation increase turbulent flow, Reynolds numbers, and increase in sheer forces and the ability to physical alter surface of calcium hydroxide that these voids come in contact with. It is probable that phosphate and calcium hydroxide can react directly on the surface of the calcium hydroxide particles after surface disassociation. Yavors'kyi hypotheses [21] the cavitation can create $\text{Ca}(\text{OH})_2 \rightarrow \text{Ca}(\text{OH})^+$ on the surface of calcium hydroxide. This phiso-chemical reaction may provide a base for the formation of calcium phosphate salts on the surface of the $\text{Ca}(\text{OH})_2$ when phosphate is present in the solution. This combined with cavitation action continuously removing newly formed salts and reforming $\text{Ca}(\text{OH})^+$ may allow for the reuse of calcium hydroxide in this reaction and the collection of the calcium phosphate salts for industrial use.

1.2 Project Scope

In this research project, a continuous flow process was examined as a possible alternative for phosphate removal for large scale industrial, municipal and agricultural process applications. The research project investigated two forms of hydrodynamic cavitation produced by jet nozzles and orifice plates using calcium hydroxide as chemical reactant.

2. MATERIALS AND METHODS

2.1 Waste Water and Cavitation Apparatus

Phosphor content of waste water was simulated by adding 3.50 g of ammonium dihydrogen phosphate from Bean Town Chemicals to 30 L of tap water stored in the influent tank of the hydrodynamic cavitation set up Fig. 1. The artificial wastewater containing a 50 mg/l of PO_4 was than pumped through 1 inch tubing using a Dyton model 3YU60A brand .5hp pump, to a static mixing flange designed to, mix and cavitate calcium hydroxide as shown in Fig. 1.

The total length of this apparatus was 1.10 m, and included a 10:1 Venturi pump for the introduction of 20% wt calcium hydroxide ($\text{Ca}(\text{OH})_2$) slurry. The $\text{Ca}(\text{OH})_2$ slurry was made

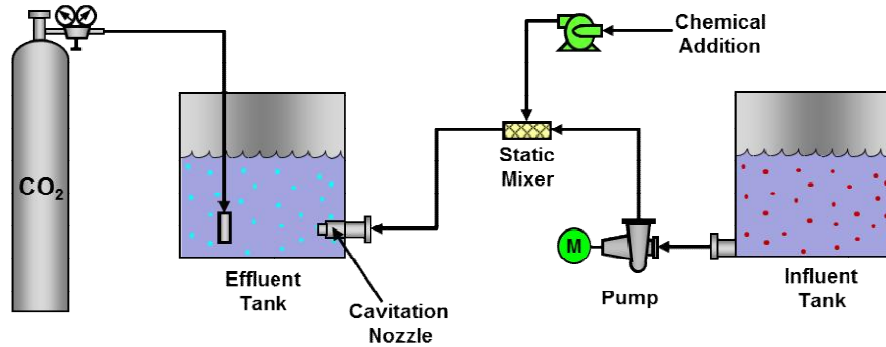


Fig. 1. Process sketch of hydrodynamic cavitation set up

from Sig-Aldrich brand $\text{Ca}(\text{OH})_2$ and 80%wt tap water and pumped using a paulsetronic brand parasitic pump at rate of 80.00 ml / min or 16.00 g of $\text{Ca}(\text{CO})_2$ diluted slurry per minute. The slurry was continually stirred during the experiment and hoses purged with tap water after each run to prevent settling with in the lines.

After the Venturi pump the slurry entered a commercially available pvc static mixing flange. The remainder of the unit was 1" PVC pipe with a pressure gauge and temperature gauge. The same unit was used in all experiments, but modified for orifice plate cavitation and jet nozzle cavitation.

2.2 Orifice Plate Design

Two orifice plates were constructed of machined aluminum. One containing 19, 1 mm holes in a one inch diameter circular area (Fig. 2a), to be evenly spaced out over the inner diameter of the PVC pipe, and were modeled after the orifice plates designed by Vichare et al. [23]. This created a flow rate of 13 l/min at 47.5 psi. A second containing 19, 2 mm holes (Fig. 2b) creating a flow rate of 60 l/min at 5 psi. The rate of chemical addition remained the same. The jets of water produced by the orifice plate were introduced into the wastewater pond at the bottom (Fig. 2).

2.3 Jet Nozzle Cavitation

Jet cavitation was conducted using the identical apparatus, but the flange holding the orifice plate was replaced with a $\frac{1}{2}$ in PVC "T" adapter connecting two $\frac{3}{4}$ " inner-diameter 5 foot tubes connecting to two identical nozzles. In trial one two 9mm nozzles were used than followed in the next trial by two 4mm jet nozzles were used to cavitate wastewater. Each tube was attached to

an adjustable bevel that could easily be fixed at angles 90° , 120° , 150° , 180° , both size nozzles were arranged in this manner. Fig. 3 shows the 90° arrangement. Once trials with the 9mm and 4mm nozzle sizes and 5 foot tubing we completed and analyzed the length of one hose was shortened, and jet nozzles were set to 90° the most efficient angle to reduce phosphate. This produced a near continual flow of $\text{Ca}(\text{OH})_2$. Shortening the hose length is done to offset the timing of $\text{Ca}(\text{CO})_2$ delivery by the peristaltic pump. With even tubing length pulses of $\text{Ca}(\text{CO})_2$ were delivered simultaneously. By calculating the velocity of water in the system and timing the delivery of each delivered $\text{Ca}(\text{OH})_2$ pulse from the peristaltic pump, the hose could be cut to deliver calcium hydroxide pulses 180° out of phase. This was confirmed mathematically and by the addition of colored dye which could be seen moving through the clear tubing.

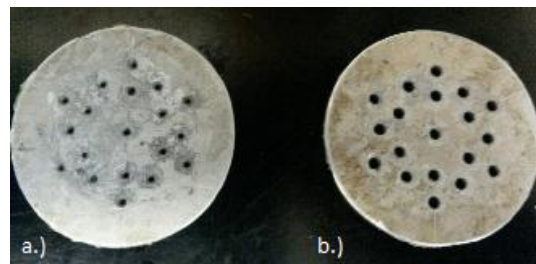


Fig. 2. Orifice plates used to produce cavitation

a.) 1 mm, 19 holes b.) 2 mm, 19 holes

2.4 Detecting the Presence of Cavitation

The presence of cavitation was confirmed using solution of 0.5M KI Bean Town Chemicals in tap water was used to verify cavitation. KI was used in the identical apparatus as the manufactured

wastewater and calcium hydroxide. The disassociation of KI is a known indicator of cavitation by measuring the change in absorbency caused by the dissociation of potassium from iodine incited via cavitation [23]. The change of absorbency is measured using a Hach DR 1900b portable spectrometer at 355 nm. This method of measuring the change in absorbency at 355nm was used to confirm cavitation in all methods. Iodine has a color absorbency around 355nm; the higher the absorbency the more iodine that is dissociated or released by the ionic potassium iodide salt [23].

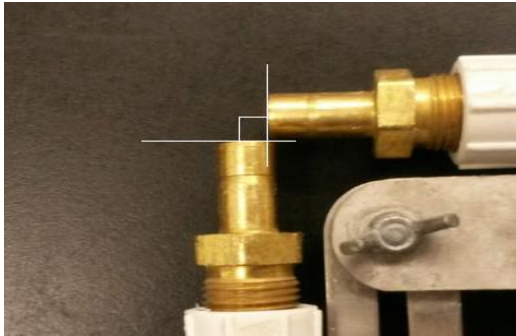


Fig. 3. Example of Jet Nozzle setup at 90°

2.5 Sampling and System Cleaning

A total of three samples were taken for testing in all trials: The first sample was collected from the influent tank (Fig. 1) to confirm the amount of phosphate in the manufactured waste water prior to treatment. The second sample was collected from the effluent tank before the jet nozzles became submerged. In both cases the set up used for nozzle and orifice plate cavitation approximately 5 cm existed between the bottom of the container and where jet nozzles and the orifice plate were located. The third sample was collected from the effluent tank at the completion of the experiment to test the treated wastewater. To verify the exact concentration of phosphorus at each step the Hach Test n' Tube High Range Reactive Phosphate 0-100 mg/L Hach reagent set #2767345, and read on the preprogrammed Hach DR 1900b portable spectrometer following manufacture methods and procedures. All sample to be tested by this method were taken from the middle of the sampling vessel as to collect as little calcium hydroxide as possible.

After each trial the wastewater containers, catch basin and apparatus were rinsed and cleaned to remove as much ammonium dihydrogen

phosphate and $\text{Ca}(\text{OH})_2$ as possible. The catch basin and manufactured wastewater pond are first triple rinsed with tap water than rinsed with a 0.5M hydrochloric acid solution. The pump and $\text{Ca}(\text{OH})_2$ mixing apparatus were rinsed through the Venturi pump with tap water where $\text{Ca}(\text{OH})_2$ is introduced for a minimum of 5 minutes. Collection and test vessels were rinsed with 6M HCl as per Hach testing specifications.

2.6 Neutralization

Removal of excess $\text{Ca}(\text{OH})_2$ and neutralization was done. Due to low solubility and supersaturation calcium hydroxide and produced calcium products settle very quickly. One liter of clear treated wastewater was collected from the waste water basin after being allowed to settle. A digital pH meter was submerged and CO_2 gas bubbled through until neutralization occurred to a pH of approximately 8.0.

2.7 Waste Water Application

The hydrodynamic test apparatus was tested using municipal wastewater at the CERF facility located at wastewater treatment plant of the Village of Minoa, New York State. The Identical process was applied to municipal wastewater using the cavitation apparatus with 4mm jet nozzles under a 90° angle and applying calcium hydroxide as a reactant (Fig. 1). For analyses of the phosphate the Hach Test n' Tube high rang phosphate test was used as described in the materials and methods section. The phosphate concentration was averaged to be 29.01 mg/L of reactive phosphate in the wastewater. Applying the calcium hydroxide and cavitation method the amount of the phosphate was reduced to below 3.00 mg/L. This achieved an 89.7% reduction of phosphate without CO_2 neutralization.

3. RESULTS AND DISCUSSION

The use of jet nozzle cavitation and orifice plate cavitation produced a greater removal of phosphate than controls alone. The greatest method removed was 8.8 times more of a percentage of phosphate than the base control (Table 1). Factors influencing the removal of phosphate included, size of nozzle or orifice hole, continuous or alternating introduction of calcium hydroxide, and whether orifice plates or nozzles are submerged in treated wastewater. It should be noted that even before the orifice plate or jet nozzle is reached by the water, cavitation will

occur between phosphate and Ca(OH)_2 at the end of the Venturi and within the static mixing flange.

Table 1. Total percentage of phosphate removed by various method

	Method	% PO_4 removed
Ca(OH) ₂ 180° out of phase	90° 4 mm Nozzle cut tube with pH Neutralization	89.30
	90° Small 4 mm Nozzle cut tube	70.15
	90° Small 4 mm Nozzle cut tube	62.30
Orifice plate	Orifice plate 19, 1 mm holes	58.89
	Orifice plate 19, 2 mm holes	56.66
Jet nozzle	90° Small 4 mm Nozzle	53.23
	120° Small 4 mm Nozzle	47.64
	150° Small 4 mm Nozzle	29.74
	180° Small 4 mm Nozzle	9.56
	90° Large 9 mm Nozzle	21.00
	120° Large 9 mm Nozzle	16.90
	150° Large 9 mm Nozzle	17.00
	180° Small 4 mm Nozzle	3.42
Controls	Control Jet large 9 mm Jet Nozzles no angle	15.91
	Control Jet Small 4 mm Jet Nozzles no angle	12.36
	Control Stirred Beaker	10.56
Jet nozzle municipal wastewater	90° Small Nozzle cut tube	>90.0

The use of a peristaltic pump first acted as what was thought as a detriment to the experiment. Data collected showed that the peristaltic pump does not deliver a continuous flow of the calcium hydroxide slurry. The pump delivers approximately 333 mg / pulse. This turned out to be a control with useful information and insight about the effect of the physio-chemical reaction that is taking place between calcium hydroxide, phosphate, and cavitation. Using a peristaltic pump allowed us to observe a greater reduction

in phosphate when Ca(OH)_2 was delivered out of phase in a near continuous manner meaning more phosphate and Ca(OH)_2 interacted under the physio-chemical conditions, compared to when the Ca(OH)_2 was delivered in straight pulses. During pulse delivery, more time would have been spent without Ca(OH)_2 and phosphate interacting under cavitation conditions.

When comparing mixing calcium hydroxide and phosphates in a beaker as a control to cavitation, data revealed it is probable that the forces formed by jets of water themselves did not directly affect the removal of PO_4^- , but it was the combination of Ca(OH)_2 and PO_4^- in cavitation type conditions that produced the best removal of phosphate and formation of $\text{Ca}_3(\text{PO}_4)_2$ and other calcium salts. This result can be interpreted by comparing pulsed delivery of Ca(OH)_2 , with near continuous delivery. When pulse of Ca(OH)_2 went through the identical length tubing reaching the jet nozzles at the same time PO_4^- was reduced by 53.23%. When pulses of Ca(OH)_2 reached the nozzles 180° out of phase or nearly continuously, PO_4^- was reduced by 70.15%. Both results were achieved with the 90° angle and small 4 mm nozzle. Indicating that cavitation action on Ca(OH)_2 molecules is more important to the removal of phosphate in the system than the amount of Ca(OH)_2 present in the reaction. Although pumps and apparatus did not change pressure and there for time did vary. When using orifice plate cavitation flow rates were lowered meaning more time to pump the 30L of manufactured waste water was needed, therefore more of Ca(OH)_2 was introduced.

The angles of the nozzles influenced the amount of PO_4^- removed (Table 1). Angles tested using both 4mm (Fig. 4) and 9 mm (Fig. 5) nozzles were 90°, 120°, 150°, 180°. The trends of PO_4^- removal were similar for both large and small nozzle trials. Jet nozzles held perpendicular or at 90° to one another produced the greatest results. Jets at a 90° most efficiently transfer energy into a ratio of maximum turbulent flow and the production of useful cavitation voids; that increase the dissociation of surface area alleviating the issue of poor solubility. At 90° it is possible that the Venturi effect aids cavitation by maintaining a low-pressure area by quickly circulating liquid by the nozzle. With the Venturi effect taking place the super cavitation within the nozzle will be maintained, this will prevent flipping and collapse of super cavitation. Jets directed exactly towards one another or at 180° seemed to have a negative effect on the removal of phosphate. This is most likely due to the loss

of cavitation within the nozzle. As water is forced into the other nozzle velocity may be lost, and liquid will infiltrate the cavitation void causing collapse and loss of cavitation.

Similar phenomena resulting in the cancellation or reduction in the ability of cavitation to increase the rate of a reaction was observed during bench scale acid hydrolysis reactions by Losev et al. [24]. In their experiment, hydrodynamic cavitation effects were reduced what they hypothesized as resonance within the system. As propeller speeds increased so did the rate of reaction peaking at 4000 rpms and reducing after. It is possible to compare the rotation of a propeller, or jets of liquid because the same hydrodynamic cavitation type voids are produced [24].

Orifice plate cavitation is produced by forcing fluid through numerous or small holes into a body of standing fluid. In this experiment manufactured wastewater rich in PO_4^- was mixed in an apparatus with $Ca(OH)_2$ and forced through

1 mm, and 2 mm. The size and number of holes is proportional to that of plates made designed by Vichare et al. optimization of cavitation paper [23]. Experimentally orifice plate trial 1) with nineteen 1 mm holes removed more phosphate from wastewater than orifice plate trial 2) with nineteen 2 mm holes. The respective pressure, flow rate, velocities, and cavitation numbers (σ) were 47.50 psi and 13.00 L /min total, 3.41 m/s, and $\sigma = .2765$ for each 1 mm hole; 7.5 psi and 60.00 L/min total, 16.75 m/s, and $\sigma = .2600$ for each 2mm hole. Due to the large difference in flow rate the time to empty the 30L influent tank was 138s versus 30.00s respectively, the amount of $Ca(OH)_2$ available in total may have influenced the difference phosphate reacted to calcium phosphate. The amount of $Ca(OH)_2$ injected into the system was 46.20 g for the 1mm holes verse 10.00 grams for the 2 mm holes trial. Having greater amounts of $Ca(OH)_2$ in the trial 1 system could be the reason for the increased removal of phosphate opposed to the small difference in cavitation numbers.

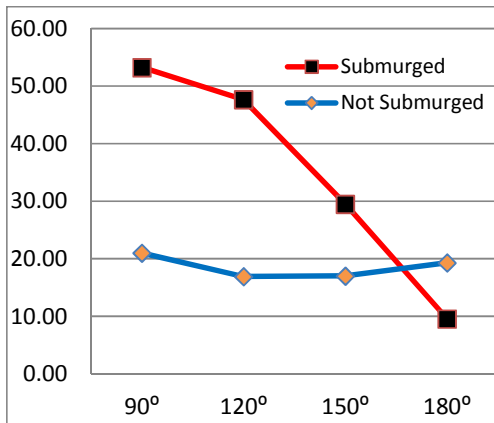


Fig. 4. Total percent PO_4^- removed using 4mm nozzle and submerged and not submerged

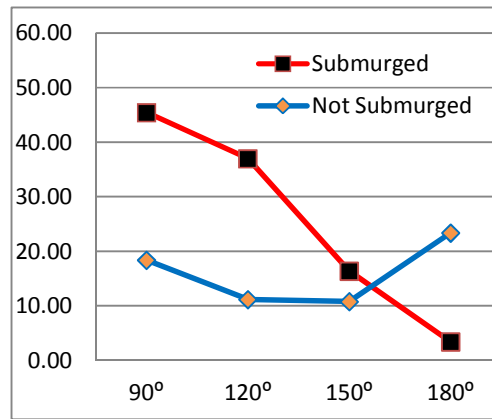


Fig. 5. Total percent PO_4^- removed using 9mm nozzle submerged and not submerged

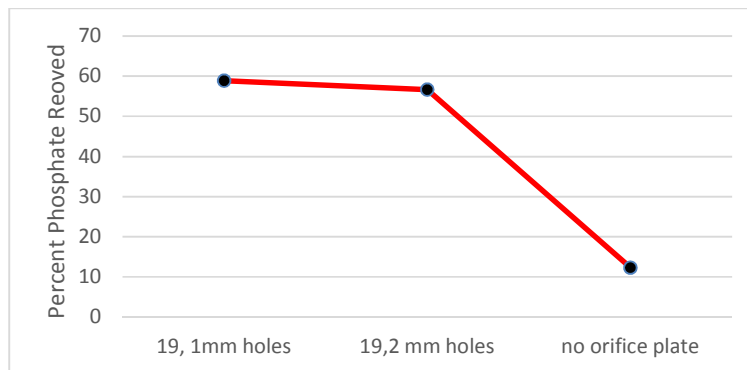


Fig. 6. Reduction of phosphate via orifice plate cavitation

In all experiments use of excess calcium hydroxide not only provides ample surface area for cavitation to effect phosphate reduction, it also provides supersaturation of the wastewater solution and may promote the growth of calcium phosphate related crystals. These crystals will also precipitate out of solution and along with excess calcium hydroxide it will more quickly fall out of solution because of super saturation [19].

As this experiment aims to produce a viable and cheap solution to the issue of phosphates in wastewater, the effect of neutralization of Calcium Hydroxide rich treated wastewater was conducted with CO₂. First excess calcium hydroxide was settled out of the treated waste water, and any calcium hydroxide that collected on the surface of the treated waste water was recovered. Only the clear supernatant was used for neutralization. Then carbon dioxide gas was bubbled through the treated wastewater resulting in $\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$. This had three effects one bringing the pH from 12.30 to 7.35, it also produced calcium carbonate, and helped reduce phosphate content further. During this neutralization, $\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$, and in turn further reduced the amount of phosphate in the wastewater by a total of nearly 90%. It is possible that during neutralization the formation of calcium carbonate also trapped phosphate within its structure as an impurity. It is probable that more phosphate would be removed if the pH of the neutralized solution was kept above 7.4, the point which calcium phosphate salts become more soluble in an acidic solution [25]. It is very possible that this method of wastewater treatment may be just as effective as many of the currently used methods of wastewater like using ferric chloride.

Collection and reuse of excess calcium carbonate the produced calcium phosphate salt, and left over calcium hydroxide solids not only serves a cost saving purpose, there is also a chance that more calcium phosphate salts will be produced. This if from seeding or creating the presence of supercritical nuclei that lays the first building block for crystal growth. As calcium hydroxide is reused the amount of calcium phosphate presents in and on the calcium hydroxide will increase aiding in super nucleation.

To examine the hydrodynamic cavitation effect on real municipal wastewater, the wastewater treatment plant in Minoa, NY was visited and wastewater was run through the cavitation

apparatus (Fig. 1). For this test, the 4mm jet nozzle with a 90° angle arrangement (Fig. 3) under submerged condition was used. Ca(OH)₂ was supplied 180° out of phase. The tested wastewater was not neutralized, yet a reduction of phosphate over 90% was achieved. The reason for this most likely has to do with the high number of contaminants contained in municipal wastewater that could enhance calcium phosphate formation through nucleation. Not only were solid contaminants present but the exact chemistry of the wastewater is unknown. The amount of reactive phosphate was tested but other contaminants were not. Jet nozzle cavitation did not only reduce phosphate, but quick flocculation, and settling of contaminants was observed in the effluent tank of the cavitation apparatus used. Flocculants settled both on top of the water and sank to the bottom of the effluent tank (Fig. 2) where collection could be made easy.

For further study of municipal treatment of wastewater, it would be recommended that CO₂ neutralization of wastewater also occurred followed by further testing of PO⁴⁻ in the wastewater column. Additionally, tests to reuse the Ca(OH)₂ should be conducted. Since the solubility of Ca(OH)₂ is so low and PO⁴⁻ is attached to the surface of the calcium hydroxide particle sequential cavitation would break further down the calcium hydroxide particle. This would allow to produce calcium phosphate salts on the additional surface area available of the calcium hydroxide particle.

4. CONCLUSION

The likely hood that calcium hydroxide with the use of cavitation can be a viable means of wastewater treatment. With further research and optimization of wastewater treatment processes that utilizes calcium hydroxide to remove phosphate with hydrodynamic cavitation it is likely, that this method can compete on a percentage of removal basis with any current method of phosphate removal from wastewater. Areas of study that would be beneficial to the optimization process would be the confirmation of super cavitation within each nozzle used to process the wastewater. Flipping nozzle cavitation could be a detriment and available study into this phenomenon using angular jet cavitation. It is not known from this study if the venturi effect prevents the flipping action from forming. The venturi effect may aid super cavitation by preventing the collapse of the

cavitation void due to the velocity of flow past each nozzle helping maintain the low-pressure environment.

Validation of the effectiveness when reusing calcium hydroxide and how many times it can be used before its effectiveness is reduced should be studied. Due to the formation of acid soluble calcium phosphate it is likely that a point will be reached, where the balance of calcium phosphate to calcium hydroxide will no longer form calcium phosphate at an industrially acceptable rate.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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