

THE DEVELOPMENT AND APPLICATION OF THE HYBRID CENTRIFUGAL – DISSOLVED AIR FLOTATION SYSTEM FOR WASTEWATER TREATMENT

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ABSTRACT

Solid/liquid separations are integral part of any wastewater treatment system. Particles heavier than water are commonly separated in sedimentation clarifiers. On the other hand, particles with densities lower than that of water are most often separated with flotation systems. This manuscript describes the development of hybrid centrifugal - dissolved air flotation system. The system was developed by combining high-energy centrifugal mixing of a liquid – liquid cyclone with pressurized dissolved air as a source of flotation bubbles. It is the only dissolved air flotation system in which 100% of the influent is aerated. Nucleation of bubbles occurs at the same time with nucleation of flocs inside the hydrocyclone columns. Solid/liquid separation occurs inside the columns under the influence of centrifugal forces. Tanks are only used for sludge skimming. Such design results in smaller footprint, sludge with higher solids content, lower coagulants and flocculants consumption and faster response times. These advantages are particularly important when using flotation as a pretreatment for membranes or bioreactors, since any overdose of chemicals can foul membranes or interfere with microorganisms metabolism. Classical hydrocyclone heads were also replaced with controlled mixing energy designed heads. Centrifugal forces with controlled mixing energy allow for application of high performance viscous flocculants and coagulants. Centrifugal vortex mixing is very efficient at activation of flocculant molecules and growth of large flocs without breaking either polymer chains or flocs.

KEYWORDS: solid/liquid separations, hybrid liquid cyclone – dissolved air flotation, membrane pretreatment

1-INTRODUCTION

Solid/liquid separations are commonly the first (primary treatment) step in any wastewater treatment. Such technologies are mature and new developments are rare. However, in the last decade some significant improvements in separation techniques for industrial wastewater pretreatment have been implemented. Advances in the technology include more efficient, faster centrifugal mixing of treatment chemicals and wastewater contaminants, “in situ” continuous flow coagulation and flocculation, implementation of very high molecular weight flocculants and development of more efficient flotation technologies.

Flotation is one of the most effective removal systems for suspensions that contain fats, oil and grease mixed with low density organic suspended solids and colloids. Flotation is a process in which one or more specific particulate (particular) constituents of a slurry or suspension of finely dispersed particles or

droplets become attached to gas bubbles so that they can be separated from water and/or other constituents. Gas/particle aggregates float to the top of the flotation vessel where they are separated from water and other non - floatable constituents.

Flotation processes in water and wastewater treatment are designed to remove all suspended particles, colloids, emulsions, and even some ions or soluble organics that can be precipitated or adsorbed on suspended solids. In this case, the process is optimized by the maximum recovery of cleaned water with the lowest concentration of contaminants. It is also often desired that the recovered sludge contain a high percentage of solids. Such solids can sometimes be recycled and reused. The design features and operating conditions of flotation equipment used for this purpose must be modified accordingly. It is evident that the processes causing water loss to the froth phase or migration of solids to the water phase must be minimized and appropriate conditions established for complete particle recovery.

Dissolved-air flotation (DAF) is the most common system in the treatment of oily wastewater (Bratby and Marais, 1977; Bratby et al., 2004). In DAF, a stream of wastewater is saturated with air at elevated pressures up to 5 atm (40-70 psig). Bubbles are formed by a reduction in pressure as the pre-saturated water is forced to flow through needle valves or specific orifices. Small bubbles are formed, and continuously flowing particles are brought into contact with bubbles. There is a price to pay for having such small bubbles (up to 20 microns): Such bubbles rise very slowly to the surface of the tank. This is the main driver of the large dimensions for DAF tanks. Final solubility of gas in water, even at high pressures, also results in fairly low air-to-water ratios. Air-to-water ratios of 0.15:1 by volume are common in DAF systems, and it is very difficult to achieve higher ratios. Therefore, classical DAF systems are not efficient in treating wastewater with more than 1% of suspended solids.

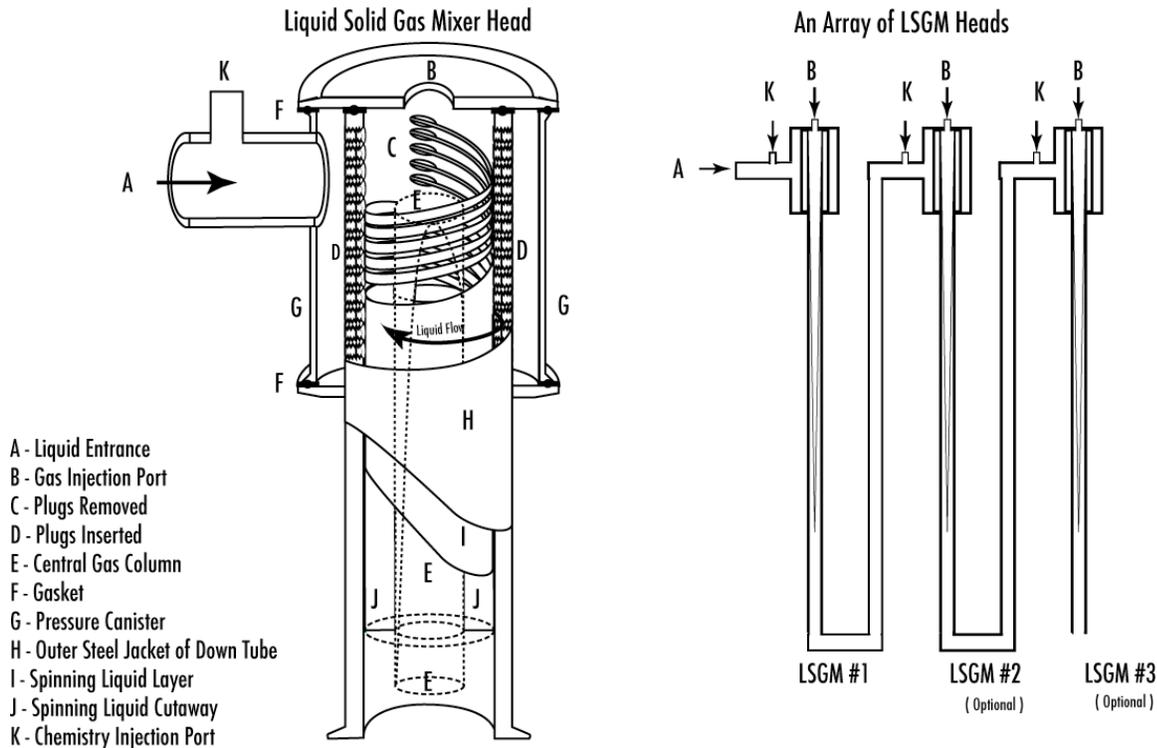
In dissolved-air flotation, bubbles are formed by a reduction in pressure of water pre-saturated with air at pressures higher than atmospheric and up to 120 psi. The supersaturated water is forced through needle valves or special orifices, and clouds of bubbles 20 to 100 microns in diameter are produced. Yet, to avoid clogging of such orifices with particles, only 20% of already cleaned water is pressurized and recycled to the wastewater stream. This results in a low-energy mixing of the main wastewater stream and the bubble stream. Treatment chemicals, coagulants and flocculants have to be added in mixing tanks upstream. As already described earlier, floc separation happens in this tank, which requires quiescent conditions and a large footprint (Kiuri, 2001).

One of the recent developments in flotation technology circumvented some of these problems. In particular, the air-sparged hydrocyclone (ASH) couples a porous cylindrical membrane with design features of a centrifugal liquid hydrocyclone (Miller, 1981). Gas is introduced through the porous membrane while wastewater is pumped through the hydrocyclone. Such a device is not dependent on the gas solubility and can introduce air-to-water ratios as high as 100:1. Because the bubbles are sheared off the wall of the porous membrane due to the high velocity and centrifugal forces inside the hydrocyclone, they are broken up into very small sizes comparable to those observed in the DAF. Thus, even though the ASH is essentially a mechanically sparged device similar to the early flotation devices, it does not suffer from similar problems (large bubbles). The ASH is one of the first centrifugal flotation techniques that was developed and applied in the treatment of wastewater. However, dissolved air still produces the smallest bubbles.

2-THE DESCRIPTION OF THE HYBRID CENTRIFUGAL-DISSOLVED AIR FLOTATION SYSTEM

We proposed that a more efficient flotation system 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 bubbles (Morse et al., 2001; Morse et al, 2004a; Morse et al., 2004b). Coagulants and flocculants can be delivered *in situ* directly into the flotation hydrocyclone unit. Pressurized air can be delivered to

Figure 1 – Schematic Presentation of the LCPP/LSGM



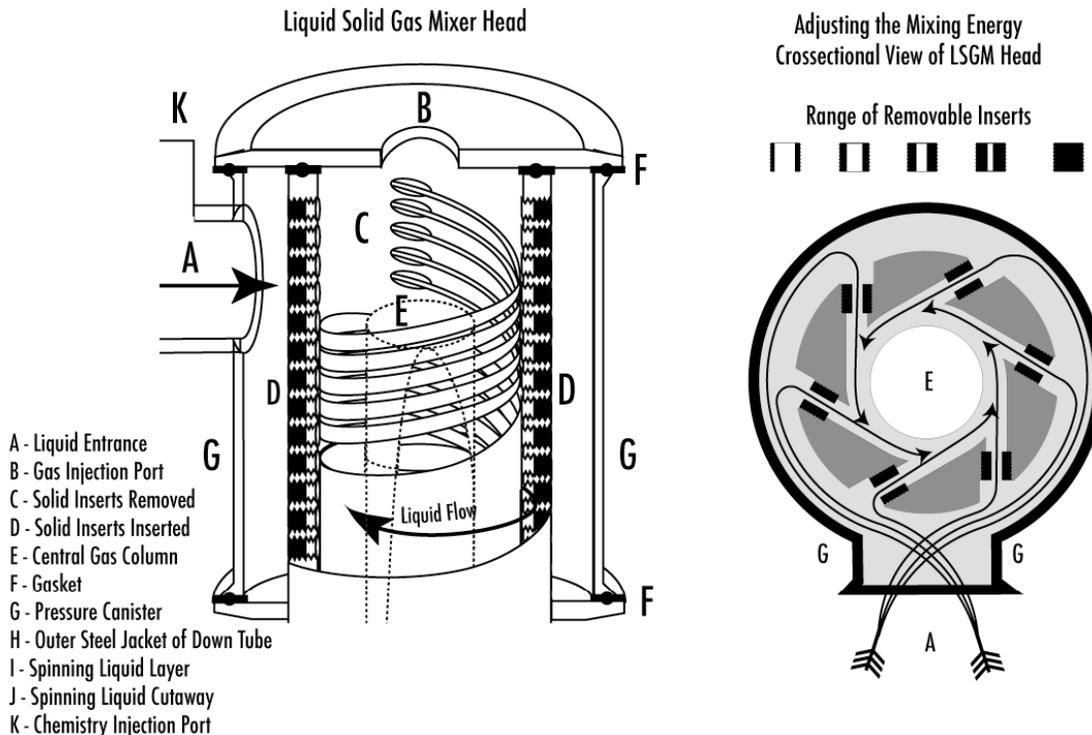
LCPP heads at the same time as flocculants. Such a procedure results in flocs, which are very porous and loaded with entrained and entrapped air.

As shown in Figure 1 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 2. 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.

Hybrid centrifugal – dissolved air flotation technology (The GEM System developed at CWT [see Figure 3]) 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

Figure 2 – Schematic Presentation of the LSGM Heads



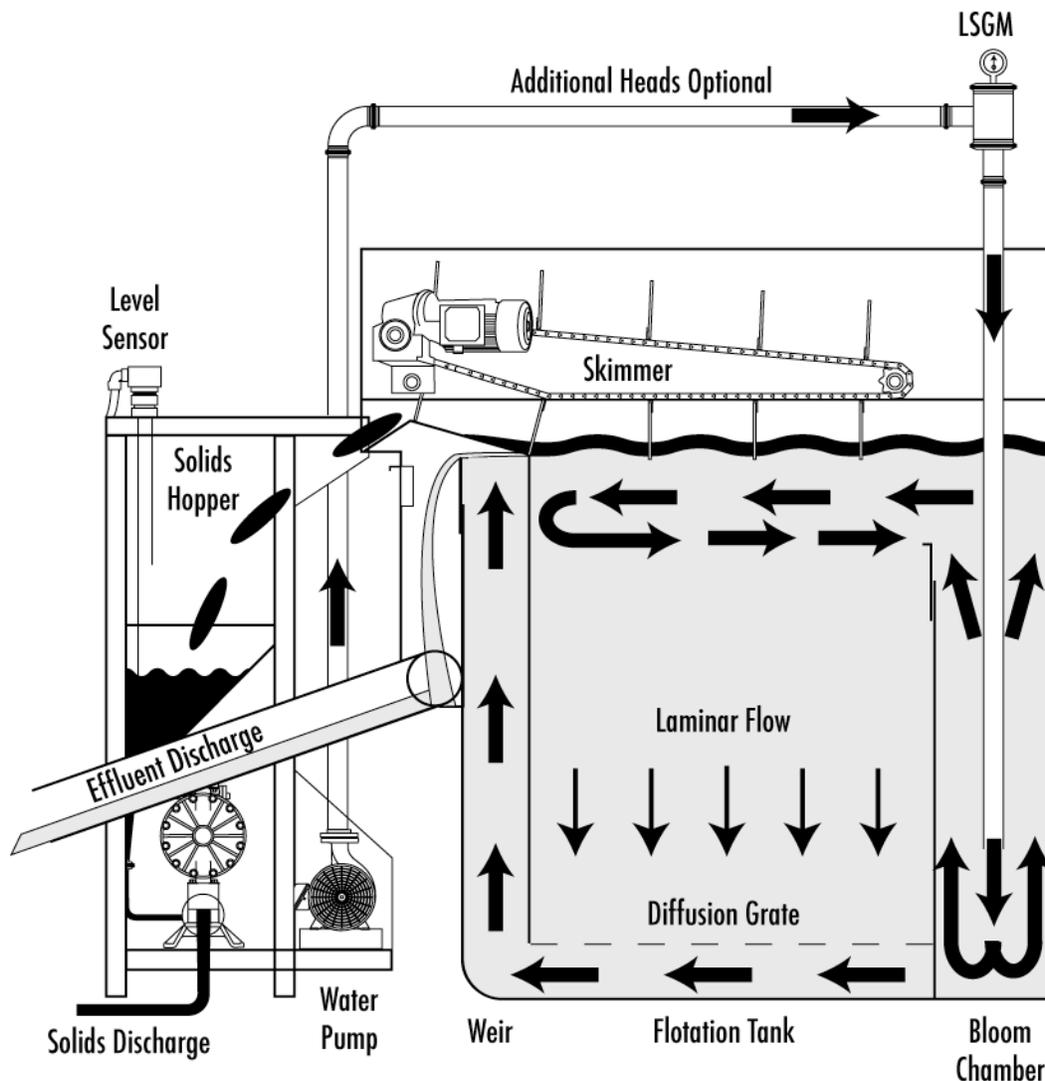
and treatment of the total wastewater stream (no recycling characteristic for DAFs). The design of on-line turbidity or fluorescence driven sensors for automatic control of coagulant and flocculant dosage is also underway. Computational fluid dynamics (CFD) has been used to design better flotation tanks with a vertical flow pattern that results in the formation of a dense air bed inside the tank (Ta et al, 2001; Desam

et al., 2001). Such fine bubble layers prevent sedimentation of already floated heavier particulates, which results in significantly higher flotation rates.

3-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 3 – 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 4).

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 (Carissimi and Rubio, 2005). 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 5).

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 polydiallyldimethyl 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° Celsius) or high salinity (over 10,000 micromhos/cm) cationic flocculants could not flocculate colloidal components anymore. Cationic polyamine 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.

DUAL POLYMER FLOCCULATION

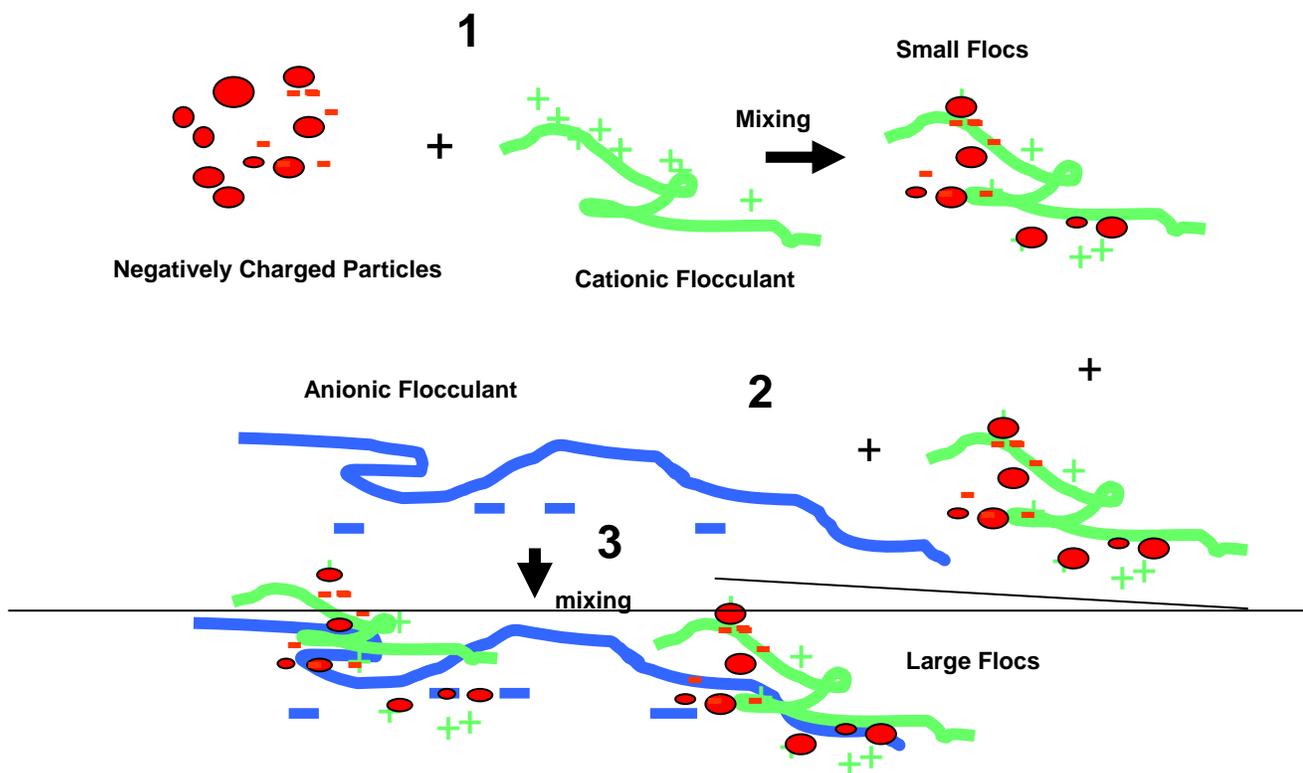


Figure 4. Dual polymeric flocculant approach.

UNCOILING (ACTIVATION) OF POLYMERIC FLOCCULANTS

Coiled Flocculant

Partially Uncoiled Flocculant

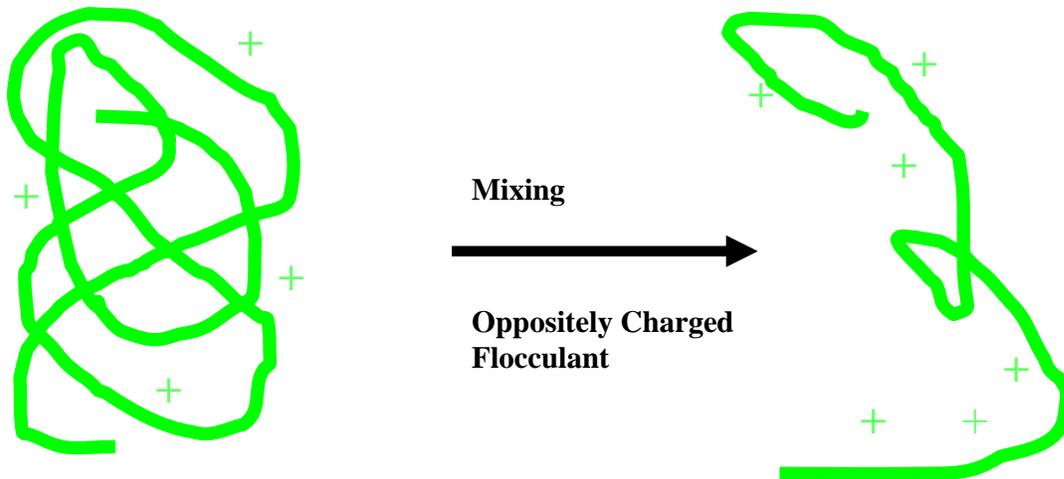


Figure 5. Uncoiling of high molecular weight polymeric flocculant molecules.

Examples of pilot plant and full – scale operating installations performance of hybrid centrifugal – dissolved air systems are presented in Table 1. It is customary to evaluate the performance of primary wastewater treatment systems as efficiency in removal of total suspended solids (TSS) [solids that remain on 1 micron filter]; and chemical oxygen demand, COD, measured according to USEPA Standard Methods of Wastewater Analysis. COD (organic materials that can be oxidized) can be in the form of particles, emulsions and large macromolecules (which can be removed with flocculation – flotation) or in the form of small molecules that cannot be removed with primary treatment. However, TSS and emulsions as well as free oils should be removed from wastewater prior to secondary or tertiary treatment. Secondary treatment (biological reactors) can remove small molecules much faster than oils, or TSS. Membrane separations are also significantly impaired with the presence of oils and TSS. Such materials cause membrane fouling and increase the cost of treatment (larger membrane surface area and cleaning chemical amounts needed). Another advantage of high efficiency controlled flocculant mixing with the GEM system is the ability to minimize presence of any free polymer molecules after wastewater treatment. Any free flocculant residual can and will adsorb on membranes, resulting in irreversible membrane fouling. Dual polymeric flocculant approach also ensures that any residual flocculant

molecules are anionic. It has been shown that since membranes are also negatively charged, anionic flocculants do not adsorb or cause any membrane fouling.

Table 1 - Examples of pilot plant and full - scale operating installations of GEM flotation systems

Type of Wastewater	TSS before	TSS after	COD before	COD after
Seafood processor	3,500 ppm	120 ppm	27,000 ppm	10,000 ppm
Seafood processor	28,000 ppm	150 ppm	62,000 ppm	12,000 ppm
Rendering plant	25,000 ppm	10 ppm	67,000 ppm	13,000 ppm
Food processing	1,500 ppm	35 ppm	12,000 ppm	3,000 ppm
Municipal	285 ppm	10 ppm	320 ppm	180 ppm
Juice processing	385 ppm	10 ppm	9,000 ppm	5,500 ppm
Salad dressing	120,000 ppm	10 ppm	150,000 ppm	12,000 ppm
Jeans washing	30 ppm	3 ppm	100 ppm	60 ppm
Laundry	5,500 ppm	5 ppm	24,000 ppm	3,500 ppm
Snack food plant	45,000 ppm	55 ppm	130,000 ppm	10,000 ppm

4-COMPARISON OF CENTRIFUGAL – DISSOLVED AIR FLOTATION WITH OTHER SYSTEMS

Wastewater treatment depends on many interdependent factors. These factors should be carefully considered when selecting and designing integrated water-treatment systems. Flotation devices are an

excellent choice for treatment of water contaminated with fats, oils, and grease, as well as particles with low density and particulates with tendencies to float rather than sediment, such as algae or biological sludge.

Total flow of wastewater to be treated per day, and peak flows at different times of day are to be taken into account when selecting a flotation system. For large flows and low contaminant loads at municipal wastewater treatment plants, classical dissolved-air flotation (DAF) devices are still the best choice (Bratby et al., 2004). DAFs can be scaled up to flows of more than 20 m³/min. Centrifugal flotation devices perform well at low and medium flows (20 l/min to 3 m³/min) (Rubio et al., 2002). Such systems are particularly efficient for treatment of industrial wastewater with high loads of suspended solids (TSS more than 5000 mg/l) and high loads of FOGs (more than 500 mg/l). Centrifugal systems have so far not been tested for sludge-thickening applications. Centrifugal flotation systems (CFS) have been quite successful in treatment of food-processing wastewater (snack-food preparation, dairy, rendering, chicken, beef, poultry processing, bakeries, breweries, sausages, sauces, mayonnaise, vegetable processing, fruit and juice processing, desserts, fish processing, corn food, potato food, etc.). Application of CFS in the treatment of petroleum, automotive, washracks, laundry, and textile wastewater has also been described.

Flotation system size (footprint) for a given flow of wastewater is commonly described in terms of hydraulic loading rates (HLR). In the SI system, the units of m³/h for flow and m² for equipment size and used; therefore, HLR units are m/h (flow divided by equipment area). The HLR values for various flotation systems are summarized in Table 2. The DAFs used in wastewater treatment usually have a low HLR, between 5 and 50 m/h. Centrifugal flotation systems can operate at HLRs that are an order of magnitude higher; therefore, such systems have a significantly lower space requirement. Additional space savings are achieved by *in situ* flocculation within the centrifugal mixing devices. As described earlier, fast mixing and flocculation in such systems occurs in seconds, as opposed to minutes in classical flocculation tanks.

The concentration of solids (solids loading) in the produced sludge is another important parameter to consider when choosing the appropriate equipment/strategy for solid/liquid separations in wastewater treatment. DAFs produce sludge with solids loading between 1 and 6%. Centrifugal flotation systems produce sludge with up to 20% solids. Ironically, this may produce a problem, since such sludge is very viscous and dries fast. Adequate pumps and sludge disposal equipment should be available; otherwise, sludge has to be diluted for further processing. More research is needed in how to efficiently remove concentrated sludge without disturbing the bottom layer and causing the transport of particulates into the clean water product (Bratby et al., 2004). No matter how efficient flocculation may be, incomplete transport will decrease the performance of the flotation system.

Average bubble size, size distribution, bubble stability, and rise time in tanks are also important parameters for flotation systems. Average bubble sizes for some common flotation devices are summarized in Table 3. Centrifugal forces inside CFS further reduce the average bubble size. Detailed measurements of average bubble size in the ASH system compared to bubbles produced with air sparging only, showed bubbles with almost an order of magnitude smaller diameter. Jet flotation (Clayton et al., 1991) also produces bubbles with average sizes that are 2 to 4 times smaller than those produced in other induced-air flotation (IAF) systems (Rubio et al., 2002). As explained previously, centrifugal forces in the CFS induce solid/liquid separation inside the chamber before water even enters the separation tank. Therefore, rise time for solids and bubbles inside tanks is much shorter, comparable to noncentrifugal flotation systems.

Table 2 - Average hydraulic loading rates (m/h) for some flotation devices used in wastewater treatment systems. Abbreviations used: IAF: induced-air flotation, DAF: dissolved air flotation,

ASH: air sparged hydrocyclone flotation, BAF: bubble accelerated flotation, GEM: gas energy management flotation, FF: flocculation-flotation

Flotation technique/system	Hydraulic loading rate (m/h)
IAF	30-500
DAF	5-50
Jet flotation	50-350
ASH	100-800
BAF	20-400
GEM	20-350
FF	140-2000

Table 3 - Average bubble size reported for some flotation systems used in wastewater treatment. Abbreviations used: IAF: induced-air flotation, DAF: dissolved air flotation, ASH: air sparged hydrocyclone flotation, GEM: gas energy management flotation, FF: flocculation-flotation, EF: electroflotation, CAF: cavitation air flotation (see more details in Rubio et al., 2002).

Flotation technique/system	Average bubble size, μ m
IAF	1000
DAF	20-50
Jet Flotation	300-600
ASH	80-200
GEM	15-40
FF	100
EF	15
CAF	30-200

5-CONCLUSIONS

Centrifugal flotation systems offer an alternative to traditional dissolved-air flotation with several advantages. The centrifugal flotation systems float contaminants more effectively than DAF, because all wastewater is treated in the centrifugal contactor. Centrifugal forces provide for very efficient mixing of contaminants, bubbles, and treatment chemicals. The hybrid dissolved-air centrifugal flotation systems such as GEM are particularly effective. The efficient mixing action inside the LCPP head means that very high-molecular-weight polymeric flocculants can be used for treatment. The tanks included in GEM systems are considerably smaller in volume and footprint than DAF tanks. This leads to savings in material costs and land usage. The fast response time of the GEM system (seconds) is also convenient for

rapidly changing industrial wastewater influent treatment (on-line chemistry dosage sensors). GEM systems have been installed and operated in a number of situations, of which only a few are mentioned here as examples. The GEM system performs exceptionally well for removal of FOG from industrial wastewater. However, removal of colloidal particles, including hydrophilic materials such as quartz, is also very efficient. Removal rates of over 99% of total suspended solids (TSS), 80% of chemical oxygen demand (COD), and 95% of FOG (over 99.5% of suspended emulsified FOG) are not uncommon. Soluble contaminants such as heavy metals or organics can also be removed if precipitated or adsorbed. The system operates best when used with the granular dual-polymeric flocculants to aggregate suspended particulates. *In situ* ultrafast coagulation and flocculation occur within the LCPP, with no need for additional mixing tanks. Modular mixing energy application inside the LCPP can mix low-molecular-weight coagulants at relatively high energy and high-molecular-weight flocculants at relatively medium or low mixing energies. The GEM system can be used to treat wastewater with up to 100,000 ppm of TSS, which is much higher than that treated by DAF.

Other centrifugal flotation systems such as flocculation–flotation (FF) (DaRosa and Rubio, 2005) or modified Jameson–jet flotation (Rubio et al., 2002) offer similar advantages. In spite of their many advantages, the above-described high-throughput, high-efficiency flotation systems have their problems. Air-handling pumps as well as modified centrifugal pumps use more energy when compared to classical DAFs (Ross et al., 2003). Closer tolerances of such pumps or heads of LSGM in the GEM system require good screening to remove large particles such as sand that can cause wear and reduce pump lifetime. To achieve the high removal efficiency of contaminants and sludge with high solids loading, more expensive high-molecular-weight polymeric flocculants have to be used in systems such as GEM or FF. Development of coagulant and flocculant dosage systems that respond to changes in wastewater properties is also needed to fully automate such fast response systems without loss of efficiency.

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