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A hybrid flotation–membrane process for wastewater treatment: an overview

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ABSTRACT

Wastewater produced from many industries such as dyeing, textile industry, minerals processing/phosphate beneficiation, food processing and deinking is either reused after being treated by conventional treatment methods or pumped to drainage systems without treatment. This represents a serious environmental problem and causes challenges to the countries which face water shortages. A hybrid dissolved air flotation (DAF)-membrane process is a promised technology which can be used for treatment of many types of wastewater. Froth flotation is usually used to remove large proportion of suspended or dissolved solids while the membrane cell can reject very small particles. In this paper, a comprehensive review on the treatment of wastewater using DAF process alone as well as a hybrid flotation membrane was discussed. Various ways of hybrid flotation–membrane filtration such as flotation–microfiltration (MF), flotation–ultrafiltration (UF), flotation–nanofiltration (NF), and flotation–reverse osmosis (RO) are also addressed. The review showed that the hybrid flotation membrane system can achieve high separation performance with reasonable price compared with the traditional DAF or membrane-based filtration systems. This extends the use of this emerging technology to treat new types of wastewater or improving the existing technologies which reduce the effect of harmful effluents on the surrounding environment. Moreover, using flotation in combination with MF/UF has reduced membrane fouling and extended their useful working time. This leads to a reduction in operation cost and improves the efficiency of membrane performance. Hybrid flotation–NF/RO is a new technology for wastewater treatment which produces high quality water with greater recovery and lower energy and reagents consumption. Finally, the review also addressed the new application of DAF as pretreatment for the desalination processes.

Keywords: Dissolved air flotation; DAF; Membranes; Hybrid system; Wastewater treatment

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1. Introduction

Froth flotation is an important separation process patented in the 19th century. It was firstly used in minerals processing industry to separate gangue from valuable minerals. This process relies on the difference in surface chemistry of particles and their behaviour in the existing interfaces (gas/liquid, gas/solid and liquid/solid). In flotation, hydrophobic particles attach themselves to the rising bubbles forming froth at the surface of the liquid phase. Hydrophilic particles may also be entrapped within a bubble particle aggregate (carrier flotation) and mixed with hydrophobic particles at the surface of the liquid interface [1–7]. Impurities to be separated by flotation can be soluble or insoluble in the liquid phase. Flotation is currently used in a wide range of applications such as mineral separation, potable water purification, remov-

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ing toxics from industrial effluents, bacteria and algae removal, dewatering and sludge thickening, paper pulp deinking, and removal of fat and oil from oily wastewater [8–10].

Flotation can be classified according to the bubble generating mechanism or the way impurities are removed at the liquid surface. It is called dispersed air flotation if bubbles are generated by forcing the air into flotation cell. This utilizes the shear forces generated by the rotational impeller or forcing the air through porous media at the bottom of flotation cell to form air bubbles. This type of flotation which is widely used in mineral processing industry is sometimes called macro flotation due to the size of bubbles (>600 micron) used in this type of flotation [11–15]. In dissolved air flotation (DAF), bubbles are generated by dissolving air in water at high saturation pressure. Sudden pressure decrease in flotation tank generates fine (<100 micron) bubbles which rise to the top surface (2.5–10 mm/s) carrying the undesired impurities to the surface of the liquid phase. Due to the size of water and wastewater impurities, this type of flotation is used in many water and wastewater treatment applications [16–20]. Furthermore, flotation can be categorised according to the separation of impurities from the liquid phase. In froth flotation, thick foam (froth) is formed where a mechanical scrapper is used to remove it. Alternatively, the scum/impurities can be also removed by froth overflow of a flotation tank. This type of flotation is widely used in mineral processing where selectivity between solids is very important. On the contrary, non foam flotation separates impurities from liquid phase near the surface of water without forming a froth layer. On the other hand, membranes are an efficient and ecologically suitable technology for decontamination of wastewater generated in many industries. But the major problem of wastewater is water recovery rate, which should be close to 100%. To achieve this target, many researchers investigated an integrated membrane system. Rautenbach and Linn [21] and Rautenbach et al. [22] used a new concept of integrated membranes consisting of reverse osmosis (RO)/nanofiltration (NF)/high-pressure RO. The integration can achieve water recovery rates of more than 95% in the case of dumpsite leachate, which promises an almost zero discharge process.

In this review paper, we will shed some light on the recent development in the applications of DAF in water and wastewater treatment, its use as a pre-treatment in membrane filtration and its role in reducing membrane fouling. So, the next sections will address treatment of wastewater using DAF technology and a hybrid process of DAF with all types of membranes: microfiltration (MF), ultrafiltration (UF), NF and RO.

2. DAF process for wastewater treatment

In the past 50 years, DAF gradually replaced sedimentation clarifiers in water and wastewater treatment due to its higher hydraulic load, lower water retention time and higher load to size ratio. According to Lawrence et al. [23] a comparison between conventional sedimentation and DAF showed that:

- DAF reduced water retention time from 30 to 3 min.
- DAF requires only 15% of the sedimentation tank space.
- DAF requires only 5% of the sedimentation tank volume.
- With higher flow rate in DAF, both clarifiers give the same degree of clarification with the same amount of chemicals.
- DAF operational costs are slightly higher, but this may be offset by considerably lower cost of its installation's financing.
- DAF clarifiers have better construction flexibility for possible future changes.

DAF systems commonly have three types of configurations according to the percentage of pressurised flow. These types are full, partial and recycle flow pressurization. The use of each of these systems depends on flotation operating parameters such as effluent flow, characteristics of effluent and concentration of impurities [23]. Full flow pressurization requires all influent feed to be pressurized before entering the flotation tank. In partial pressurization only part of the influent is pressurized while in recycle flow part of DAF effluent is remixed with the influent in the saturation tank (Fig. 1).

In addition to the differences in generating gas bubbles, the main differences between flotation of ores (dispersed air flotation) and flotation used in water treatment (DAF) as mentioned by Rubio et al. [24] can be summarised as follows:

- In DAF, minimum turbulence in the flotation cell is required in order to minimise the effect of turbulence shear forces on floc–bubble aggregates which is not a critical problem in mineral flotation.
- Solids to liquids ratio is high in mineral flotation (>10%) while in DAF high solid content is undesirable. Solid concentration is normally in the order of part per million (ppm).
- Separation type in mineral flotation is usually solid/solid/liquid phases while in wastewater treatment separation may be solid/liquid, solid/liquid 1/liquid 2 or liquid/liquid.
- Formation of stable froth at the free surface of the flotation cell is necessary in minerals
- Flotation, while in water treatment flotation formation of stable froth is not important.

DAF has recently become an important water treatment process used for clarifying different types of wastewater. So, in recent years, DAF fundamentals and applications in water treatment have been investigated

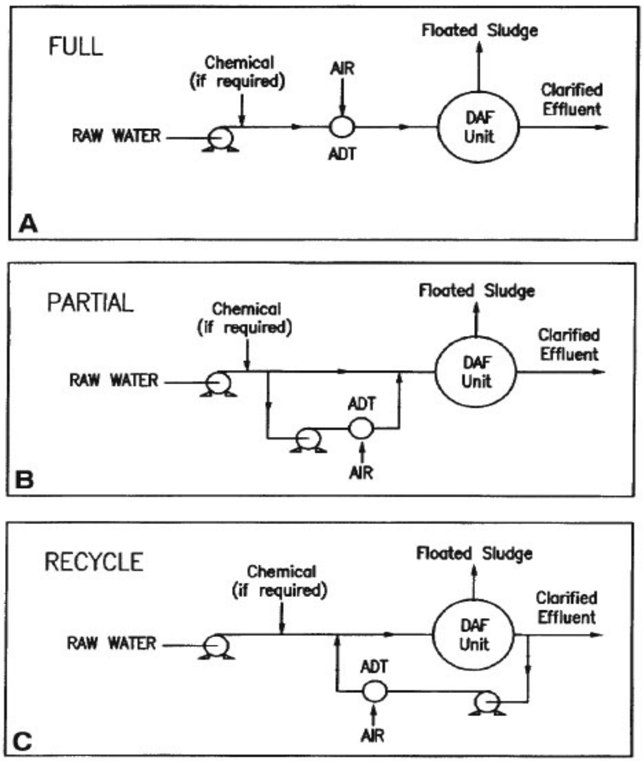

Fig. 1. Schematic diagram of DAF systems [23].

by many researchers, to mention some, Edzwald [25] addressed detailed description of DAF fundamentals and its uses as clarification process. He presented a DAF performance model describing the key operating parameters such as coagulation–flocculation chemistry, contact zone, and the separation zone determination, bubble rising velocities and their relation with the hydraulic load, floc–bubble collision, and attachment and detachment mechanisms. Considering the cost of different water clarification techniques, Edzwald [25] reported that DAF is an excellent choice for treating water with low turbidity, natural colour, and algae problems. In another study, Al-Shamrani et al. [26,27] investigated the use of DAF to clarify synthetic oily industrial effluents. They used a non-ionic surfactant (Span 20) as a collector and aluminium sulphate and cationic polyelectrolytes to destabilize the emulsion. The authors mentioned that increasing saturation pressure has less effect on the separation of oil droplets than the recycle ratio. Using the optimum chemical dosages, recycle ratio, and pH, more than 99% oil removal efficiency was achieved. Also, Hanafy and Nabih [28] investigated the use of DAF for the removal of emulsified oils from oily wastewater. The authors carried out a fundamental study to evaluate the effect of DAF operating parameters on the removal efficiency of oil droplet from synthetic and real oil water emulsions. Furthermore, Sohair et al. [29] used DAF to remove oil and soap from highly polluted water using ferric chloride and alum as coagulants, The authors reported high efficiency removal of organic contaminants and more than 90% removal of COD, BOD and turbidity. Recently, Bensadok et al. [30] used DAF to clarify water contaminated by industrial cutting oil. They used different dosages of calcium chloride, ferric chloride and aluminium sulphate to destabilise the emulsion and oil/water concentration ratios. The authors found that calcium chloride was the most effective coagulant in both separation efficiency and emulsion turbidity reduction. Tansel and Pascual [31] statistically evaluated the effect of some operating parameters [(oil concentration, detention time, water type, coagulant use and operational mode (batch or continuous)] of DAF for the removal of petrol hydrocarbon (PHC) from industrial waste. The factorial analysis showed that for batch mode operation, oil concentration, detention time, coagulant use and water type significantly affected PHC removal, while in continuous operational mode the only statistically significant parameter was the detention time.

In using DAF to remove toxic/valuable ions from industrial waste, Zamboulis et al. [32] used sportive flotation to remove copper, zinc, and chromium (V) from wastewater. They used zeolite as sorbent of ions (ion exchange), then zeolite particles were removed from the solution by DAF using sodium dodecyl sulfate, dodecylamine or hexadecyl-trimethyl-ammonium bromide as collectors. The authors reported that the removal efficiency of more than 95% of the toxic ions was obtained. Lazaridis et al. [33] also used DAF for the recovery of copper ions from a mine and mineral processing wastewater plant. Copper ions were firstly precipitated by xanthates, and then sportive flotation using zeolite was applied. Under the studied conditions, the authors obtained more than 95% ion recovery. In another study, Hua et al. [34] used an electrocoagulation–flotation (ECF) system to treat high fluoride-content wastewater. Following the precipitation of fluoride ions by adding lime, the precipitated calcium fluoride was then treated by sodium dodecyl sulfate (SDS) as anionic collector and removed with the scum (froth) at the top of the cell.

DAF was also used in algae removal. Henderson et al. [35] used DAF to remove algae (*Microcystis aeruginosa)* cells from water by modifying air bubbles within the saturation tank using cationic surfactant. Using different surfactant dosages and load recycle ratios, the authors obtained maximum algae removal efficiency of 85%. Recently, DAF was used as a pretreatment process in clarifying slaughterhouse wastewater. Nardi et al. [36] studied the improvement of DAF performance for wastewater treatment at a poultry slaughterhouse. Using polyaluminum chloride (PAC) associated with anionic polymer as coagulant; the authors reported that recycling of 40% of DAF effluents, removal efficiency of more than 70% and 90% of suspended solids and oil can be achieved. Furthermore, Al-Mutairi et al. [37] evaluated the use of combination of DAF and contact-assisted activated sludge (CAAS) in treatment of slaughterhouse wastewater. Using two DAF stages with CAAS, the authors obtained more than 80% and 70% removal efficiency of suspended solids, and oil and grease, respectively. A new approach using nano-bubble flotation technology (NBFT) with coagulation/flocculation for treatment of chemical mechanical polishing (CMP) wastewater was investigated through laboratory and pilot-scale experiments [38]. In this work, a new nano-bubble generator (NBG) was applied in the flotation system. The measured size of bubbles in the flotation tank was in the range of 30–5000 nm and the volume percentage of bubble size under 100 and 1000 nm was 25.3% and 86.1%, respectively. At the bench scale, polyaluminum chloride (PAC)/sodium oleate (NaOl) were used as a combination of activator/collector, respectively. The application of this combination in the NBFT with the coagulation process increased the wastewater clarification efficiency by 40% as compared with the traditional coagulation/flocculation process. On the other hand, more than 95% turbidity, total solid and total silica removal efficiencies were observed in the pilot-scale experiments. Therefore, the authors found that the new approach treated CMP wastewater efficiently at a minimum cost in comparison with coagulation alone as shown in Table 1.

Table 1
A comparison of cost between NBFT and coagulation processes [38]

Item (US$/m^3 CMP wastewater)	NBFT	Coagulation
Chemical cost	0.3	1.20
Power cost	0.15	0.18
Maintenance cost	0.15	0.20
Personal expenses	0.15	0.15
Total operation	0.75	1.73

3. A hybrid flotation-MF/flotation-UF

A new hybrid process combining flotation–membrane microfiltration has been recently proposed for cleaning wastewater, combining the advantages of flotation and microfiltration for solid/liquid separation where the membrane step replaced more traditional filtration [39–44]. This hybrid process combined the advantages of both membrane separation and flotation: the flotation cell removed a large proportion of suspended solid particles, while the membrane module produced clean water permeate effluent. Suspended solid separation is an essential element in almost any wastewater treatment system [45,46]. In comparison with sedimentation and filtration, flotation has been reported to have the widest operational ranges concerning influent suspended solid concentration and particle size and considerable load-bearing capacities [39].

The proof of concept for the hybrid solid/liquid separation process was investigated using an aqueous suspension of ultra-fine zeolite particles [41]. Process parameters investigated were liquid and gas superficial velocities and backflushing. Promising results were reported regarding solid/liquid separation, including a case study of mine wastewater; attention has also been paid to the economics of this integrated process. The experiments were conducted at different conditions for the comparison of simple MF (with and without air sparging) and the hybrid process. The results have shown a spectacular improvement of cell performance by adding the collector and inducing flotation conditions in the hybrid cell. After 5 h of operation the transmembrane pressure (TMP) had increased only to 0.03 bar, leading to a total resistance of 1.28×10^{11} m^{-} and a considerably smaller permeability decrease. By comparing these results with the simple MF case, an improvement of 88% was observed.

Air flow rate is one of important parameters in the flotation process. Experimental results published by various researchers indicate that flotation recovery increases to its maximum and then decreases as the airflow rate increases [47]. In this work, the author found that a combination of high suspension and gas flow rates lead to a worse hybrid cell performance. This process was applied to a real industrial wastewater with using flocculation to enhance the effectiveness of separation. The obtained recoveries of solids were satisfactory, in the range of 80% which found to be improved with a higher collector and flocculent concentration.

Also, economics of these processes (Fig. 2) was investigated using the software tool SuperPro Designer (Inettigen) [39]. For the price cost planning, a wastewater feeding flow rate of 10 m^3 h^{-1} and for the MF process a filtrate flux of 25 L m^{-2} h^{-1} were assumed. The results indicated that the cost of the combined process was not mere addition of the individual processes costs (see Table 2): the required membrane surface, which was a major cost factor, was lower in the hybrid process since flotation

Table 2
Brief review of the cost (US$) of each process [39]

Process	Flotation	MF	Hybrid: MF + flotation
Equipment purchase	101–480	294–700	189–130
Working capital	71–320	207–420	132–310
Total capital investment	594–300	1728–480	1102–610

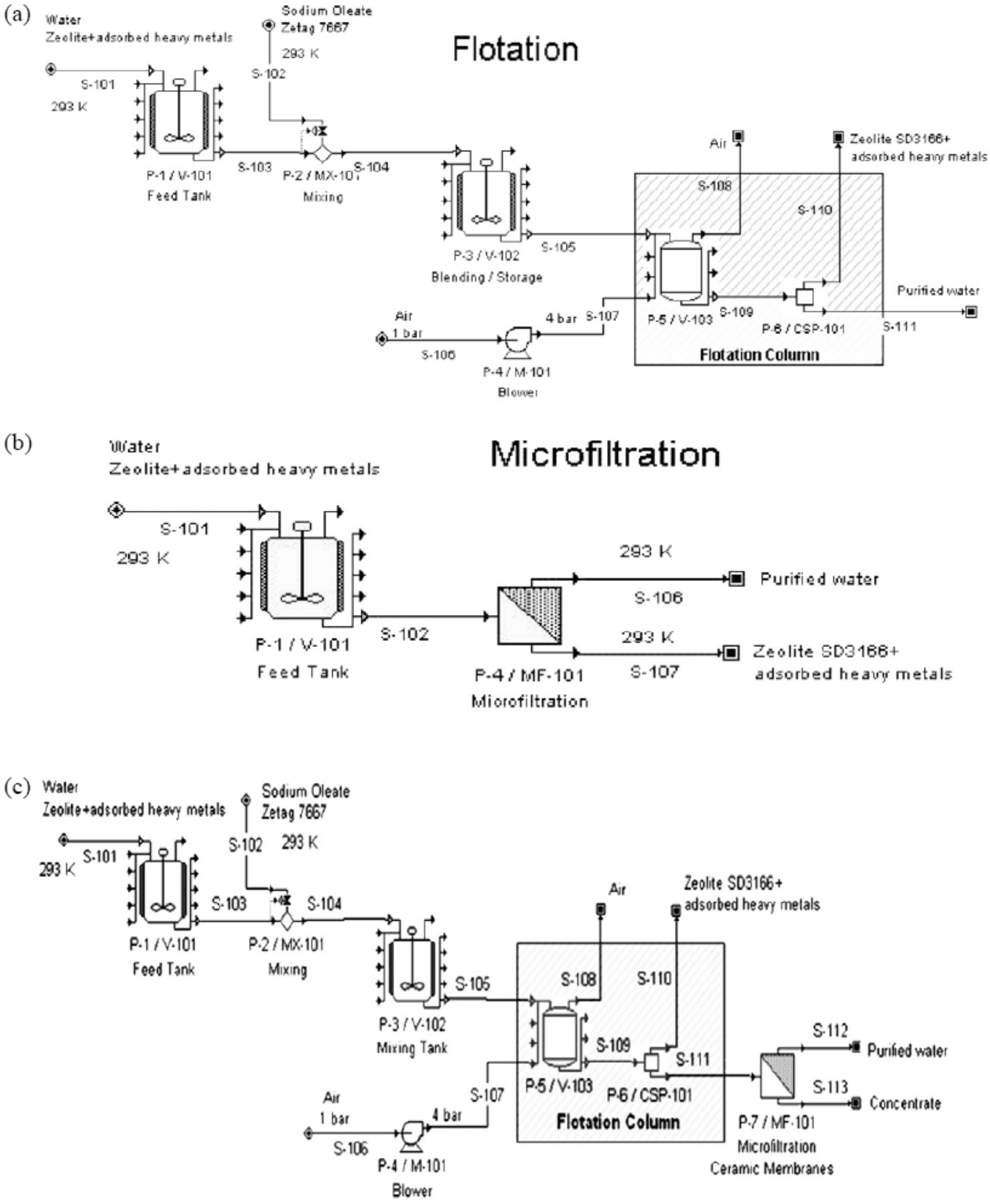

Fig. 2. Technical-economical flowsheet analysis of (a) the flotation process, (b) membrane microfiltration, and (c) the combined, hybrid process [37].

removed the majority of solid particles, and therefore a smaller membrane area was required to yield the same permeate. In another work, Peleka et al. [40] investigated the performance of the hybrid process using an aqueous suspension of iron colloidal particles produced in situ. Process parameters, including the effect of gas flow rate, frequency and length of backflushing, were studied. A hybrid process of a flotation column equipped with a gas sparger and a membrane module comprising a twin set of parallel, double-sided ceramic (97.1% Al_2O_3 and 2.9% SiO_2) membranes was applied for the removal of phosphate ions from artificially polluted water. Phosphate was first sorbed on iron colloidal particles and then the suspension was fed into the hybrid cell. Naol was used as collector and in some cases ethanol was used as frother in order to reduce the bubble size and to prevent their coalescence. The results indicated that the increase of airflow rate positively affected the hybrid cell performance, up to a critical value. Backflushing, on the other hand, resulted in an improvement of the hybrid cell performance.

The main objective of Peleka and Matis' work [40] was the investigation of the flotation effect on the potential reduction of membrane fouling which is the major obstacle in the extensive use of MF in wastewater treatment. Fouling is a generic term that describes the gradual deterioration of membrane performance as a result of solid accumulation on membrane surfaces. Fouling leads to a reduction of flux rate and an increase in operating pressures which increase operating costs and frequent cleaning [48].

In both previous studies the presented hybrid flotation–membrane cell has shown less membrane fouling. As the solid particles are partially removed by flotation, clean water was obtained from the membrane module. Fewer solid particles remaining in the dispersion were deposited on the surface of the membrane; thus, gradual fouling of the membrane was greatly reduced and the membrane module useful life was considerably extended.

Another promising application for the hybrid flotation–microfiltration cell is in the removal of heavy metal ions from aqueous solutions [40–42, 49–51]. Firstly, the metals were bonded into a special bonding agent, and secondly, the loaded bonding agents were separated from wastewater stream by the separation process using a hybrid system. Blocher et al. [42] investigated utilization of a hybrid process developed by integrating specially designed submerged microfiltration modules directly into a flotation reactor. The feasibility of this process was proven using powdered synthetic zeolites as bonding agents. Stable fluxes of up to 80 L m^{-2} h^{-1} were achieved with the ceramic flat-sheet multi-channel membranes applied at low transmembrane pressures (<100 mbar). The process was applied in lab-scale to treat wastewater from the electronics industry. All toxic metals in question, namely copper, nickel and zinc, were reduced from initial concentrations of 474, 3.3 and 167mg L^{-1}, respectively, to below 0.05 mgL^{-1}, consistently meeting the discharge limits.

A similar study was carried out where cross-flow microfiltration was used for the separation stage for low-contaminated wastewater while a hybrid process combining flotation and submerged microfiltration was used for highly contaminated wastewater [50]. The separation of the zeolite loaded with metal by the hybrid process combining flotation and immersed microflltration multichannel Al_2O_3 ceramic flat sheet membranes was conducted with a stable flux of 40 L/m^2h (transmembrane pressure of 40 mbar, backwashing every 30 min for l0 s). It was found that zeolite could be concentrated in the flotation froth up to 500 g zeolite/kg froth [50].

In another study, flotation was applied as a pretreatment stage for ceramic microfiltration modules of multichannel geometry [43]. Promising results were achieved regarding the air presence, bubble size (experienced by inserting in the solution a frother or changing the porosity of the used air diffuser) and solid concentration against the transmembrane pressure (TMP). In this work, flotation was conducted on a real mine effluent. The results showed that in the range investigated, the finer the air bubbles were used, the lower was the transmembrane pressure through the membranes. The efficiency of flotation, as found macroscopically, was shown to have as outcome more than 90% of solids to be floated [43]. A hybrid process combining DAF and MF in one unit was applied for zinc ions removal [44]. The main parameters investigated were zeolite concentration, solution pH, membrane backflush, collector type and concentration. The higher was the zeolite dose, the lower permeability was observed. Backflush found to have little effect on hybrid cell operation while the collector type was a crucial parameter. 90% zeolite recovery was obtained by flotation. They showed that no energy was necessary for fouling control in addition to that needed for flotation separation. This showed an advantage for the compact volume of the hybrid cell. In another work, Matis et al. [50] studied the removal of two metal ions (copper or chromates) by employing a hybrid flotation–MF process. They applied two flotation techniques; precipitate and adsorbing colloid flotation. Under the studied conditions, they observed that the higher the surfactant or frother concentration the lower the transmembrane pressure. The interesting results were shown by obtaining 0.5 mgL^{-1} for copper and 0.1 mg L^{-1} for chromium in the outlet, from initially 50 mg L^{-1}. In a recent work a pilot-scale hybrid system integrating in the same cell where used at a Bulgarian mine wastewater for metal recovery [52]. It was shown that dispersed air flotation was capable for a preliminary solids recovery of the order of 90%, with the Cu content in the froth concentrate approaching 6%. They obtained promising results finding that the residual heavy metal (Cu, Mn, Fe and Pb) concentrations in the membrane permeate were below 0.05 mg L^{-1}. The combination of electro-coagulation and flotation with MF in a cross-flow system was investigated to treat municipal wastewater [53]. The results showed that the investigated hybrid system successfully produced water with total disinfection of a cutoff threshold of 0.1 ppm which is suitable for agricultural reuse.

A study on the treatment efficiency and flux of various, new ceramic membranes in UF of board mill wastewater fractions was conducted by Laltmen et al. [54]. The wastewater fractions studied were the disk filtered and flotation treated circulation wastewater and the overflow from the clarification basin of coating colour wastewater. Both wastewater fractions studied had a fairly low COD content and hence the reduction in COD was low. Odour was removed from the treated circulation wastewater. Removal of odour forming properties is important since the box board manufactured in the board mill is used for food, cosmetics and cigarettes. In a recent study, Choo et al. [55] evaluated the potential of a combined system (coagulation and UF processes) to replace the existing treatment for textile wastewater reclamation which is composed of a flotation tank and a series of filtration beds including sand, granular carbon, and diatomaceous powders. Regardless of the type and dosage of the coagulants, the UF system achieved substantial colloidal particle removal (>97% of turbidity was removed), but membrane fouling was mitigated in a different manner. The degree of fouling reduction was highly dependent upon the type of coagulants used, even though the turbidity and organics removal efficiencies were nearly the same. They used different types of feed water for UF membranes from the existing treatment facility. It was noticed that the flux declined very sharply with wastewater, but after flotation the flux level improved by 55%. Consequently, it was thought that an appropriate pretreatment method should be employed prior to the UF process in order to minimize colloidal fouling. This improvement in the UF flux by using flotation as pretreatment indicates a potential for a hybrid flotation–UF system in wastewater treatment.

4. Hybrid flotation-NF/flotation-RO

Membrane filtration can be applied in combination with flotation to treat all types of water including surface, ground, waste, and sea water with high rejection and pure water recovery. Hybrid flotation-NF is a new technology investigated by a few researchers as a pretreatment to NF to prevent membrane fouling which increases their efficiency and life time [56,57]. To mention some, an integrated coagulation/flocculation with DAF was investigated as bench scale pretreatment for spiral-wound module nanofiltration (SWNF) to treat the Tagus River surface water in Valadas, Portugal [58]. This new pretreatment method was chosen as an alternative to the expensive conventional method which included coagulation/flocculation, sedimentation and media filtration [59]. DAF performance was evaluated through the measurement of the silt density index (SDI) and the modified fouling index (MFI) of the treated water. These indices are commonly used to evaluate whether the concentration of colloidal and particulate matter of the water is adequate for SWNF. The SDI of the untreated surface water was between 18.1 and 19.4%/min, which was very high when compared to the typical values between 3 and 5%/min recommended by most membrane manufacturers, while the MFI should be lower than 10 s/l^2 [58].The authors studied the effect of DAF operating conditions such as dissolved air saturation pressure, the ratio of the recirculation flow rate of air-saturation, and the concentration of the coagulation/flocculation (aluminium sulphate, ferric chloride, and chitosan) on the MFI and SDI of the treated water . They concluded that although the use of coagulants improved the DAF efficiency in the reduction of fouling indexes, these values were still higher than the standard ones. Therefore, the results showed that the DAF process must be integrated with media filtration or microfiltration in order to obtain acceptable values of MFI and SDI which may provide a good pretreatment for the SWNF of the Tagus River surface water.

In another work, Ribau Teixeira et al. [60] studied the removal of cyanobacteria (blue-green algae) and associated microcystins from a synthetic wastewater using hybrid dissolved gas flotation–NF preceded by the coagulation/flocculation process. In this study, two types of gases were used in the flotation process, air and a mixture of carbon dioxide and air (CO_2/air). The CO_2 gas was used to decrease the pH value (produced by CO_2 dissolution) in the flotation and NF processes. The results showed that the suggested hybrid process of DAF–NF was able to completely reject cyanobacteria and decrease microcystin concentration in the treated water to a value below the World Health Organization (WHO) guideline of 1 mg/L for microcystin-LR (MC-LR) in drinking water at water recovery rate up to 84%. Although decreasing in the pH decreases the required amount of coagulant demand for particle destabilisation and effective coagulation, as shown in a previous work [61], the CO_2/air mixture had no benefit to the hybrid flotation–NF, both in terms of toxin release to water during flotation and lower natural organic matter removal by NF [60].

In another work, a hybrid process consisting of DAF/sand filter was successfully used as pretreatment for NF [62] to treat different types of wastewater. A new flotation process is called membrane floatation in which microporous ceramic membranes are used as air diffusers [63]. In a very recent study, this flotation process has been integrated with commercial RO membranes and NF spiral wound membrane modules to treat wastewaters containing copper and other heavy metals [64]. Different ways of combinations of integrated membrane-electroflotation and NF/RO were investigated in this work. Two optimal combinations were concluded with different findings (Fig. 3). The first combination produced water with greater recovery, but lower rejection, energy and reagent consumption; the second one, on the contrary, showed lower recovery, but higher rejection, energy and reagent consumption. Therefore, an optimization study is indispensable for the proper choice of a hybrid process based on capital and operating costs and the treated water requirements.

Chuang et al. [65] investigated two hybrid processes in Taiwan to treat wastewater for reuse in high-tech industries such as semiconductor and information-related technologies. The first combination system (AC–RO–IE) consisted of a sand filter, an activated carbon (AC) bed, a microfiltration module, an RO membrane and ionic-exchange (IE) columns, while the second system (DAF–AC–RO) consisted of coagulation/flocculation, DAF, an AC bed, a microfiltration module and an RO membrane.

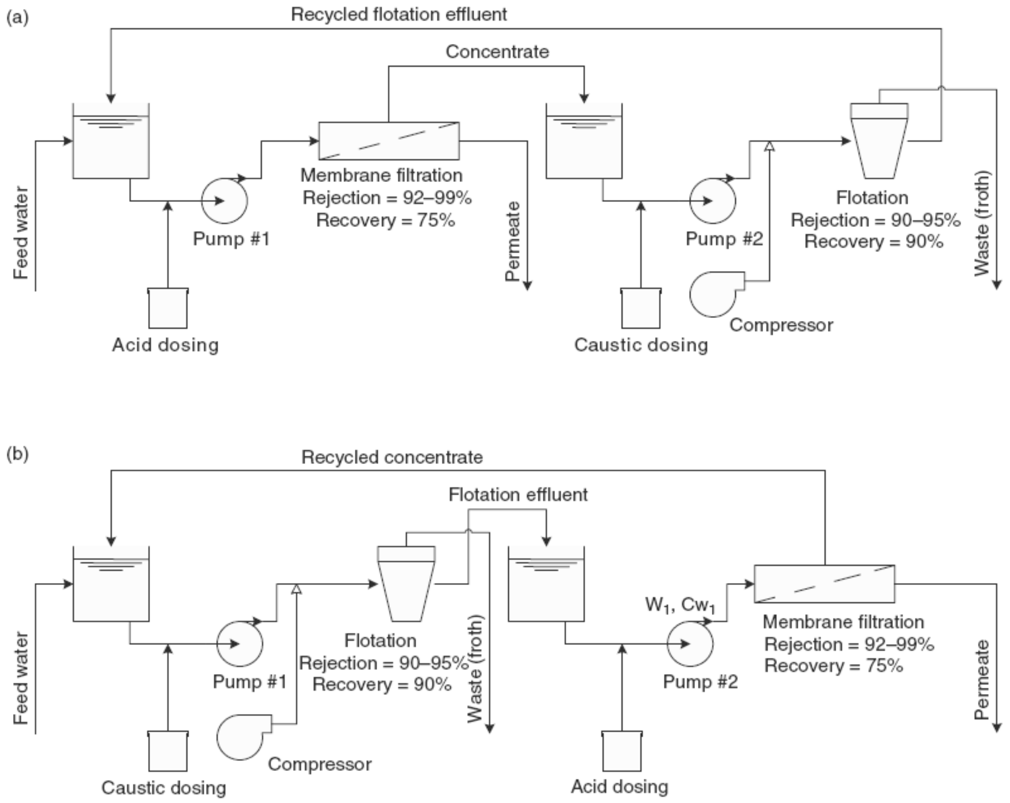

Fig. 3. Combination of NF/RO and flotation for copper-containing wastewater treatment: (a) greater recovery, lower rejection; (b) lower recovery, greater rejection [64].

The study was carried out at a pilot-scale plant in situ that operated for approximately 1 year. For long run, it was shown that both combination systems had a potential for rejecting organic and inorganic contaminants from the investigated wastewater and the treated water was suitable for reuse or make-up water in the high-tech industrial park. However, the removal efficiency of TDS, SiO_2 and COD in the second system (DAF–AC–RO) was higher by 19.8%, 70.1% and 44.4% than that of the first system (AC–RO–IE). Finally, the authors suggested to use PAC-coagulation and the DAF combination system as pre-treatment to RO in order to improve the rejection of dissolved species, decrease hardness, modify the form of dissolved silica, and reduce the SDI and MFI values.

In another application, DAF has been suggested to be used in the pretreatment for the desalination processes since 1984 [66]. Pretreatment process is one of the major factors determining the success or failure of a desalination process. Different pretreatment methods such as conventional pretreatment (i.e., coagulation, flocculation, acid treatment, pH adjustment, addition of anti-scalant and mediafiltration) [67], MF [68], UF [69], and NF [70] were usually used. A hybrid DAF with direct filtration or ultrafiltration was used as pretreatment for RO performed on open seawater intake as a pilot plant located in the Persian Gulf [71]. Another pretreatment pilot plant consisting of coagulation and dual media filter for open intake seawater had been also investigated in this work for nine months. The later pilot plant was located in the Gulf of Oman (Indian Ocean) which has better surface seawater intake than the Persian Gulf. In this study, the parameters taken into account for the water quality characterisation were suspended solids, turbidity, fouling tendency, organic matters and algae content. The filtered water obtained by the second pilot plant was very steady, and SDI was below the required value. Based on these promising results, a full industrial plant, a 37.5 MGD open seawater intake desalination plant located in Fujairah, was constructed. The results also showed that the first plant gave good results in terms of turbidity, algae and hydrocarbon removal, leading to a reliable SDI far bellow 3.

Recently, some RO companies have tended to use DAF as the main unit in the pretreatment method for desalination processes. The SingSpring RO plant designed by Hyflux Company consists of filter screens, coagulation, DAF/filtration unit, and RO [72]. According to the company, contaminants such as oil, grease and suspended solids are rejected through the pretreatment process. Moreover, Veolia Water Company constructed a SWRO plant in the

Sultanate of Oman with a capacity of 80,200 m^3/d using DAF and pressure filtration as pretreatment [73]. The main objective of the pretreatment unit will be removal of algae, suspended solids and residue. More details about the application of DAF in desalination processes are found elsewhere [74].

5. Conclusion

Based on this review, the following conclusions can be drawn:

- DAF is an effective method in clarifying different types of wastewater. It has been recently accepted in many wastewater applications due to its high hydraulic load and cost compared with traditional clarifying methods such as sedimentation and filtration.
- Using chemicals (coagulants/destabilizers) to form large flocs or modify bubble characteristics (charged and nano bubbles) not only improves DAF performance but also extends its use to new wastewater treatment applications (e.g. ion flotation, sorptive flotation).
- Further improvement of DAF performance can be achieved by integrating this process with membrane cells. The innovative hybrid flotation–MF/UF reduces membrane fouling leading to extending of the membrane life. Further, promising results were obtained by applying this system in the removal of heavy metal ions from aqueous solutions. The significance of the process was illustrated with its application to real industrial wastewater in different studies.
- A hybrid flotation–NF/RO was able to treat wastewater with high quality comparable to the WHO requirements. The review confirmed that DAF must be integrated with a suitable filtration unit such as media filtration or microfiltration in order to obtain accepted values of MFI and SDI. Recently, DAF was successfully used as the main unit in the pretreatmnet for the desalination process.

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