New Developments in Mixing, Coagulation, Flocculation and Flotation for Industrial Wastewater Pretreatment

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Abstract

Solid/liquid separations are a mature technology area and few new developments occurred in seventies and eighties. However, last decade witnessed appearance of a significant number of new innovative systems in this field. (Rubio et al., 2002) This paper describes new developments in mixing, coagulation, flocculation and flotation systems for industrial wastewater treatment. (Ross et al., 2000; Desam et al., 2001; Morse et al., 2001; Morse et al., 2004a; Bratby et al., 2004, Kiuri, 2001, Colic et al., 2005) Case studies and design details will be discussed. New high throughput flocculation and flotation systems have successfully been tested and installed for applications in industrial high strength wastewater pretreatment, municipal sludge thickening (including thickening of combined primary and secondary sludge), agricultural wastewater treatment and drinking water treatment. Recent applications of flotation technology have occurred in pretreatment of water ahead of membrane separation systems or bioreactors. Post treatment of wastewater after aerobic, anaerobic and moving bed biofilm reactors has also been tested and implemented. Suspended solids and fats oil and grease can now be removed from wastewater that is up to 500 times more concentrated in solids and colloidal particles, such as emulsified oils, than municipal wastewater. (Colic et al., 2001, 2005, Ross et al., 2000) We will also discuss advances in mixing of coagulants, flocculants and other treatment chemicals with wastewater contaminants in flotation system. High energy mixing in some novel systems is also used to further reduce size of bubbles in flotation systems. New air - handling pumps can introduce air into water much more efficiently, with close to 100% efficiency and pressures up to 120 psig (Ross et al., 2000). Computational fluid dynamics (CFD) is used to optimize fluid flow conditions in flotation tanks for maximum clarification with minimum chemical dosages. (Desam et al., 2001). It is also possible to add flocculants "in – situ" inside flotation aeration and mixing system. This enables nucleation of bubbles and flocs at the same time. (Morse et al., 2004a,b; Colic et al., 2005) Systems that can respond within seconds to changes in wastewater composition and adjust dosage of chemicals needed to treat wastewater have been developed. One of the remaining challenges is to reduce cost of treatment – chemical dosage and energy consumption in flotation systems. More detailed discussion of some of these developments will be presented below.

Keywords: wastewater pretreatment, flotation, mixing, flocculation, coagulation, sludge thickening

Introduction

Solid/liquid separations in wastewater treatment processes are one of the main markets for inorganic as well as organic coagulants and flocculants. Inorganic coagulants dominate drinking and municipal water treatment markets. On the other hand, high strength industrial wastewater often contains significant amount of emulsified oils and fine light organic suspended solids. Polymeric coagulants and flocculants are often needed to successfully treat (clarify, thicken and dewater) such wastewater streams. While mixing of inorganic coagulants with drinking and low strength municipal wastewater is rather straightforward, many recent developments occurred in mixing, coagulation, flocculation and solid-liquid separations, such as flotation, of high strength industrial wastewater. In this presentation we will review some of these new developments.

The goal of water and wastewater clarification is to remove insoluble contaminants from water streams. Such contaminants include suspended inorganic and organic particles and colloids (particles with the diameter less than one micron). Industrial wastewater influents often contain stable oil in water emulsions mixed with particles. It is well known that it is difficult to remove fine colloidal particles and highly emulsified oil from industrial wastewater. Often, industrial wastewater bears tens of thousands of milligrams per liter of such contaminants.

Clarification of such wastewater streams removes suspended and emulsified matter through coagulation, flocculation and solid liquid separations (flotation, sedimentation or filtration). Coagulation is the process by which colloidal particles are destabilized by neutralizing their surface electrical charge. Attractive surface forces such as van der Waals forces, hydrophobic forces or hydrogen bonds can bring these destabilized particles together and form small pinpoint flocs. Often, larger flocs are needed for faster solid – liquid separation processes. Flocculation is the process of agglomerating such small, destabilized particles and aggregates to form large, strong flocs that are shear resistant and can be efficiently separated with solid –liquid separations.

Numerous solid-liquid separation techniques are applied in wastewater treatment but sedimentation, flotation and filtration are most common. Heavier particles such as inorganic mineral solids sediment fast and are commonly removed with sedimentation clarifiers. On the other hand, organic materials such as fats, oils, grease or organic suspended solids and dispersed colloids are lighter than water and have natural tendency to float rather than sediment. Flotation is a process in which one or more specific particulate 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.
Filtration through media with certain pore size is usually used only as polishing step to remove small amount of suspended flocs and particles, with concentrations often not more than 50 mg/l.

Suspended particles, colloidal dispersions and emulsions in industrial wastewater are predominately negatively charged. Both inorganic and organic coagulants can be used to neutralize these charges. Inorganic salts of aluminum, iron or calcium can be used to destabilize such contaminants by neutralizing such charges. Iron and aluminum salts further hydrolyze to form insoluble precipitates that can entrap the particles. Alternatively, water soluble cationic

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low molecular weight, high charge polymers can be used to neutralize particle charge. Combinations of inorganic and organic coagulants (blends) are also commonly used. While inorganic coagulants are cheaper, there are many advantages of using organic polymeric coagulants: a) polymeric coagulants are effective over wider range of pH, b) no iron or aluminum residue in effluent, c) reduced volume of sludge, d) easier sludge dewatering – less hydrophilic sludge, e) decreased dissolved solids, f) sludge that can be used as animal feed – lower cost of disposal.

Cationic flocculants are high molecular weights, broad range of charge and structure (linear, branched, partially hydrophobic). Typically, most synthetic flocculants used nowadays in industrial wastewater treatment are cationic polyacrylamides with incorporated functional cationic monomers incorporated into the polymerization process to form copolymers of varying degrees of ionicity (charge%), from 5 to 60%. Molecular weights of cationic polyacrylamide available are from 1 to 20 millions Dalton. Charge densities range from less than 1 to 5.5 meq/g. Cationic flocculants produce flocs with unparalleled size and strength. Any high energy solid – liquid separation such as centrifugal flotation or centrifugal sludge thickening cannot operate without application of such polymers.

Cationic polyacrylamide flocculants are manufactured as emulsions, granular powders or dispersions (water or oil based). Emulsion and granular polymeric flocculants are basically made of billions of tiny, tangled bundles that are dry in the center. The polymer must first be activated (dissolved in water). Further, once in water the polymer must be untangled and those bundles fully hydrated. Then, single polymer molecules must be uncoiled and partially linearized to uncover charged sites so that it can bind with the oppositely charged particles and form large flocs. The dissolving, hydration, uncoiling and untangling processes must be efficient to create successful flocculation. Fully activated polymer chain can attach itself to hundreds of smaller particles to create large strong flocs.

Same principles apply for flocculation process. Flocculation of suspended particles takes place after mixing with polymeric flocculant. Polymer activation is followed by adsorption with subsequent floc buildup. As in the case of polymer water mixing, the flocculation process must be efficient to enable successful solid – liquid separation.

High energy mixing is needed in the first stage of both polymer dissolution and polymeric flocculation. Prolonged, high energy mixing results in polymer chain breakup and floc breakup. (Colic et al., 2005) Low energy mixing is needed to prevent those processes. However, mixing must still have adequate energy to yield desired clarification of wastewater.

Mixing to dissolve polymer or achieve polymeric flocculation of suspended particles in wastewater can be achieved in batch agitated tanks or basins, with static mixers or dynamic in line mixers. Flotation and sedimentation processes have been designed with in line "in situ" mixing of flocculants during flotation or sedimentation process. (Morse et al., 2004a,b, daRosa and Rubio, 2005)

Historically, batch mixing in agitated tanks or basins was the only practical way to either dissolve polymers or flocculate contaminants present in the wastewater. The flow patterns in such vessels may be divided into two classes: axial flow from a propeller type impeller and radial flow from a turbine type impeller. The non-uniformity of agitation intensity and shear forces in such vessels is tremendous. Short circuit inside the vessels, dead zones with almost no mixing, high mechanical and electrical energy and gear box requirement and high maintenance cost are only some problem encountered with batch mixing systems. In addition long mixing time in batch mixers produces substantial breakage to the polymer chains, creating useless polymer remnants. Also, long mixing results in irreversible breakage of created flocs. (Colic et al., 2005)

Static mixers, sometimes called motionless mixers, consist of alternate internal structures juxtaposed to one another inside a pipe. Mixing occurs as the wastewater stream is forced through the pipe past the elements, which progressively divide and combine the flow stream. As a result, the homogeneity of the existing flow stream largely depends upon the geometry and the number of mixing elements within a unit. Static mixers do not have any moving parts. Therefore, they offer lower operating and maintenance costs. The application of static mixers may be successful in low viscosity mixing such as mixing acid, base, inorganic coagulants or diluted organic coagulants with wastewater stream. On the other hand, even a slight fluctuation in flow has a direct effect on the degree of mixing. There is no control or capability to change shear rate once the mixing energy is set by the design of the unit because pressure drop is a limiting performance factor in static mixing. Therefore, it may not be desirable to use static mixers for a process in which high or variable mixing energy is required for a short time, such as mixing of high molecular polymeric flocculants with wastewater contaminants.

In – line mixers typically consist of pipes or conduits through which wastewater is pumped towards the solid –liquid separation units. The main advantage of using in-line units is the possibility of taking advantage of the kinetic energy of transfer of the hydraulic fluid to promote the agitation needed to disperse coagulants or flocculants and promote flocculation. Curved configuration of circular tubes, such as bends and helical coils are commonly found in the industry. (Carisimi and Rubio, 2005) Secondary flow induced by centrifugal forces when a flow passes through curved pipes causes a movement toward the outside of the curve, giving more uniform mixing and gentle flocculation.

Modified in – line mixers consist of additional turbine or paddle –type impellers inside conduits, pipes or other mixing compartments. The above described axial mixing induced by fluid flow is combined with radial mixing from a turbine type impeller. This accomplishes complete mixing in rather short residence time. If shear rate of turbine mixers is changed, such mixers can also operate at controllable variable mixing energies. Furthermore, tapered mixing was developed for efficient, fast polymer dissolution and mixing. In such devices, after initial high shear mixing in impeller zone stream is subjected to continuously decreasing shear rates over a longer period of time. This zone includes a number of cylindrical concentric baffles, which creates a lengthened path for the stream to travel, while permitting the solution to swirl inside the cylinder. Such mixers are particularly efficient in dissolution and activation of polymeric flocculants. Several systems with similar principles have recently been developed for in – line flocculation and flotation of contaminants from wastewater streams. In such systems flocculants are added at the same time when air bubbles are nucleating. This results in simultaneous nucleation of bubbles and large stable air filled flocs. Such systems will be described later in this paper. In these systems axial mixing is combined with the radial swirl flow. One such system also introduced mixing heads that allow control of mixing energy independent of the incoming flow.

Sedimentation is one of the favorite gravity-separation methods to remove contaminants in water treatment. Most oils have low density and cannot be separated by sedimentation from water streams. Thus, flotation is a much more suitable technique to remove oil and particles with low density from water during or after de-emulsification. Flotation is a process in which one or more specific particulate 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. A recent review summarizes new developments in flotation as a wastewater treatment technique (Rubio et al., 2002).

It is particularly common to encounter wastewater that contains a mixture of suspended particles and stable oil emulsions. It is difficult to remove oily contaminants from wastewater and other natural and industrial systems containing oil. Oil can be present as a nondispersed surface layer, usually floating at the air/water interface. Such layers can easily be removed. On the other hand, if oil is present as a dispersed phase in the form of fine droplets (oil in water emulsions), separation is much more difficult. Many emulsions are stabilized with surfactants or other emulsifying agents. Modern emulsions often contain droplets, which are very small (size range of less than 10 microns) and stabilized with powerful emulsifying agents. De-emulsification and oil extraction from such systems present particular challenges. Moreover, such processes have to be economically feasible to be accepted by industry.

One of the key steps in the flotation method is the introduction of air bubbles into water. In early flotation machines, coarse bubbles (2 to 5 mm) were introduced into the contaminated water by blowing air through canvas or other porous material. In some impeller-based machines, air could be introduced from the atmosphere without compressors or blowers. This type of flotation, in which impeller action is used to provide bubbles, is known as induced-air flotation (IAF) and also produces fairly coarse bubbles. Such flotation methods are not suitable for wastewater treatment and oil extraction. Jameson (Clayton et al., 1991) developed an improved version of induced-air flotation, which was more successful in the removal of fats, oil, and grease from the wastewater. Another flotation method, called dissolved-air flotation (DAF), is much more common in the treatment of oily wastewater (Bratby and Marais, 1977; Kiuri, 2001). 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 this manuscript we will discuss some recent developments along with improvements in mixing, flocculation, flotation, tank design and sludge collection. Such developments enabled the application of flotation in pretreatment of high strength industrial wastewater.

New Developments in Mixing, Coagulation, Flocculation and Flotation

As it was described above, the improvements in mixing of coagulants and particularly flocculants with wastewater and flotation of contaminants to clarify high strength industrial wastewater are needed. Below, we will discuss new developments for better in-situ mixing of flocculants inside flotation units, improvements in flotation units design and performance and application of coagulants and flocculants dosage control units. Some case studies and current needs and further developments will be discussed.

Advances in DAF Design for Industrial Wastewater Pretreatment

Advances in DAF design include improved air saturation systems, recycle pressurization, flotation tank design, skimming and sludge handling design. Improvements in air saturation design have had perhaps the most dramatic effect on the design and specifications of DAF systems over the past two decades (Ross et al., 2000). Over the years most DAF manufacturers have made a transition from full-flow pressurization to recycle-flow pressurization for the creation of whitewater to induce flotation. Pressurizing the total wastewater influent to the flotation cell was possible only at low pressures below 50 psi, which limited the amount of air going into solution and number of nucleated bubbles. Coagulation and flocculation upstream of full-flow pressurization system exposes the flocs to high shear forces and turbulence inside the pressurization pumps, pressurization tanks and pressure control valve/orifice prior to entering the flotation cell (Ross et al., 2000). This tends to destroy flocs, thereby producing carry-over (particles in clarified effluent), thereby limiting the effectiveness of the system. Recycle pressurization involves pressurization of a sidestream of clarified effluent for return to the flotation cell. Systems with recycle pressurization can operate at higher pressures and minimize the destruction of flocs formed in the flocculation units.

Recently, hybrid centrifugal – dissolved air systems have been described, which overcome this problem and pressurize full-flow inside a centrifugal flotation chamber during simultaneous floc nucleation and bubble formation (Morse et al., 2004a 2004b, daRosa and Rubio, 2005, Carissimi and Rubio, 2005).

We will first discuss improvements in air saturation and bubble nucleation (whitewater) systems for DAF systems that occurred during the last few decades (Ross et al., 2000, 2003, Bratby et al., 2004, Kiuri, 2001). Most early DAF systems used centrifugal process pumps to force wastewater flow into a pressurization tank at a design pressure of less than 50 psi. Air compressors were used to produce compressed air at pressures 10-20 psi greater than the recycle pressure. Compressed air was then injected into the recycle stream somewhere between the pump discharge and the pressurization tanks. The combined pressure and retention time in the tank forced the air into solution. Water surface elevation under the layer of air was regulated. Typical saturator tanks include some of the following features (Bratby et al., 2004): packing within a tank to encourage turbulence and better mixing of incoming water with the pool of water inside the pressurization tanks, a mixer to provide turbulence and additional air/liquid contact, poor outlet configurations that allow large bubbles to escape, and variable speed pressurization pumps intended to allow operator adjustments of the air/solids ratio. All of the above features had some serious flaws, as described in detail in Bratby et al., (2004). For instance, packing within a tank allowed the formation of biomass, which plugged the tank.

While investigating problems with the classical DAF saturation systems, Bratby et al., (2004) made following conclusions: dissolution of gas in water is a simple and straightforward process, depending on the pressure, temperature, the solubility of gas in question in water and the surface area of the liquid available for gas transfer; the solubility of nitrogen in water is roughly half the solubility of oxygen, thus for air (78% nitrogen and only 21% oxygen), accumulation of nitrogen in the space above the water level in the pressurization tank rapidly lowers the efficiency of the water saturation with gas to 2/3 of the initial degree of saturation. Continuous venting to remove nitrogen from the headspace atmosphere is essential for process optimization and maintenance of process efficiency. Modifications of the water entering/exiting the pressurization tank systems are needed to avoid unstable hydraulics that could lead to vortex formation and rogue bubble formation in the pressurized flow discharged to the flotation tank, where such large bubbles can disrupt stability of the sludge on top of the tank, and result in carry – over of fine particles in the effluent. The details of the optimized saturation tank design are described in Bratby et al. (2004). In short, recycle wastewater from the pressurization pump enters the tank through a nozzle, sized for an exit velocity in the range of 12 to 18 m/s to provide sufficient energy to disperse the pressurized flow stream. Water droplets hit the top impingement baffle, which further enhances mixing of water and air. Water then falls to the bottom of the tank where it hits the bottom baffle, which prevents vortex formation and rogue rough bubble formation ("burping"). Nitrogen concentration in the headspace over the liquid is controlled via the continuous purging system, with timed bursts to vent off excess accumulated gas. Such modified whitewater systems work with air saturation efficiency close to 97%, as opposed to 65% or lower with the classical DAF air saturation systems.

Another notable improvement in the air saturation systems in DAF is the use of air-handling recycle pumps that can pressurize water with entrained air without causing cavitation or vapor lock (Ross et., 2000, 2003). These air - handling pumps include regenerative turbines and special multi-phased centrifugal pumps, which can handle limited air injection (10-20% v/v). The advantages of air-handling pumps include the ability to operate at higher pressures (up to 120 psi) vs 50 psi for traditional centrifugal pumps and higher air saturation efficiency due to high shear forces of the pump impeller. High pressure and higher saturation efficiency result in better volumetric efficiency (up to 250% more dissolved air per unit volume of recycle. The mechanical energy of the pump can also produce small bubbles from undissolved air in the pressurization solution. Pressurization tanks in such systems are only used to prevent rogue bubble formation and allow for venting excess air. Therefore, pressurization tanks in such systems can be much smaller. Finally, since air - handling pumps create vacuum suction at the location where air is injected air can be drawn from external ambient air or low pressure compressors. In traditional DAFs with classical centrifugal pump design compressed air must be supplied at 10 to 20 psi greater than the pump operating pressure. The major disadvantages of air-handling pumps are greater horsepower requirements and closer tolerances needed in manufacturing regenerative turbine pumps. Wear caused by solids in the clarified effluent can reduce pump effectiveness over time.

Another significant advance in the design of the DAF and other flotation systems happened in the area of flotation tank design. Multiphase computational fluid dynamics (CFD) models have been applied to optimize tank geometry and flow of water with suspended gas and flocs inside the tank (Ta et al., 2001). The general flow pattern has been compared with flow visualization using the underwater cameras and various soluble and insoluble dyes (green, red etc.). Comparison of average fluid velocity was carried out using acoustic Doppler velocimetry ADV measurements.

Such studies identified two major possible changes in the tank design that could allow much higher flow velocities without floc breakup and appearance of resuspended solids in the clarified water effluent. The first tank modification included the addition of square baffles inside the tank. The height, location and angle of such baffles have been varied until flow with low turbulence and minimum floc breakup was identified. Details of CFD calculations, and experimental tank design have been described by Desam et al., (2001).

Another recent development in flotation tank design has been the introduction of a false bed -- a thin stiff plate with numerous large round orifices above the real bed inside the flotation tank. Such plate has low flow resistance and modifies fluid flow inside the tank. In classical flotation tanks, the layer of bubbles thins along the length of tank. However, introduction of false bed results in vertical flow of water in the flotation space above the plate and distributes it evenly throughout the horizontal cross-section of the tank. This results in continuously regenerated thick micro-bubble bed in the tank. This bubble layer filters out any sedimenting small particles. The lower surface of the micro-bubble bed is really a horizontal one. It is located somewhat above the false bed plate controlling the flow in the flotation space. The clarified water below the micro-bubble bed is totally clear. It can be said that in such tanks filtering of particles through the micro-bubbles layer plays a crucial role in the removal of the suspended solids (Kiuri, 2001).

Centrifugal Flotation Systems: In – Line Mixing Flocculation and Flotation

As mentioned earlier, DAF systems have some serious limitations. While small bubbles used in such systems yield better contaminant removal efficiencies than induced air flotation or other flotation techniques, there is a price to pay for small bubbles: rise time of particles attached to bubbles is minutes, which results in long water residence time inside flotation tanks and a large footprint – tank size. The solubility of air in water and a necessity of recycling instead of full flow treatment limit the number of bubbles that can be produced in such systems. Until recently, these matters limited the use of DAF systems for applications in which high strength industrial wastewater was treated. Coagulation and flocculation are performed ahead of bubble nucleation. Therefore, bubble attachment is the only mechanism of particle removal. If gases could nucleate inside simultaneously nucleated flocs, more efficient processes can be developed. To address these and other limitations of DAF systems other flotation techniques have been developed and applied in industrial wastewater pretreatment.

In centrifugal flotation systems bubble particle contact occurs inside a column or liquid hydrocyclone chamber. The liquid wastewater stream is introduced tangentially into the column – chamber and centrifugal forces result in swirl flow with good axial and radial mixing. Air can be introduced into the column by air sparging, induction or pressurization – depressurization. Centrifugal forces further shear bubbles into smaller sizes and also produce excellent mixing of particles and bubbles during bubbles and floc nucleation. Since centrifugal forces are strong enough to cause efficient mixing and activation of coagulants and flocculants systems have been developed where treatment chemicals are added directly into centrifugal flotation chamber.

The air sparged hydrocyclone ASH was one of the first centrifugal systems used in wastewater treatment. (Miller, 1981) In this device gas is introduced through a porous cylindrical membrane, while wastewater is pumped through the hydrocyclone. Removed particles are forced through a hydrocylone overflow device known as vortex finder. This results in creation of concentrate stream with low solids loading and clean wastewater with some residual solids. Removal of vortex finder and reintroduction of flotation tank resulted in development of the bubble accelerated flotation, BAF. (Owen et al., 1999; Colic et al., 2001)

Further research resulted in the development of hybrid dissolved air – centrifugal flotation system termed gas energy mixing management (GEM).

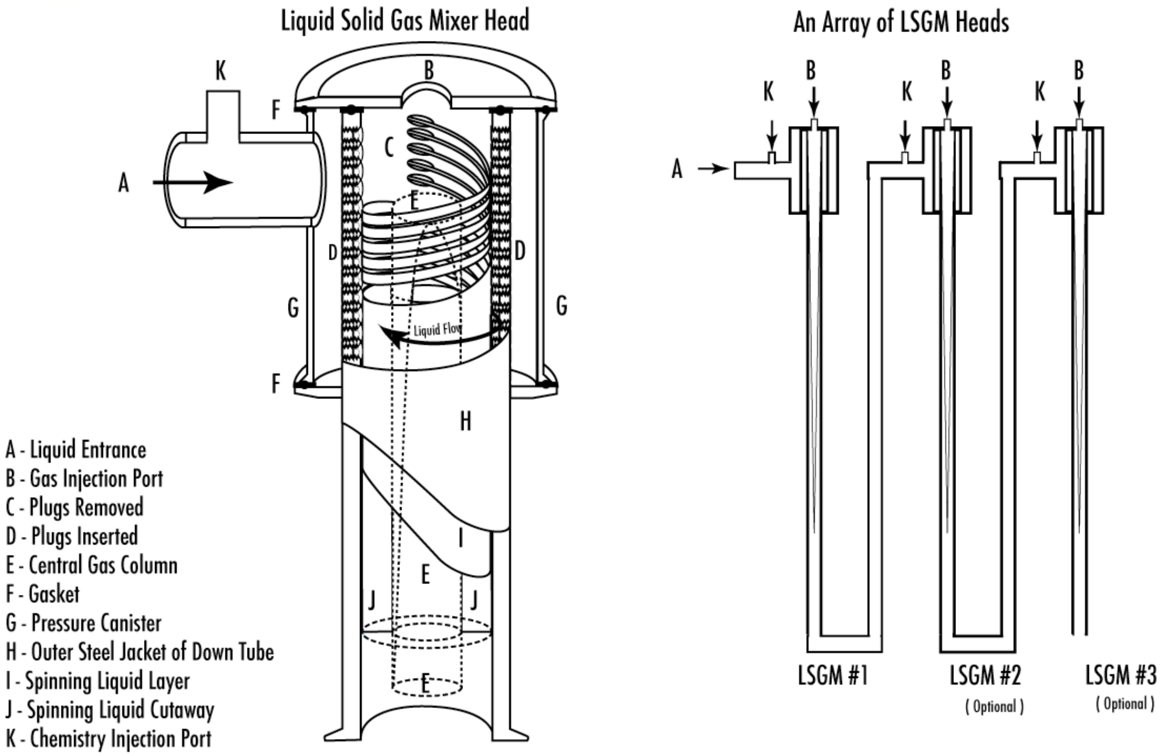


Figure 1 – Schematic Presentation of the LCPP/LSGM

As mentioned in the introduction, 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 up to 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.

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. As in the case of BAF, coagulants and flocculants can be delivered *in situ* directly into the flotation unit. The bubble chamber was replaced with the LCPP for more efficient mixing of treatment chemicals, which occurs during bubble formation and nucleation. Such a procedure results in flocs, which are very porous and loaded with entrained and entrapped air.

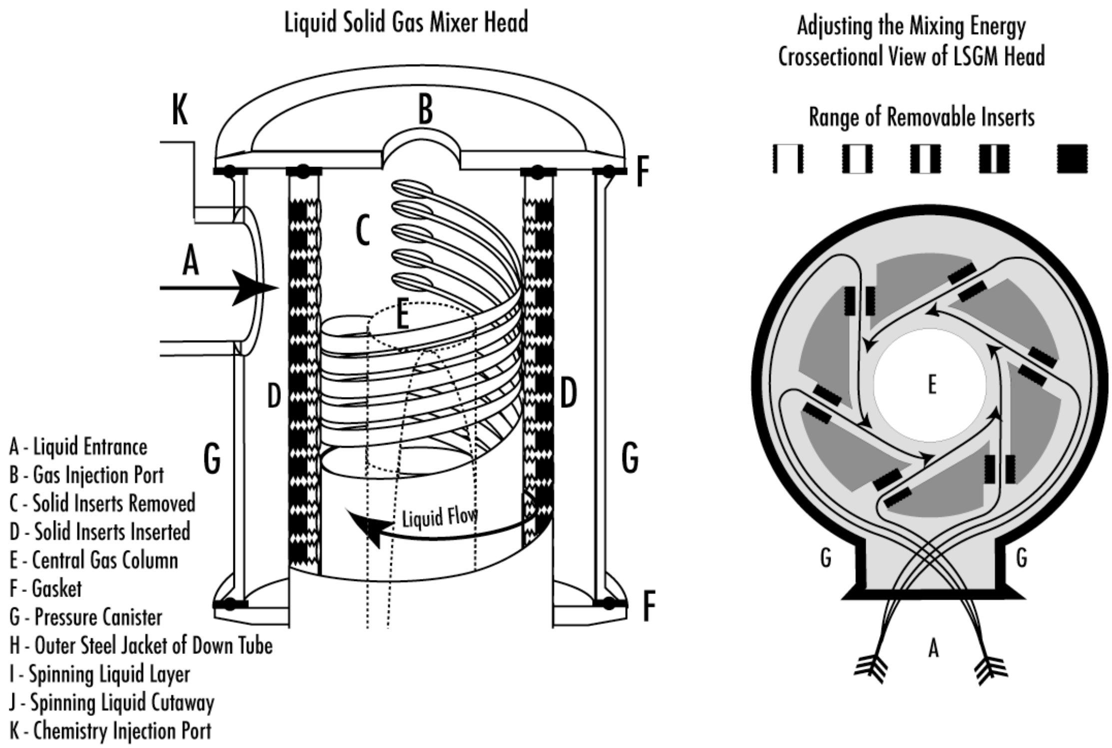
As shown in Figure 1 the LCPP also acts as a liquid-solid-gas mixer (LSGM). Replacing the classical hydrocyclone head with the LCPP provides extremely energetic mixing by sequentially transporting liquid and entrained particles and gas bubbles throughout a centrifugally rotating liquid layer. Microturbulence 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 is achieved in the LCPP. Such efficient mixing is important for proper flocculation of suspended particles.

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.

Figure 3 presents a schematic of the GEM flotation system. It should be noted that for the sake of clarity only one LSGM head is presented. If more treatment chemicals are added, the LSGM head can be used to properly mix every additional chemical at its proper mixing energy (one mixing head per addition). Water and gas are introduced into the LSGM on top and pumped through the LCPP chamber. After rapid mixing (seconds), pressure is released with the cavitation plate. Nucleating bubbles and flocs are well mixed. As mentioned before, this results in the formation of large flocs full of entrained and entrapped air. Such flocs are already separated from water inside the LCPP nucleation chamber. As flocs enter the tank, they rise quickly to the top where they are skimmed and sent to solids dewatering devices.

As compared to the ASH and BAF, the GEM system uses less energy, since there is no need for air blowers for air sparging. This also results in less noise. Controlled mixing energy produces stable flocs with much less carryover and higher solids loading. The footprint for this system is still only 10 to 20% of the classical DAF or clarifier devices. A blanket of small bubbles inside the tank acts as a "gas filter," filtering out clean water while preventing the transport of small pinpoint flocs into the clean water stream. Also, when wastewater with surfactants is treated, for some reason no foaming occurs inside the GEM system. Finally, it is possible to install sensors close to the nucleation chamber and observe any disturbance in flocculation performance almost instantaneously. This can be used to install turbidity-driven, chemical-additive dosage-control systems. Such

Figure 2 – Schematic Presentation of the LSGM Heads

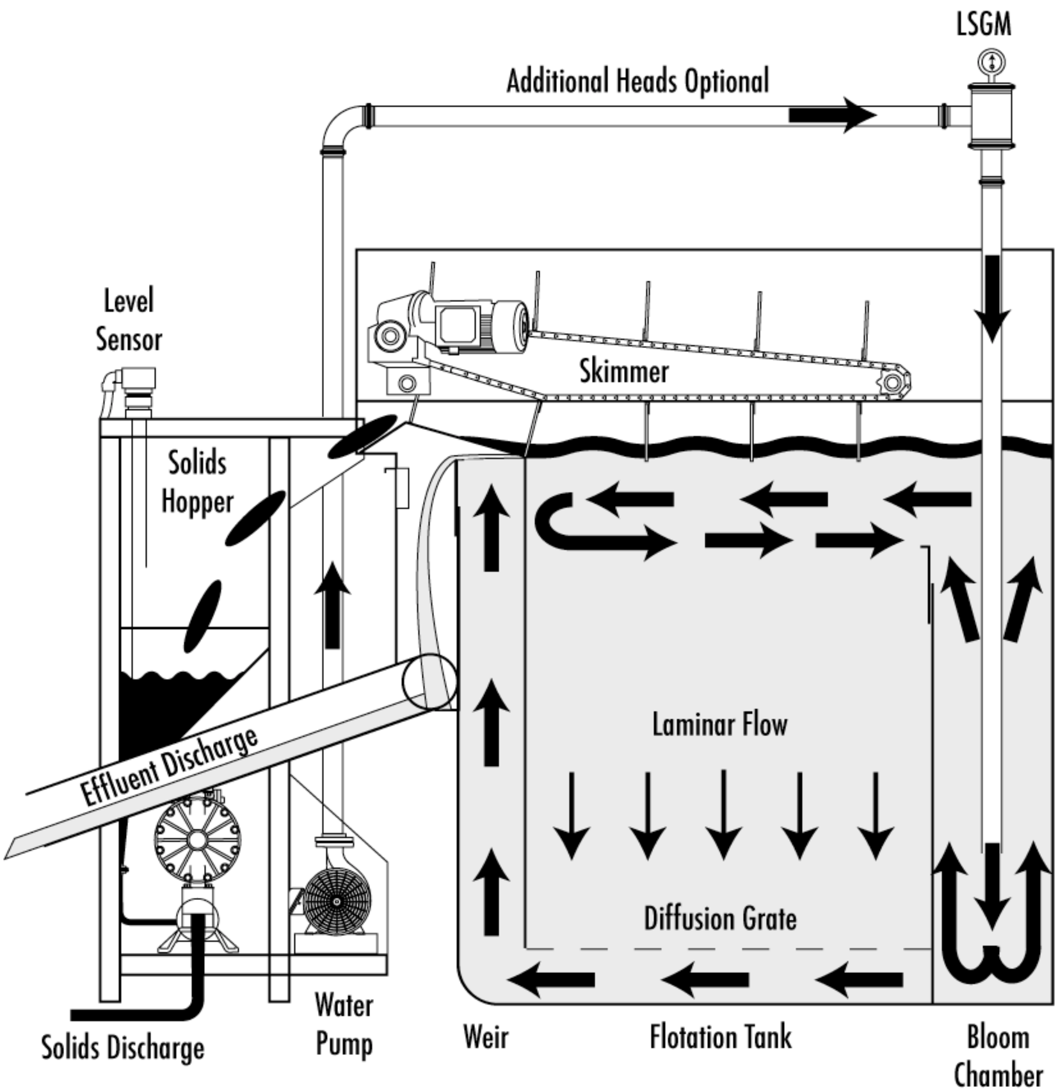


system
s can save significant amounts of money and produce a better quality of outgoing wastewater effluent. A detailed description of the GEM system can be found in Morse et al. (2004a, 2004b).

Other Centrifugal Flotation Systems

Swirl flow of fluids and mixing with coagulants, flocculants, and air bubbles occurs inside the air-sparged hydrocyclone (ASH) and other derived centrifugal flotation systems (CFS). Several versions of inverted ASH with upward water flow have been reported. Hydrocyclone flotation systems with induced or dissolved air have also been tested. All these techniques incorporate a vortex finder similar to the classical ASH with

Figure 3 – Schematic Presentation of the Hybrid Centrifugal – Dissolved Air Flotation System



the attendant problems discussed earlier. The advantage of such techniques is that they do not use large separation tanks. This results in a smaller footprint and reduced cost of equipment compared to BAF, DAF, and induced-air flotation.

Modified versions of the jet (Jameson cell) flotation system (Feris et al, 2004) have also been developed and applied. In a recent advancement of the Jameson cell technology, a new "low shear" method is used to mix the air, untreated wastewater, and flocculants. Untreated wastewater and flocculants are gently introduced into the top of the cylinder used for centrifugal mixing (termed the downcomer for Jameson cell systems). A portion of the clean effluent is recycled back into the top of the downcomer. The recycle effluent passes through an orifice, accelerating the liquid to produce a simple liquid jet. The kinetic energy of the jet results in air being entrained into the downcomer in much the same way as air might be entrained into a bucket of water using a hose. Air is dragged down into the liquid and broken up into small bubbles by the turbulence in the top of the downcomer. The Jameson cell thereby utilizes the energy of the fluid to induce air into the cell, rather than requiring an external compressor or blower. As in the case of the BAF system, the presence of air bubbles at the time of flocculation is extremely beneficial, as it results in the bubbles being entrapped within the actual floc structure. The incorporation of bubbles in the floc structure provides buoyancy and allows particles to be floated independent of their surface characteristics. The downward velocity of the bubble/liquid mixture in the downcomer is designed such that all bubbles have to descend and emerge into a reservoir (or cell) at the bottom of the downcomer. The reservoir acts as a disengagement zone, allowing the aerated floc structures to float to the surface to form a sludge layer. As in the case of BAF and GEM, separation already happens inside the centrifugal force column (in this case downcomer). The sludge overflows the reservoir into a launder, whilst the cleaned effluent passes to the next stage in the process.

Another turbulent *in situ* centrifugal flotation system, termed flocculation flotation (FF), was recently developed (daRosa and Rubio, 2005). As in the case of GEM, BAF, and the modified jet-flotation cell, polymer and air are added at the same time inside a centrifugal mixing system. Dissolved air is used for smaller bubbles. As in the case of BAF and the GEM system, large flocs entrained with air develop when high-molecular-weight flocculants are used. Multiple cylinders around the downcomer are used, similar to the modified jet-flotation cell. The air excess leaves through the centrifugal cylinders at the top, and the flocs float very fast within seconds after leaving the downcomer cylinder. A novel flocculation and helical mixing system has also been developed by the same group (Carissimi and Rubio, 2005).

Examples of performance of centrifugal flotation systems are described in detail in (Colic et al., 2005, daRosa and Rubio, 2005). Numerous approaches were used to coagulate and flocculate particulates in wastewater prior to the BAF or GEM treatment. The pH of the suspension is usually adjusted close to the pH of the isoelectric point to reduce consumption of coagulants (charge neutralizing agents). The residual charge is then partially neutralized with either inorganic coagulants or low-molecular-weight cationic polymers (polyamines, polyDADMACs etc.). Dual-polymer flocculation with high-molecular-weight (HMW) cationic and anionic polyacrylamide flocculants (PAMs) is then performed. Dual-polymer flocculation with HMW PAMs yield large, stable flocs, which float very efficiently inside the BAF or GEM tank. We also observed that if the main portion of the charge is neutralized with low-molecular-weight cationic coagulants, the BAF or GEM performance is not as good. Among the most efficient polymeric flocculants used were Cytec's C-498 HMW cationic polyacrylamide with ultrahigh-molecular-weight (>5,000,000 D), and 0.55 charge density, and Cytec's anionic polyacrylamide A-130 HMW with-molecular-weight estimated to be over 7,000,000 D. When animal feed applications of the collected sludge are desired, Cytec's "GRAS" (generally regarded as safe) polymers, such as 234 GDH cationic moderate-molecular-weight polyacryalamide, are used. When necessary, emulsion polymers were also used with the BAF or GEM system. Dual-polymer flocculation also results in very low residual polymer concentration in the effluent. This is particularly important, when flotation is used as a pretreatment ahead of membrane separation processes. Membranes are particularly sensitive to fouling with cationic polymers.

It was also observed that high-molecular-weight polymeric flocculants can be added directly into the bubble chamber head or LCPP of the GEM system. Large batch mixing tanks or floc tubes can therefore be avoided. Powerful vortex mixing and wall effects inside the bubble chamber tube result in better uncoiling of polymers with minimum polymer and floc breakage. HMW flocculants can therefore achieve superb flocculation inside the bubble chamber or LCPP. This often results in the formation of large flocs with diameters of up to 10 cm. The flocs are very stable, with high solids loading of between 10 and 30% upon short drainage. The best flocs are usually produced when using a combination of HMW cationic and anionic flocculants. Fan et al. (2000) show that dual-polymer flocculation actually results in more efficient uncoiling of the HMW polymeric flocculants. The uncoiled flocculant chains then act as better bridging agents. Vortex mixing inside the centrifugal field within the bubble chamber seems to enhance this process. Additional research should be performed to investigate these processes.

Successes and Current Needs to Improve Solid – Liquid Separations in Industrial Wastewater Treatment

New generation of mixing, flocculation flotation, sedimentation and filtration equipment can successfully treat high strength industrial wastewater with significant amounts of FOG's. However plants operators still report some problems that need urgent solutions. Following are some of the current needs to enhance existing technologies:

1) Proper screening prior to solid-liquid separation. If screens to remove large objects and particles are too fine plugging and subsequent overflow of large objects results in system failures and maintenance nightmares. Too coarse screens result in fibers and medium size objects presence in the wastewater entering flotation or sedimentation equipment. Choosing a proper screen size and mesh at acceptable price is often quite tricky. New generation of self - cleaning screens and screen filters can solve some of these problems. However, price of such screens is still quite high.

2) Coagulant and flocculant dosage control. Industrial wastewater streams often change hourly, daily and seasonally. Operators have to use classical jar test to adjust the dosage of coagulants and flocculants. However, plant operators are often too busy to react promptly. Automatic systems that identify changes in strength of incoming wastewater streams and modify coagulants and flocculants dosage are badly needed. Such systems for drinking water and light municipal and industrial wastewater already exist, but water rich in FOG's and TSS still present a challenge. Current dosage control systems use turbidity, particle charge (zeta potential as measured with streaming current monitors) or particle size as control parameters measured. All of the above mentioned sensors can fast be coated by oil and grease. One possible way to avoid this would be application of surface scattering turbidimeters. Optical components in such turbidimeters never touch the sample – this results in sensor that is virtually maintenance free. Wide measurements range – such instruments measure turbidity from 0 to 9999 NTU. Surface scatter design also reduces interferences and is easy to calibrate. Ideal dosage control sensor will measure both influent and effluent turbidity and use intelligent module to decide whether to increase or decrease the coagulant or flocculant dosage.

3) Flocculants that are already dispersed and activated. Most plant operator complain about the preparation and activation of granular or emulsion polymeric flocculant solutions. Often mistake occurs such as inadequate mixing and activation or empty polymer tanks and dry runs of dosage pumps, which result in pump damage. Dispersion polymer can directly be diluted and pumped. Brine dispersions do exist but are still expensive and not as efficient as granular polyacrylamide flocculants. Manufacturing a cost efficient high molecular weight high performance dispersion polyacryalmide flocculants is a challenge for the chemical industry. Better, more reliable and economically feasible dry and emulsion liquid polymer activation and feed systems are also needed.

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