Flocculation-Flotation vs. MBR for High MLSS Secondary Clarification

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ABSTRACT

Rendering plants produce high strength wastewater with high TSS, FOG, BOD and TKN. At one such plant it was decided to install a primary DAF followed by an anaerobic-anoxic-aerobic treatment system for TSS, FOG, TKN and BOD removal. Since wastewater is a high strength (TSS up to 10,000, FOG up to 3,000, TKN up to 350 and BOD up to 6,000 mg/l, respectively, bioreactors will produce high MLSS up to 11,000 mg/l. Pilot scale studies tested the feasibility of using either flocculation-flotation or membranes for MLSS removal. Only a small space was available inside the building, making it necessary to operate solid/liquid separation at an HRT of 5 GPM/ft^2, and a solids loading of up to 15 lb/ft^2/hr. Currently engineers consider that it is impossible to clarify aerobic MLSS at loading over 10 lb/ft^2/hr unless membrane separations are used. After the pilot studies where solid/liquid separations were achieved with the GEM flotation System, full scale System was installed in 2012 and is operating for the last three years. This manuscript describes the pilot study and full scale installation of the GEM flotation System at this plant.

INTRODUCTION

Goals and Objectives

The primary goal of this study was to compare the performance of membranes and a small footprint advanced flotation system for high MLSS clarification. After the pilot study, a full scale wastewater treatment system was to be built at a California rendering facility.

The Pilot Study

Membranes and an advanced small footprint GEM flotation System were tested at a Wahoo, Nebraska rendering facility. Return activated sludge, RAS (5%), was diluted to different concentrations of MLSS to use as a model system for high MLSS between 3,000 and 17,000 mg/l.

Membranes (flat sheet microfiltration from Kubota) were able to remove up to 17,000 mg/l of MLSS. However, high amounts of calcium (350 mg/l) and alkalinity in the water resulted in very fast calcium carbonate scaling, and an unacceptably frequent need for membrane acid cleaning (once a week). This would result in the replacement of membranes of at least once a year.

The GEM System (advanced in situ flocculation - flotation described later in the text) was able to remove between 3,000 and 11,000 mg/l of MLSS at HRT of 5 GPM/ft^2. Cationic high molecular weight high charge (55%) granular polyacrylamide flocculant C-498 HMW from KEMIRA (available in GRAS form) had to be used for the best clarification and sludge thickness (4.5-6.5 % of dry solids). After the GEM System, effluent TSS was on average 20 mg/l, FOG 0 mg/l and BOD 22 mg/l - with TKN of 12 mg/l. Sludge depth inside the tank varied between 1 inch and 3 feet. At MLSS above 12,000 mg/l and HRT of 5 GPM/ft^2 [loads above 16 lb/ft^2/hour] sludge depth was 6 feet, which resulted in a large amount of carryover inside the effluent. Including safety factors, the GEM System can be used at an HRT of 5 GPM/ft^2 to remove up to 11,000 mg/l of MLSS from an aerobic reactor. The flocculant dosage at 11,000 mg/l was 90 mg/l of C-498 HMW.

The polymer dosage did not interfere with the performance of the RAS. RAS was mixed with the incoming wastewater with the maceration pumps to break down strong flocs produced with the cationic polyacrylamide flocculant. High calcium concentrations did not interfere with the flocculation - flotation process. No scaling occurred at the tank surfaces due to high enough flow rates. Since the sludge’s dry weight was between 4.5 and 6.5%, no additional thickening was necessary (see Figure 1 for a picture of sludge skimmed from the GEM System installation). Dewatering in decanter centrifuges was easily achieved without the addition of further flocculants. Produced dry sludge could be used for composting or landfill disposal. Jar tests have to be performed and chemistry dosages adjusted to achieve the best separation efficiencies. The pH of the influent was around 7.4 and did not have to be adjusted. TDS of the influent was around 1,200 mg/l. As it is described below, the GEM System is a hybrid centrifugal - dissolved air flotation system where the mixing energy of flocculants and particles can be adjusted. Moderate mixing energies inside the liquid hydrocyclones (LCPP’s - liquid cyclone particle positioner) were used (see below for description of the GEM System). Flocculants were added after the aeration-cavitation plate to avoid floc breakage and polymer chain breakage.

Various polymeric flocculants were tested. The higher the molecular weight, the better stronger flocs were produced. Flocculants with more charge also produced better sludge at lower dosages. Granular flocculants always outperformed emulsion flocculants. When high dosages of cationic flocculant had to be used (60-100 mg/l), better results were achieved if flocculants were added in two separate LCPP's. Better results were achieved when flocculants were prepared at 0.25 % than at 0.5% (due to viscosity and mixing issues).

Figure 1 – Sludge Skimmed from GEM System at Rendering Facility

THE DESCRIPTION OF THE GEM FLOTATION SYSTEM

We proposed that a more efficient flotation system (than current DAF's) could be developed by combining high-energy centrifugal mixing of a liquid cyclone system (we termed it the liquid cyclone particle positioner, LCPP) with dissolved air as a source of flotation. Coagulants and flocculants can be delivered *in situ* directly into the flotation hydrocyclone unit. Pressurized air can be delivered to LCPP heads at the same time as flocculants. Such a procedure results in flocs which are very porous and loaded with entrained and entrapped air.

As shown in Figure 2 the LCPP also acts as a liquid-solid-gas mixer (LSGM). Replacing the classical hydrocyclone head with the LCPP provides extremely energetic mixing by sequentially transporting liquid and entrained particles and gas bubbles throughout a centrifugally rotating liquid layer. Microturbulence in such vortices results in all particles and bubbles down to colloidal and molecular size acting as little mixers. Axial and radial forces inside the LCPP help mix coagulants and flocculants with the particles. Uncoiling of polymer and better mixing of ultrahigh-molecular-weight polymers (and more concentrated emulsions) is achieved in the LCPP. Such efficient mixing is important for proper flocculation of suspended particles. Centrifugal mixing also results in less floc breakage than with commonly used impeller or floc tube mixers.

Further modification of LCPP heads, as opposed to hydrocyclone heads, introduced multiple holes with plugs inside the LSGM heads, as shown in Figure 3. By changing the number of plugs, we can modify the mixing energy and head pressure from very low to very high. In this way, we can mix low-molecular-weight coagulant at relatively high energy and high-molecular-weight flocculants at relatively medium and low mixing energy to promote final large floc formation.

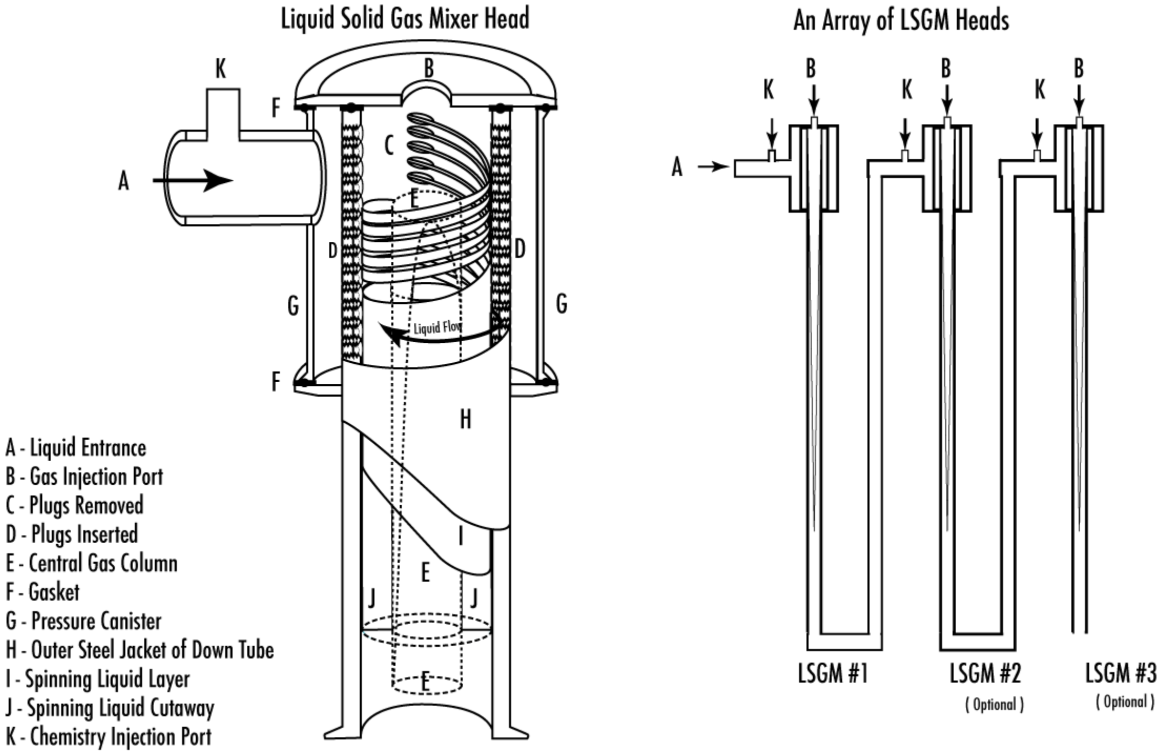

Figure 2 – Schematic Presentation of the LCPP/LSGM

Hybrid centrifugal – dissolved air flotation technology (The GEM System developed at CWT [see Figure 4]) provides the best of both centrifugal and dissolved air systems: efficient continuous flow mixing and in line flocculation with the nucleation and entrainment of fine dissolved air bubbles. This development has resulted in systems with very efficient removal of particulate contaminants, a small footprint, drier sludge, durable long lasting flocs, fast response and treatment of the total wastewater stream (no recycling characteristic for DAFs). The design of on-line turbidity or fluorescence driven sensors for automatic control of coagulant and

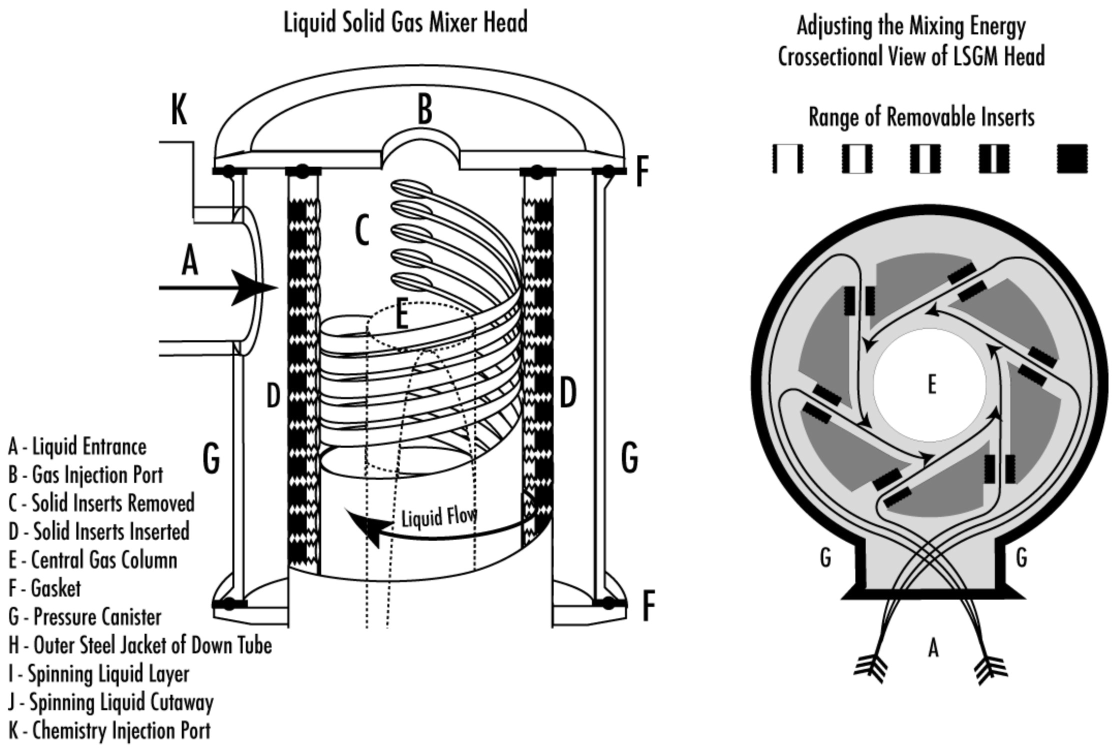

Figure 3 – Schematic Presentation of the LSGM Heads

flocculant dosage is also underway. Computational fluid dynamics (CFD) has been used to design better flotation tanks with a vortical flow pattern that results in the formation of a dense air bed inside the tank. Such fine bubble layers prevent sedimentation of already floated heavier particulates, which results in significantly higher flotation rates.

SYNERGISM OF CHEMICAL AND MECHANICAL ASPECTS OF THE SOLID/LIQUID SEPARATION SYSTEMS

Solid/liquid separation processes are only as efficient as the weakest “link in a chain”. New generation of high performance flotation units can only deliver if appropriate chemicals are used to coagulate and flocculate particles and emulsions in wastewater.

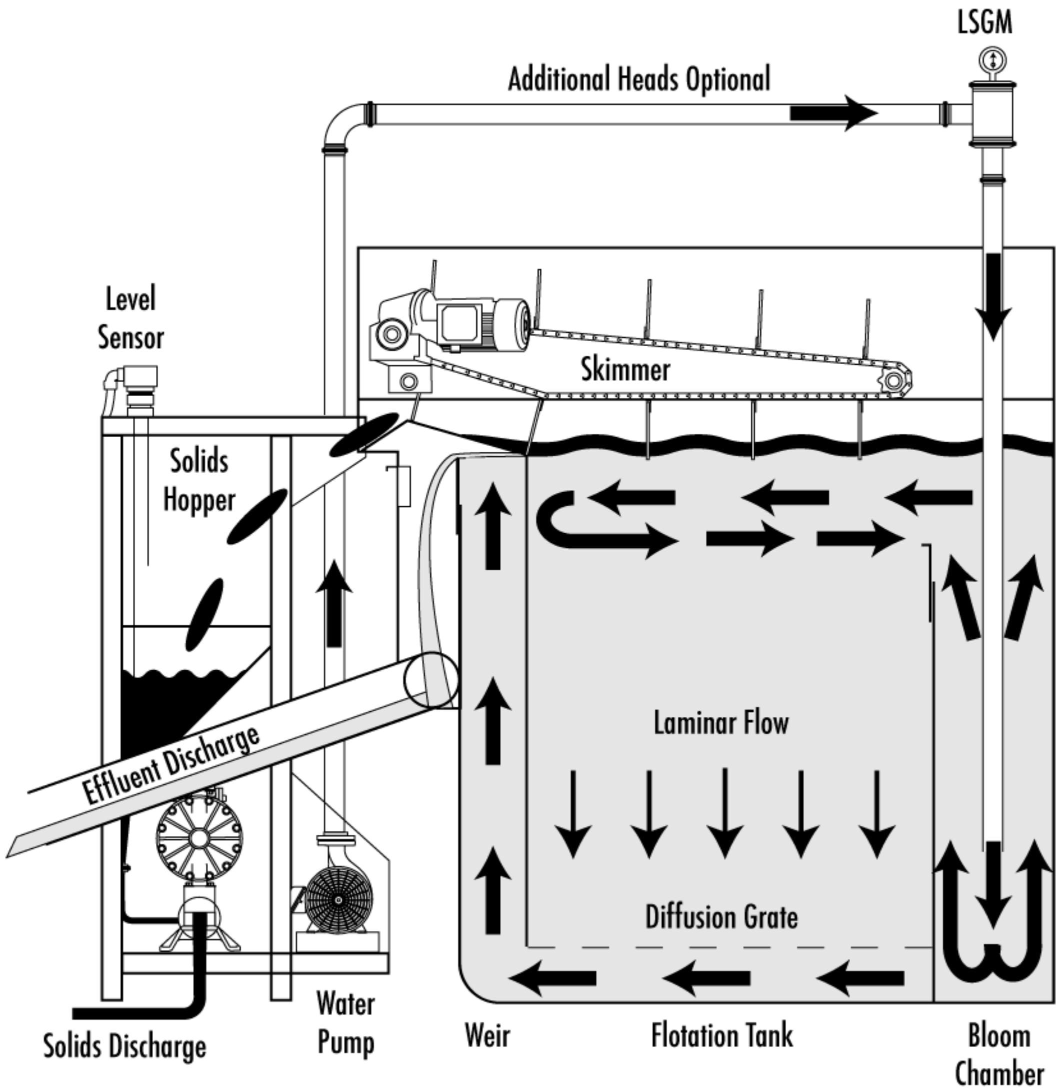

Figure 4 – Schematic Presentation of the Hybrid Centrifugal – Dissolved Air Flotation System

Coagulation, flocculation and flotation are among the most effective approaches to remove fats oils and grease, suspended solids and colloidal materials (even some proteins and macromolecules) from any industrial wastewater, such as for instance food processing. Solids, colloids and macromolecules present in food processing wastewater are generally charged. Charge stabilization often produces very stable colloidal suspensions. Solids and colloids that are charge stabilized repel each other and produce systems that have a tendency to "swim" within the wastewater bulk, rather than sediment or float. Surface charge has to be neutralized in order to get particles close together so that other attractive forces such as hydrophobic or van der Waals forces result in formation of larger aggregates that either sediment or attach to bubbles and float. Most colloids, macromolecules and solids in food processing wastewater are of organic nature.

Ionization of carboxyl and amino groups from fatty acids or proteins produces some charge. Oil and grease particles are often emulsified and charge is present in the surfactants used as emulsifying agents. Many neutral colloids will preferentially adsorb hydroxyl ions and become negatively charged.

Most colloids present in any food processing wastewater are negatively charged, probably due to preferential adsorption of hydroxyl ions and widespread surface availability of carboxyl groups. The surface charge/dissociation of such groups is pH dependent. It is possible to find a pH at which total surface charge is zero (point of zero charge). At such pH colloids are quite unstable. However, coagulants and flocculants are designed so as to promote even faster, more efficient destabilization of colloids with growth of large, stable aggregates. The pH, therefore, should be adjusted close to the point of zero charge, in order to save on dosage of coagulants and flocculants needed to neutralize the surface charge. If surface charge is fully neutralized, the performance of flocculants is low.

Once the pH is adjusted, coagulation and flocculation process follow. Coagulation is addition of oppositely charged ions or molecules in order to neutralize surface charge and destabilize colloidal suspensions. Inorganic coagulants such as sulfate or chloride salts of trivalent iron (Fe[III]) or aluminum (Al[III]) have been quite popular in food processing wastewater treatment. However, such salts hydrolyze as part of coagulation process and produce oxohydroxyde sludge that is bulky and difficult to dewater. Prehydrolyzed –inorganic polymeric aluminum reagents such as polyaluminum chloride (PAC) or aluminum chlorohydrate (ACH) are more efficient in charge neutralization. Such salts also produce less bulky sludge. Cationic polyelectrolytes (organic low molecular weight polymers) such as quaternary polyamines produce less sludge that is easier to dewater. Such reagents are also much more efficient in charge neutralization. Therefore, the dosages needed to neutralize surface charge with polyelectrolytes are often more than order of magnitude lower compared to dosages of aluminum or iron salts. However, ferric salts have to be used if blood clarification is to be achieved. Precipitation of phosphate or sulfide ions also can be achieved only with inorganic ions. Finally some proteins can be removed with proper pH adjustment and use of inorganic coagulants.

Flocculation is a process of formation of large stable flocs that either sediment or float. Flocculants are reagents that achieve flocculation. Flocculants are large polymeric molecules that bind together smaller flocs produced by coagulation. Synthetic high molecular weight polyacrylamides are the most commonly used flocculants. Cationic polyacrylamides can neutralize residual negative surface charge and also bind smaller flocs together. Flocs may also be overcharged with coagulants and cationic flocculants, with subsequent use of anionic polyacrylamide. Such approach, termed dual flocculants approach, will be described in detail later in this manuscript (also see Figure 5).

Several steps are involved in the coagulation and flocculation processes. First, coagulants are added to the wastewater with the precise dosing pumps. Then coagulants are mixed with the particles in the high energy mixing process in order to uniformly distribute adsorbed coagulant molecules or ions. Upon initial charge neutralization, flocculants are added. Even more precise dosing is needed in order to avoid under or overcharging of particles. Flocculants are mixed with less energy in order to avoid breakup of formed flocs or even polymer molecules, which are large delicate chains. On the other hand, enough mixing intensity is needed to achieve uniform distribution of polymer and adsorption on all particles, rather than over - absorption on nearby particles only. (Mixing is also needed to activate polymeric flocculants. Such giant molecules are coiled into the tight coils. Linearization is needed to achieve polymer configuration that can bind numerous smaller flocs together (see Figure 6).

Wastewater samples tested while developing the system described in the manuscript were coagulated and flocculated at numerous pHs ranging from 3 to 11. For most samples, best flocculation can be achieved at pH between 5 and 6. Removal of fine emulsions and proteins is also most efficient in this pH range. Some wastewater samples had a very small amount of TSS and colloidal materials. For such samples, the pH was adjusted between 7 and 9. Similar approach was used for samples with colloidal materials that are almost neutral. Increasing pH above 8 results in higher surface charge and stronger adsorption of flocculants. At pHs below 5, performance of flocculants was found to be sub optimal with smaller, weaker flocs and more carryover in laboratory flotation tests. At pHs above 9, consumption of coagulants and flocculants was very high.

Numerous inorganic, organic and blend coagulants were tested with food processing wastewater. Ferric (FeIII) and aluminum (III) sulfate require the highest dosages and produce sludge with the lowest % solids that is most difficult to dewater and dry. As wastewater becomes loaded with TSS and FOGs, the necessary dosages to achieve coagulation can be as high as 6,000 mg/l. These two coagulants also interfere with the performance of flocculants, producing "pinpoint" floc with very small particles and high amount of carryover (often over 200 mg/l) in laboratory flotation tests. However, if water is rich in blood proteins, small amount of ferric coagulant (10-60 ppm) is needed to clarify wastewater and reduce foaming problems.

Prepolymerized inorganic coagulants suffer from similar deficiency, namely large dosages needed; carryover after flotation produced, and sludge with low % solids produced. Needless to say, dosages are lower than that of monomeric ferric or aluminum ions based coagulants. The most popular reagents from this group are polyaluminum chlorides, (PAC) with various basicity and aluminum chlorohydrate (ACH). Also, inorganic coagulants produce sludge with tendency to sediment, rather than to float.

Organic polyelectrolyte coagulants are the most advanced new generation of coagulant reagents. Usually, those are small cationic polymers with 100% backbone charge. Polyethyleneimines were the first reagents used for such purpose. Modern quaternary polyamines, epiamine, and polydyallyldymethyl chlorides (polyDADMAC's) are most often used in wastewater treatment applications. Such reagents do not interfere significantly with the performance of flocculants. They also produce sludge with high solid % and dosages needed to coagulate the wastewater can be an order of magnitude lower than that of inorganic reagents. Total cost of wastewater treatment is actually lower when using such reagents rather than inorganic coagulants. Low molecular weight epiamines and quaternary polyamines (10,000 – 25,000 D) coagulated food processing wastewater with the lowest dosages and least interference with the performance of flocculants downstream. Higher molecular weight and crosslinked polyamines (weight over 50,000 D) interfered with the performance of flocculants, and surprisingly were less efficient in coagulating wastewater colloidal contaminants. If combination of ferric and polyamine coagulants are needed, it is often better to add them separately then as a blend. Blend coagulants contain fixed ratio of ferric to polyamine coagulants. However, when treating changing wastewater influents, the ratio of amount of ferric and polyamine ions can vary quite significantly. From economic standpoint, blend coagulants are also very expensive.

Flocculants are the key component of any successful flotation wastewater treatment. We tested granular, emulsion, direct dispersion and brine flocculants. Flocculants with molecular weight between 1,000,000 D and 70,000,000 D were tested. Flocculants with charge (mole%) between 2 and 100% were tested and the effects of ionic strength (salinity, temperature, pH and surfactant present were studied). In all cases studied, granular high molecular weight, high charge polyacrylamides performed best. Such reagents yielded best flocs, sludge with the highest % solids, and least amount of TSS in the effluent. Dual flocculant approach in which addition of cationic flocculant is followed by addition of anionic flocculant always yielded the best performance (Fan et al., 2000). Emulsion flocculants produced smaller flocs, sludge with less solids and more TSS in the effluent. The higher the % active polymer in the emulsion, the better the performance. The same applies for brine and direct dispersion flocculants. Granular high charge (50% or more), high molecular weight (5,000,000 D or higher), cationic polyacrylamides were always the cheapest solution, with the best performance, and lowest dosage needed for efficient flocculation. At high temperature (over 40^{o} Celsius) or high salinity (over 10, 000 micromhos/cm) cationic flocculants could not flocculate colloidal components anymore. Cationic polayamine coagulants were then used to overcharge colloids with the subsequent addition of granular or emulsion ultrahigh molecular weight polyacrylamides. Medium charge mole % (20-30%) or very high charge % flocculants (100%) were needed to achieve flocculation at high salinity.

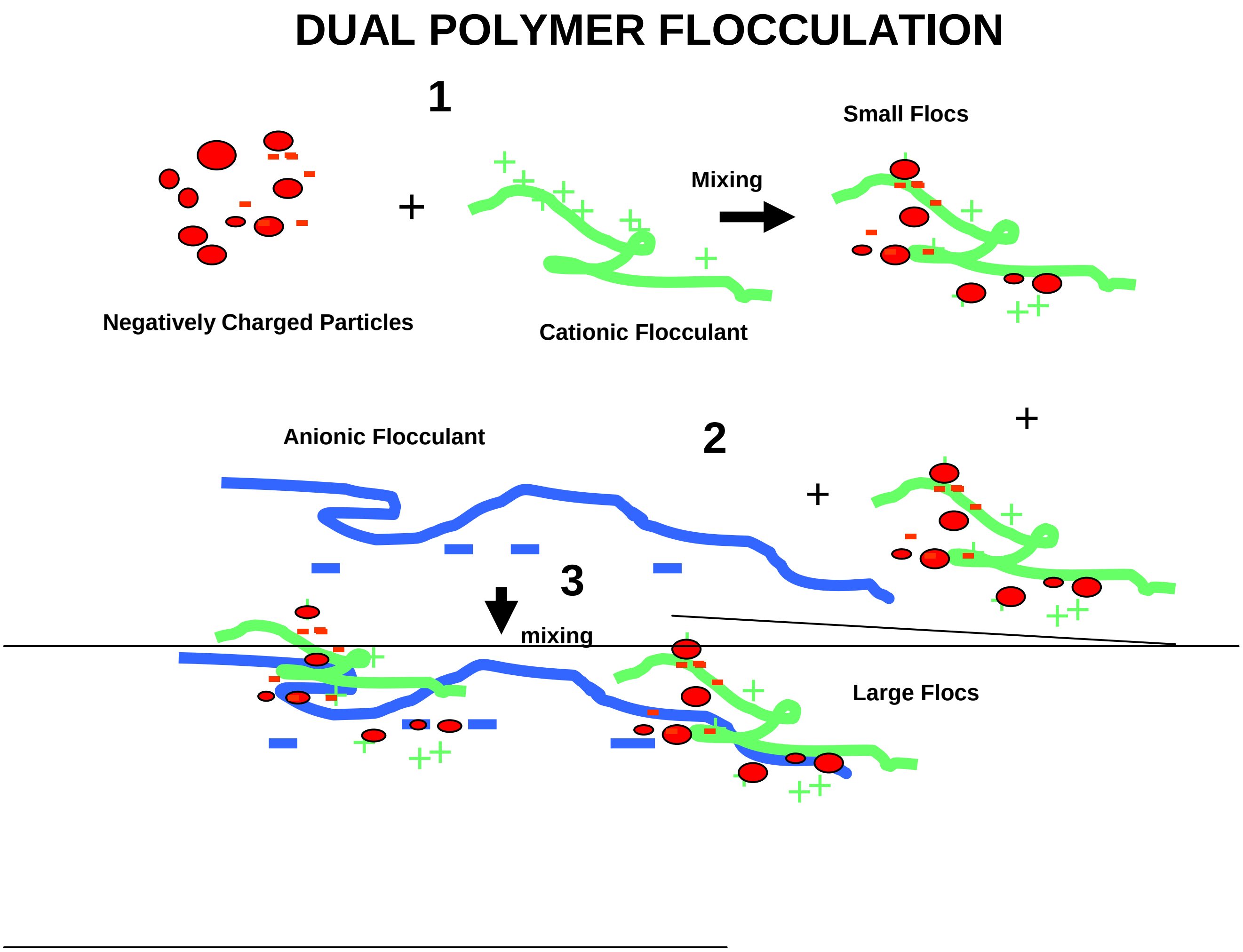

Figure 5. Dual polymeric flocculant approach.

UNCOILING (ACTIVATION) OF POLYMERIC FLOCCULANTS

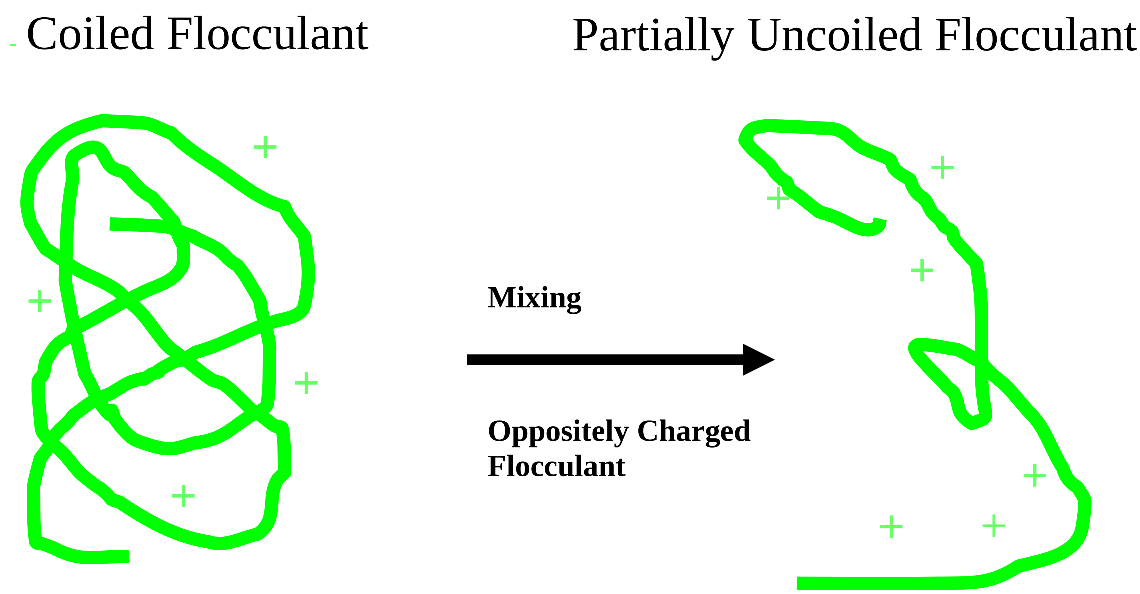

Figure 6. Uncoiling of high molecular weight polymeric flocculant molecules.

FULL SCALE INSTALLATION

A full scale GEM System running at 150 GPM was installed in the Fall of 2011. So far MLSS in aerobic reactor have reached 9,500 mg/l. Occasionally in Summer months MLSS are as high as 11,500 mg/l. Cationic flocculant (granular polyacryalamide C-=498 HMW from Kemira) dosage is 40 - 70 mg/l. System is run at an HRT of 4.5 GPM/ft^2. Average TSS after the GEM System is 25 mg/l with BOD 15 mg/l and FOG at 0 mg/l (no data for TKN). Average depth of sludge inside the flotation tank is 6 inches. By the Summer of 2014 we did experience TSS of up to 12,000 mg/l. If needed, System can be operated on a 24 hours/ 7 day basis. This would enable it to run at an HRT of 3 GPM/ft^2 if necessary. When this was achieved, it was the first time that a flotation System for MLSS removal was operated at full scale at loads as high as 15 lb/ft^2/hr. Currently the System is mostly operated at 12 lb/ft^2/hr, which is also above what the engineering community considers possible (maximum of 10 lb/ft^2/hr of MLSS).

The GEM System is a hybrid centrifugal - dissolved air flotation with aeration of 100% of the stream (no recycle). Solid/liquid separation occurs inside the solid/liquid hydrocylones and tanks are only used for skimming of sludge. Such design enables the System to run at higher HRT than classical DAF's . To achieve that with biosolids one has to use high molecular weight, high charge granular cationic polyacrylamides.

Additionally, a pressure release orifice has to be cleaned on average once a week to remove any solids deposits.

The Picture of the GEM System installed at the rendering plant is shown in Figure 7. Granular Flocculant is prepared automatically and whenever needed. Figure 8 illustrates such feeding System. Figure 9 shows the dimensions of the GEM System.

Figure 7. The GEM System installed at the rendering plant

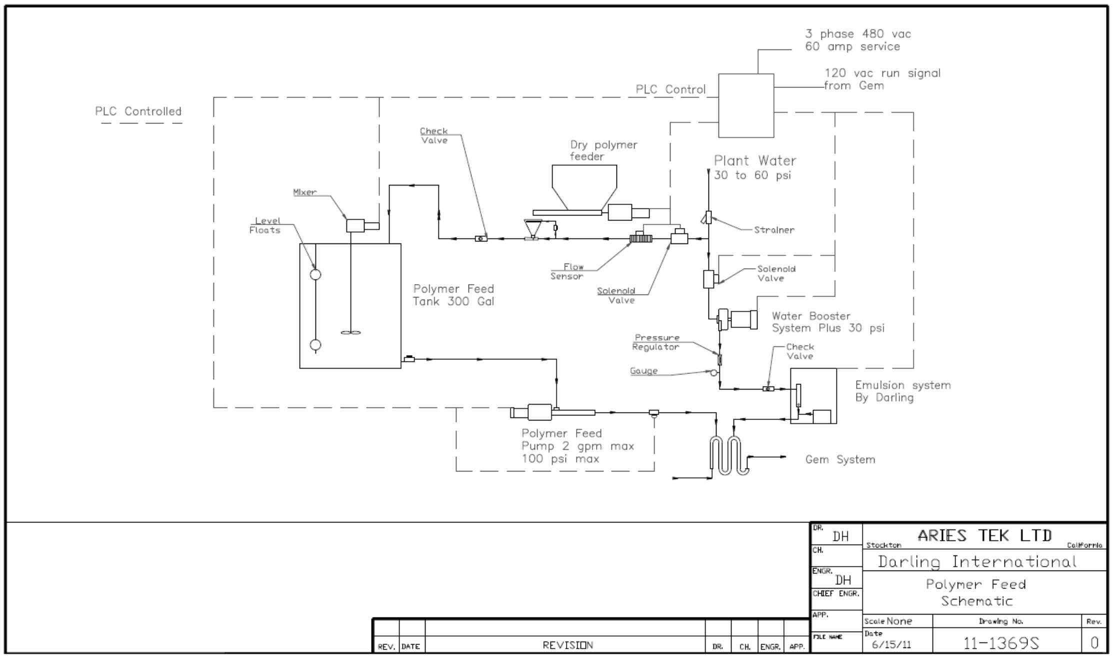

Figure 8. Automatic feed System for the granular flocculants

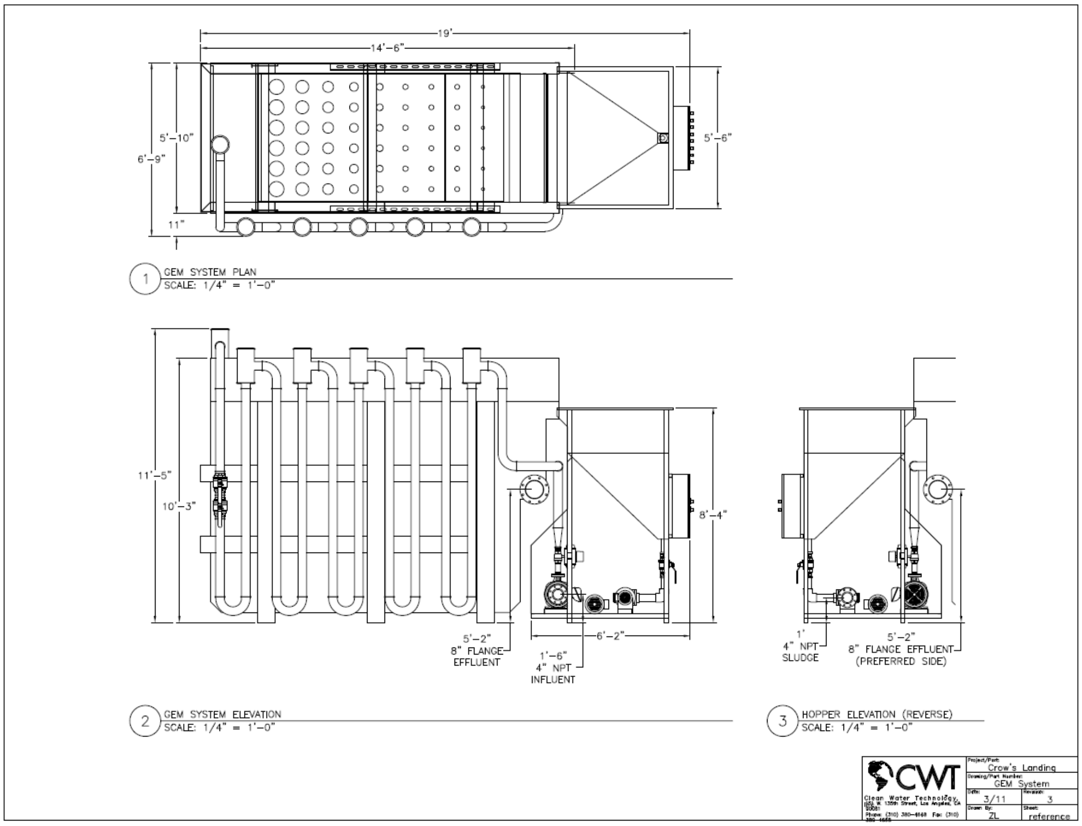

Figure 9. The Dimensions of the GEM System installed at the rendering plant