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Flotation in water and wastewater treatment and reuse: recent trends in Brazil

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Abstract: This paper summarises environmental applications of conventional and unconventional flotation to remove pollutants from waters. Emphasis is given to the design features of innovative inline reactors, namely the Flocs Generator Reactor and Flocculation-Flotation, and their applications for the flocculation and flotation in solid-liquid separations involving water (and wastewater) treatment and reuse. Applications are shown in potable water clarification, treatment and water reuse from car washing units and in the treatment of acid mine drainage. Results show that these inline flocculation (or flotation) separators have a great potential for water/wastewater treatment and reuse, especially in applications requiring high rate solid-liquid separations.

Keywords: flotation; flocculation; water reuse; wastewater treatment; water.

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Introduction

Flocculation and flotation processes in the mineral industry are originally designed to separate one particle type from another whose density is lower or has been made lower than the suspending liquid. Flotation process is known for a century in the mining and metallurgical area, and there have been rapid developments of devices and techniques being applied in drinking water plants and in many wastewater treatments.

Flotation in wastewater and domestic sewage treatment is known, for a number of years, by civil, chemical and environmental engineers, especially DAF or dissolved air flotation, which offers process advantages over filtration, precipitation, adsorption onto natural and synthetic adsorbents. Advantages include better treated water quality, rapid start up, high rate operation, and a thicker sludge (Féris *et al.*, 2001; Rubio, 2001, 2003).

The high development in the area and the new upcoming applications outside the Scandinavian countries, where this technology is very well known, resulted in the organization of more specific conferences and congresses.

- 1994: IAWQ-Flotation processes in water and sludge treatment. Orlando, Florida-USA;
- 1997: IAWQ-Dissolved air flotation technology in water treatment – an art or a science? International Conference, London and;
- 2000: IWA. The 4th International Conference Flotation in Water and Wastewater Treatment, Helsinki.

In parallel two strategic workshops took place in the last five years where the idea was to stress the exchange of flotation experience in mineral flotation and in water and effluent treatment:

- 2001: EUF-Engineering Science Foundation-Froth flotation-DAF-Dissolved air flotation-Bridging the gap, Lake Tahoe-California, 2001 and;
- 2002: Flotation + Flocculation: From Fundamentals to Applications. Strategic Conference and Workshop, Hawaii.

Mavros and Matis (1992), Matis (1995), Rubio *et al.* (1998, 2002, 2003), Voronin (1998), Parekh and Miller (1999) and Matis and Lazaridis (2002) have reviewed the great potential of the use of flotation in environmental applications presenting novel separation concepts and emerging (unconventional) flotation devices.

More, many articles (Harbort et al., 1994; Finch, 1995; Liers *et al.*, 1996; Finch and Hardie, 1999; Féris *et al.*, 2001; Filho and Brandão, 2001; Reali and Marchetto, 2001; Rubio *et al.*, 2002; Rubio, 2003; Matis *et al.*, 2004) reviewed fundamentals, techniques and general features of flotation (usually preceded by flocculation) for environmental applications, namely, electro-flotation, induced air flotation, dissolved air flotation, nozzle flotation, column flotation, centrifugal flotation and Jet flotation (Jameson type cell).

The main conclusions of these reviews, overviews and meetings are that future technologies have to treat wastewater from mining and many other industries efficiently, not only to meet legislation standards but also to recycle or reuse water, which is a finite, vulnerable and increasingly more expensive resource.

Flotation is increasingly used in waste treatment, via introduction of new, superior, flotation devices leading to new and better applications for remediation of mineral industry contaminated waters and solids. A cross fertilization of flotation experience in mineral flotation and in wastewater treatment should lead to new and improved procedures in the mineral and metallurgical industry, the chemical and petroleum industries and domestic wastewater treatment. Table 1 summarizes the very many environmental applications of flotation in distinct areas.

Table 1. Environmental applications (some) of flotation.

ENVIRONMENT (SOLID/LIQUID, SOLID/LIQUID/LIQUID OR LIQUID/LIQUID SEPARATION):
• Treatment of organic compounds (solvent extraction plants), oils, fats and dyes (agates);
• Treatment of effluent with heavy metals (As^{+3} , Cr^{+3} / Cr^{+6} , Cd^{+2}, Pb^{+2}, Mn^{+2}, Ni^{+2}, Cu^{+2}, Zn^{+2}, Se^{+2}) and anions (CrO_4, S^{-2}, AsO_4, PO_4, MoO_4);
• Water recycle (filters): Anions and calcium ions removal;
• Treatment of AMD – Acid Mine Drainage and water reuse (Menezes *et al*., 2004).
INDUSTRIAL PROCESSES
• Proteins separation;
• Removal of impurities in the sugar cane industry;
• Separation of oils, fats, surfactants (soaps), odour removal and solids wastes in the food industry;
• Plastics recycle, pigments, dyes and fibres;
• Paper ink separation, rubber, resins, printer toner pigments;
• Emulsified oil removal in the chemical and petrochemical industry;
• Thickening of activated sludge;
• Reuse (recycle) of industrial waters (PET, washing of vehicles, airplanes).
OTHERS
• Removal-separation of micro organisms (algae, fungi, bacteria);
• Metals separation for analytical chemistry;
• Treatment of soils: pesticides removal, oils and radioactive elements;
• Treatment of industrial waters in the corrosion control, removal of soaps, detergents;
• Treatment of waters for industrial and domestic use;
• Treatment of sewage (removal of biological flocs, suspended solids).

Dissolved air flotation and the new trends

The classical dissolved air flotation (DAF) still is the most common process removing fine colloidal dispersions, ultra fine and solids, micro organisms and oily emulsions. In DAF, a stream of treated wastewater (recycle) is saturated with air at elevated pressures up to 4 atm. Bubbles are formed by a reduction in pressure of the water in the saturator vessel and forced to flow through needle valves or special orifices. Clouds of bubbles (30 -70 μm) are produced just down-stream of the constriction (Rodrigues and Rubio, 2003; Rosa and Rubio, 2005).

Due to the efficient reagents and separation schemes now available, flocculation and rapid flotation have great potential as unitary or ancillary processes in many areas (Voronin and Dibrov, 1998; Finch and Hardie, 1999; Rubio *et al*., 2002, 2003).

According to Haarhoff and Edzwald (2001), Kiuru (2001) and Rubio *et al.* (2002, 2003), the big trend is to decrease flocculation times and to increase DAF loadings, developing compact (small "foot-print" areas) and efficient treatment units. Small aggregates can be easily removed at high DAF (modern design) rates, contradicting the conventional bias that large floc units and bubbles are needed for successful separation. Figure 1 and Table 2 presents most notable unconventional applications found in Brazil, namely, the treatment by flotation of sea polluted water to feed "sea pools" in beaches, treatment of contaminated parks lagoons and, even rivers waters! (Bio, 2002; Oliveira, 2004).

Table 2. Recent unconventional ("sea" pools, rivers and parks lagoons) DAF applications in Brazil.

DAF units	Loading capacity, m^3h^{-1}
Favela da Rocinha* – Rio de Janeiro (RJ) (sea pool)	1080
Carioca river (Flamengo beach) – RJ (river treatment)	1080
Lagoa da Imboassica* – RJ (lagoon)	900
Piscinão de Ramos – RJ (sea pool)	270
Lagoa da Aclimação* – São Paulo (SP) (park lagoon)	180
Parque do Ibirapuera – SP (park lagoon)	540
Parque da Aclimação – SP (park lagoon)	180
Ribeirão Guavirutuba – SP (river treatment)	720
Canal Pinheiros** – SP (river treatment)	36000
Rio Negro**– Manaus – Amazonas (AM) (river treatment)	25000

* Projects being commissioned;
** Considered the biggest worldwide DAF treatment units

(a) (b)

Figure 1. Typical stream water treatment process (Carioca River–Brazil; Abema, 2002). (a) DAF; (b) Floated material (mostly algae) removal.

Because flotation depends on multiple interconnected factors, many considerations should be taken into account when selecting a flotation device and its capacity and the techniques to be employed.

DAF industrial applications of flotation in mining and metallurgy are scarce but growing (Rubio *et al*., 2002; Rubio, 2003) and it is believed that this growth is the result of the combination of DAF (conventional or not) and flotation in high throughput devices (> 40 $m^3m^{-2}\ h^{-1}$). The later is attained by widening the bubble size distribution with mid-sized or coarse bubbles, well known in ore flotation but not in water and wastewater treatment. Another problem found in DAF is the low lifting power of the microbubbles with process limits to only about 4 % solids. This problem is also overcome by employing bubbles higher than 100 micrometers.

But, another problem that may arise is that floc and coagula may not withstand shear and may not be separated in flotation devices operating with high turbulence (centrifugal, jet). Here, DAF with microbubbles is more amenable for this separation of coagula or precipitates.

Yet, and because of the high volume of water and wastewater to treat, future DAF installations will have to change the design, incorporating new elements to enhance the hydraulic loadings. Rapid DAF is being claimed by modifying the cell design (taller tanks) and by placing lamellae inside the separation tank (Kiuru, 2001).

Developments in rapid flotation

Another form of solving the problem is the use of "rapid", high throughput flotation units, based on a wide bubble size distribution and formation of "aerated" (entrapped or entrained bubbles) flocs (Rubio *et al*., 2002, Rubio, 2003, Parehk and Miller, 1999).

This paper describes the advances in the design, development and applications of innovative in-line mixing for flocculation and flotation for solid-liquid separation processes. Successful examples are the recently developed FF (flocculation-flotation) and the FGR (Flocs Generator Reactor,) both being applied in a number of applications (Carissimi and Rubio, 2005; Rosa and Rubio, 2005). Another rapid flotation technique (device) is the BAF (bubble accelerated flotation) reported by Owen *et al*. (1999).

The FGR (Flocs Generator Reactor) and the FF (Flocculation-Flotation) system

The FGR is either a flocculator or a "flocculation-floater" and consists of a coiled (helical) reactor, a compact system whereby the flocculation of particles is assisted by the kinetic energy transfer from the hydraulic flow through the reactor and by the injection of microbubbles (30-70 μm).

The FF (flocculation-flotation) has a special design (zigzag or static mixer type) which enables the generation of very light flocs (with entrained and entrapped air, see Figures 2 and 4). These flocs are generated in the presence of high molecular weight polymers, air bubbles (from the injected air), high shearing forces (caused by the zigzag kind of flow and flow rate) and a high head loss (or velocity gradient) (Parekh and Miller, 1999; Rubio *et al*. 2002, Rubio, 2003). FF has been reported in applications to remove oil, grease, BOD, etc., forming low density flocs which are readily floated in the flotation tank separator (within seconds), as large units (some millimetres in diameter). The excess air leaves the flotation device by the top through a special water seal (avoiding flow turbulence) (Figure 2).

The FGR uses the same pneumatic in-line aggregation contactor concept as FF, however its coil design presents lower head loss than FF. Hence, this system is mainly applied for suspended colloidal particles removal, turbidity reduction, water clarification, etc. Coiled format and plug flow regime enable the aggregation of particles with entrained and entrapped air that floats easily in a separation device (Figure 3). Main features between FF and FGR are summarized in Table 3. Figure 4 shows an example of Fe $(OH)_3$ aerated floc formed with cationic polyacrylamide and Figure 5 shows an example of Fe $(OH)_3$ flocs formation and growth in the FGR (flow direction: left to right).

Both systems use the contactor-separation concept with very low detention times in the contactor. Process efficiency was found, in all cases, to be a function of the trilogy: i) head loss (or velocity gradient), ii) type (and concentration) of flocculant and, iii) air flow rate (Rosa, 2001; Rubio, 2003; Rosa and Rubio, 2005; Carissimi and Rubio, 2005).

Table 3. FF and FGR: Main features.

	FF	FGR
Hydraulic flow regime	plug flow	plug flow
Contactor design	zig-zag	coiled
Main application	o/w emulsions	colloidal particles
Foot print area, m^2 (equipment and pumps)	3	3
Typical* head loss, m	10	5
Typical* velocity gradient, s^{-1}	2600	1800
Typical* Reynolds number, dimensionless	31770	8400
*Typical flow velocity, ms^{-1}	1.3	0.7

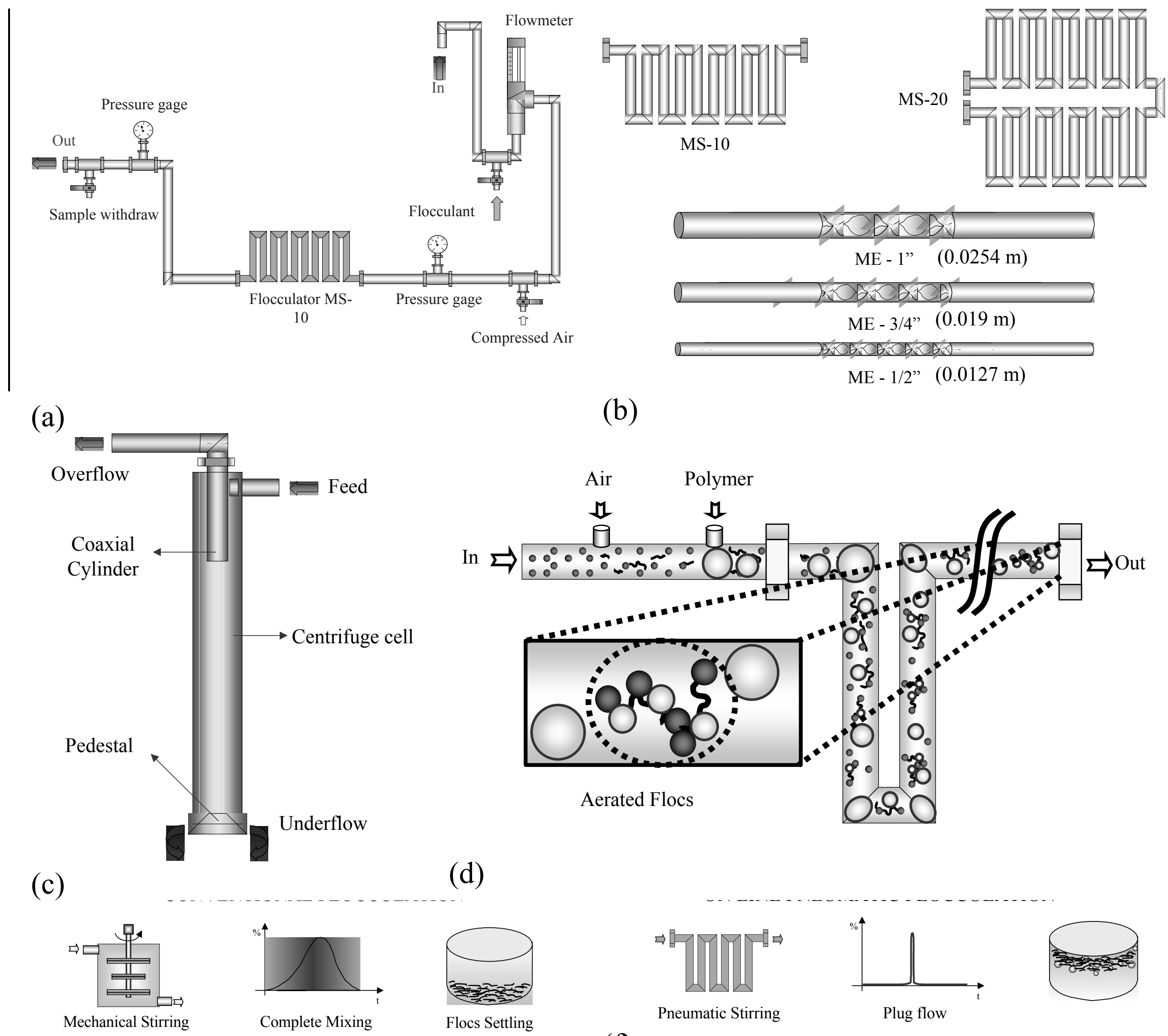

Figure 2. FF-Flocculation-flotation system. (a) In-line pneumatic flocculation; (b) Types of flocculators; (c) Separation device; (d) Aerated flocs formation in flocculator MS-20; (e) Conventional flocculation hydraulic flow regime; (f) FF process hydraulic flow regime.

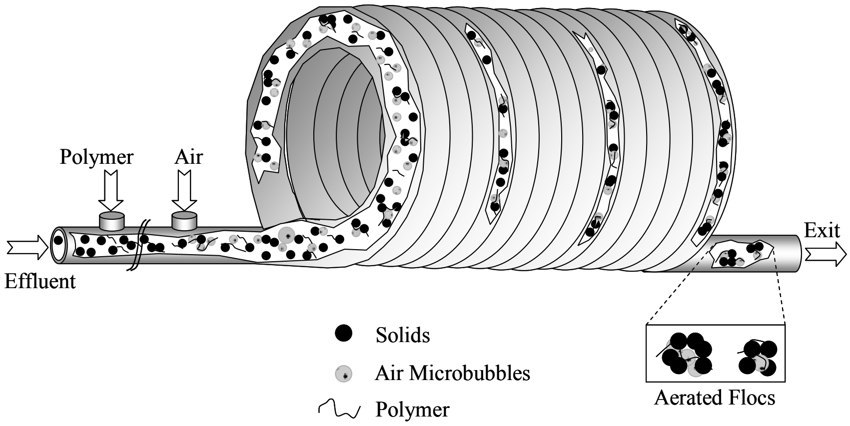

Figure 3. Aerated flocs generation and growing inside the FGR.

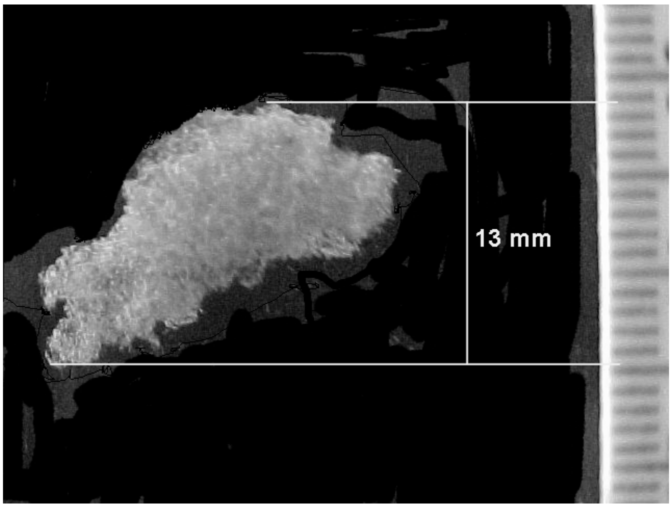

Figure 4. $Fe(OH)_3$ aerated floc formed with cationic polyacrylamide.

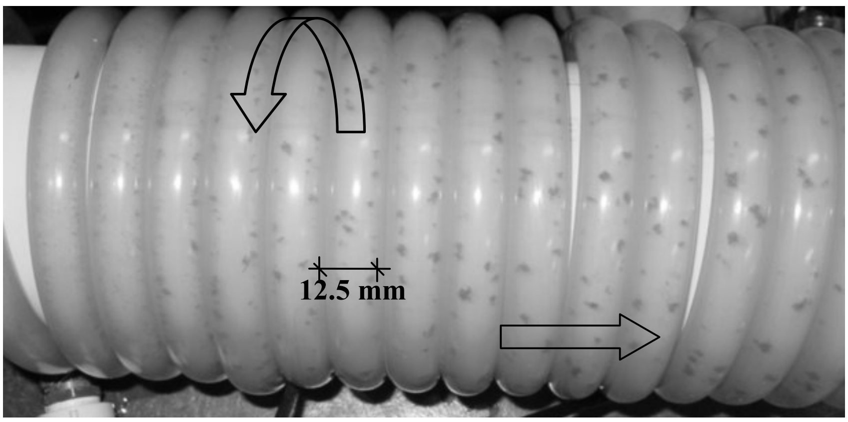

Figure 5. $Fe(OH)_3$ flocs formation and growth through the FGR (flow direction: left to right).

FGR Applications

Tap (potable) water clarification

For potable water clarification studies, three (3) different coiled reactors (FGRs) were constructed for the aggregates generation at semi-pilot scale, with flow rates 0.3, 0.6 and 0.9 m^3h^{-1}, named FGR 1, FGR 2 and FGR 3. These different diameter reactors were especially designed to change the feed rate and consequently the loading capacity in the separation cell (3.3, 6.6 and 10 $m^3m^{-2}h^{-1}$) keeping the velocity gradient (G≈ 1800 s^{-1}) and Reynolds number (Re≈ 8470) practically constant in the FGR (Carissimi and Rubio, 2005). Coupled to FGR, a flotation cell, named FADAT (high rate flotation unit) was designed with a volume of 0.15 m^3 for the solid-liquid separation studies (Figure 6).

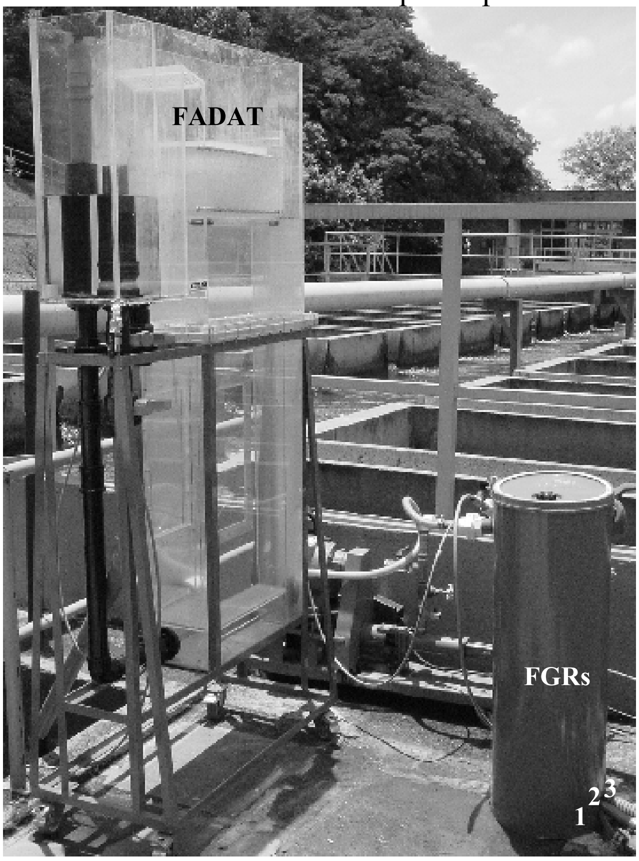

Figure 6. FGR-FADAT applied to the potable water clarification at a water treatment plant.

Raw water was pumped from Guaiba Lake (Porto Alegre/Brazil) and conducted to a water treatment plant (São João), receiving the addition of the chemical reagents used in the water treatment. For water clarification studies, using FGR-FADAT, water was pumped before the plant settling tanks entrance (after chemical reagents addition), and an extra reagent addition was required to allow the generation of flocs in the FGR. The need of this extra polymer concentration in these coiled reactors was previously reported by some authors (Gregory, 1988; Carissimi, 2003; Carissimi and Rubio, 2005), who verified that despite the favourable hydrodynamic condition (higher G values), these kind of flocculators need a higher dosage. A fraction of the clarified water was recycled and saturated in a vessel at a constant pressure and microbubbles, formed by the depressurization of the saturated water through a needle valve, and introduced in the FADAT cell. Flow feed rates varied between 0.3 and 0.9 m^3h^{-1} and the recycle rates were 20, 30, 40 and 50 %. In all cases, a 30 % recycling ratio was found to be the

optimal, while keeping the saturation pressure at 4 atm. Process efficiency was evaluated measuring water turbidity (Hach model 2100N) and apparent colour (Merck model SQ 118). Other analyses followed the Standard Methods for Water and Wastewater Examination (APHA, 1998).
Physical, chemical and physico-chemical parameters of the raw water quality in the treatment plant are summarized in Table 4. Data shown corresponds to the period of January and February of 2005 (summer). During these months, the raw water presents low turbidity and low organic matter, due, mainly, to the lack of rains and to the deposition of suspended solids on the lake bed.

Table 4. Physical, chemical and physico-chemical parameters of the raw water.

Parameter	Raw water
pH	6.5
Turbidity, NTU	15
Colour, mgL^{-1} Pt-Co	55
Organic Matter, mgL^{-1} C	5.0
Alkalinity, mgL^{-1} $CaCO_3$	21
Free CO_2, mgL^{-1}	11.8
Dissolved Oxygen, mgL^{-1}	1.95
Temperature, ºC	27.6
Total Solids, mgL^{-1}	167
Suspended Solids, mgL^{-1}	141
Dissolved Solids, mgL^{-1}	26
Conductivity, μScm^{-1}	71.8
Surface Tension (water/air), mNm^{-1}	70.6
Total Hardness, mgL^{-1} $CaCO_3$	91.7

Results with different reactor (loading rates) are discussed and compared with the results obtained in the conventional water treatment plant (coagulation-flocculation-settling). Figure 7 shows best turbidity reduction (about 87%) was obtained using FGR 1 (lower feed rate), which enables a good formation of flocs. The process efficiencies decrease with the increase of the loading rate (FGR 2 and 3) to about 76%.

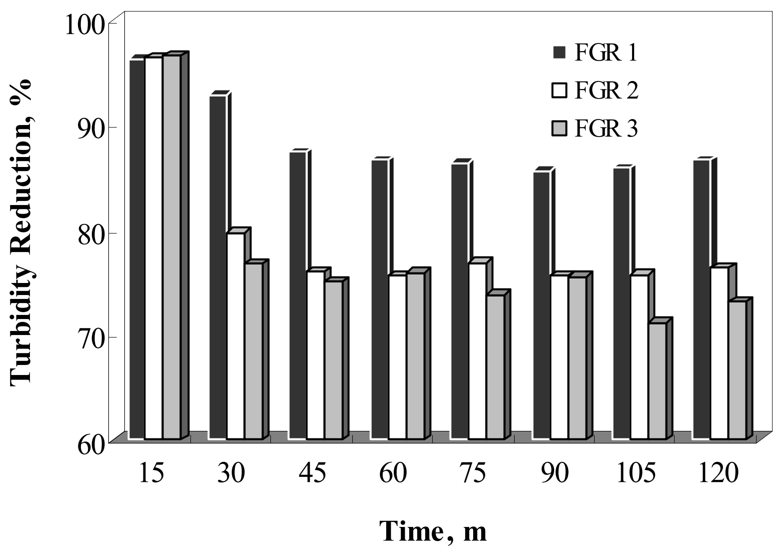

Figure 7. Turbidity reduction as a function of the FGR (loading rate). Conditions: feed rate= 0.3 m^3h^{-1} (FGR 1), 0.6 m^3h^{-1} (FGR 2), 0.9 m^3h^{-1} (FGR 3), recycle ratio = 30%,

saturation pressure = 4 atm, [AS 920 PWG-polymer flocculant] = 4 mgL^{-1}, pH 6.6 ± 0.4.

FGR 1 and 2 present a similar turbidity residual (about 2 NTU) and FGR 3 (higher loading rate) a higher turbidity (3 NTU). All values of the residual turbidity were below the Brazilian potable water quality standards (5 NTU) and similar to the mean results obtained after the conventional flocculation-settling process (2 NTU). Main advantage found with the FGR-FADAT procedure is the higher hydraulic loading capacity leading to shorter residence times (especially in the flocculation stage), and a smaller foot print required (Table 5).

Table 5. Flocculation time, hydraulic loading rate and foot print area using FGR-FADAT and flocculation-settling process.

	Settling	**FGR 1-FADAT**	**FGR 2-FADAT**	**FGR 3-FADAT**
Flocculation time, s	4032	18	35	53
Loading rate, $m^3m^{-2}h^{-1}$	3.5	3.3	6.7	10
Surface area required, m^2	2032	2162	1079	720

AMD treatment

A 2 m^3h^{-1} FGR-FADAT pilot unit was installed at Carbonífera Metropolitana (South Brazil) treating an Acid Mine Drainage (AMD) from the coal mining industry (Figure 8). The process included heavy metals precipitation (pH 9), aggregates formation in the FGR and separation by dissolved air flotation (DAF). Results of AMD treatment using FGR and solid-liquid separation by DAF are summarized in Table 6. Analyses were conducted according to the Standard Methods for Water and Wastewater Analyses (APHA, 1998). Results show a higher rate of application of the process compared to conventional DAF, resulting in similar residual turbidity.

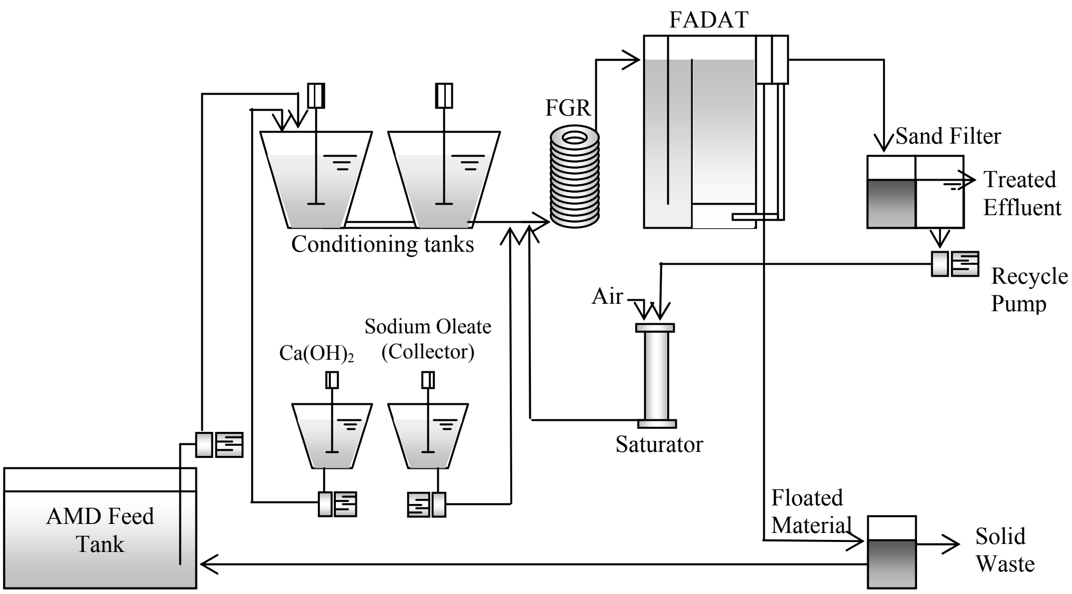

Figure 8. FGR-FADAT pilot unit to treat an Acid Mine Drainage (AMD) from the coal mining.

Table 6. FGR-FADAT application to the treatment of an AMD from a coal mining (South Brazil).

	FGR-FADAT	Conventional DAF
Flowrate, m^3h^{-1}	2	5
Throughput (hydraulic loading), $m^3m^{-2}h^{-1}$	14	8
[Sodium oleate], gm^{-3}	18	23
Residual Turbidity, NTU	8.5	8.0
pH	8.5-10.0	8.5-10.0

FF Applications

Oil separation from oil-in-water emulsions (refinery effluent)

Studies were conducted with a typical petroleum refinery effluent using the FF equipment shown in Figure 9. Main parameters of the refinery effluent used for separation by FF are shown in Table 7.

Table 7. Main parameters used in the emulsified oil in water separation by FF.

Parameters	Values
Oil	77 – 115 mgL^{-1}
Turbidity	55 – 67 NTU
TSS – Total Suspended Solids	43 – 51 mgL^{-1}
OM – Organic Matter	480 – 515 mgL^{-1}
Oil mean droplet diameter (volumetric), $d_{4,3}$	12 μm

Figure 9. FF pilot system used in the removal of oils from oil-in-water emulsions.

Results in Figure 10 show that, despite the high degree of emulsification, oil separation of the aerated floc was very rapid and almost complete. The kinetics was very rapid within seconds, yielding hydraulic loadings higher than 130 $m^3m^{-2}h^{-1}$. Flocs formed very quite big (cm), elongated and extremely light because of the trapped air.

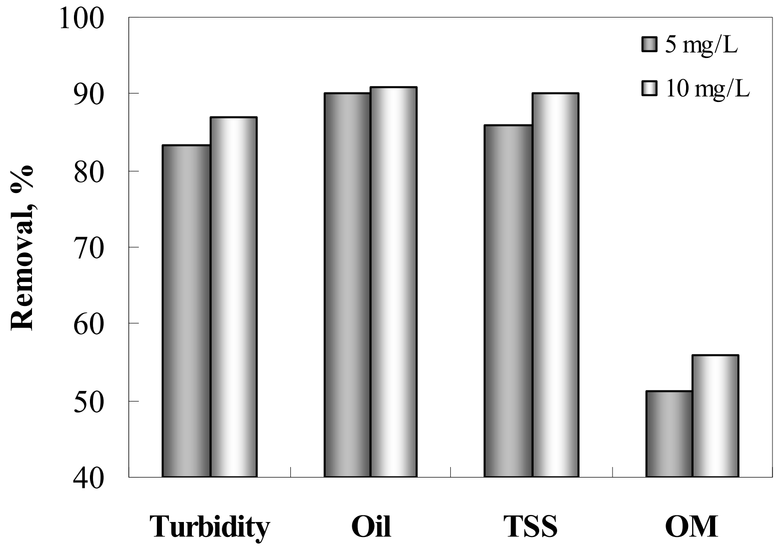

Figure 10. Oil-in-water emulsion (petroleum refinery effluent) separation by the FF process, using two different polymer concentrations (Nalco 8589, a cationic polymer).

Flocculation-flotation of suspended (dispersed) solids

After flocculation-flotation, FF% values were calculated from the dry weights of mineral suspensions, before and after the separation (Rosa and Rubio, 2005).

Table 8 summarizes comparative results obtained in each case. With the exception of bentonite, a difficult to flocculate solids suspensions, the FF separations of all other solid models was efficient, almost complete and proceeded at a very rapid rate. The flocs formed, in the case of solids are of the order of centimetres and are sticky like chewing gums!

Table 8. Flocculation-flotation values for various solids mineral suspensions.

Solids dispersions (2% by weight)	FF % at various polymer concentrations, [Nalco 8589], mgL^{-1}			
	1	3	5	10
Hematite	77	80	80	79
Quartz	70	96	94	82
Bentonite	35	77	90	98
Coal beneficiation tailing	80	90	87	83

Water treatment and reuse from vehicles washing

FF (flocculation-flotation) has been applied for the treatment and reuse (back to the washing process) of waters from vehicles washing (cars, buses and airplanes), removing oils, residuals solids, greases and surfactants (soaps). In some cases, an activated carbon filtration unit was introduced to remove residual surfactants after FF. In all cases studied, the reuse of the water was of the order of 80% and the results showed reductions up to 90% of turbidity and efficient removal of suspend solids; oils and greases. The aerated flocs are formed rapidly (in seconds) with air-bubbles formed under turbulent flow regime and only in the presence of high molecular weight polymers (mainly cationic). The floated product is dried in a sand drying bed and because of the small volume, it is discarded rather easily.

The process appears to have a good potential because this service consumes huge amounts of water (0.3 m^3 per bus approximately), the unit is compact small and presents a high process efficiency in terms of water reuse, pollution control, and separation kinetics.

A Brazilian bus company with 140 vehicles, for example, uses about two thousand cubic meters of water per month costing about US$ 8100. With this FF system, the monthly bill went down to US$ 1900 already enclosed electrical energy and chemicals consumption. This saving, in some cases, corresponds to about 1/8 of the total capital investment. Moreover, this business sector has further ecological advantages, by reducing pollutants emissions and potable water (municipal) consumption. Water volume consumption in vehicles washing is very high worldwide. In Brazil, there are about 32,700 gas stations (about 75% have washing units) with a water consumption of about 3 million and 700 thousand cubic meters per month, equivalent to what a city with 600 thousand habitants consumes in 30 days.

Figure 11 shows some FF applications in wastewater treatment and water reuse from cars and airplanes washing units.

Figure 11. FF applied for the water treatment and reuse from cars, buses and airplanes washing units (Porto Alegre/Brazil).

Conclusions

Conventional and non conventional flotation for water (and wastewaters) treatment and reuse is rapidly broadening their applications in many different areas in Brazil. Flotation is now being used in the treatment of lagoons, rivers, sea water, vehicle washing treatment/reuse, AMD treatment, potable water treatment and wide industrial effluents requiring high rate solid (droplets)/water separation. Recent in-line reactors for rapid flocculation and flotation have been developed, in our laboratory, namely the Flocs (aerated or not) Generator Reactor (FGR) and the Flocculation-Flotation (FF) and applied successfully in the water treatment and wastewater reuse from industrial effluents. Studies showed that efficiency in the potable water clarification using FGR were similar to the actual plant settling process but with much higher loading capacities. Other successful examples were obtained removing emulsified oil and solids removal from water, in effluents and in vehicle washing units and showed, in all cases, high efficiencies (> 90 % removal and 80 % water reuse). Both devices require short residence times and generate light, well structured flocs withstanding high shear forces. Due to the high efficiency and high loading capacity shown by both techniques, it is believed that both, FGR and FF systems have a good potential as in-line flocculation (or flotation) separator devices in applications requiring high rate solid-liquid separations.

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