Raw water clarification by flotation with microbubbles and nanobubbles generated with a multiphase pump

A. Azevedo, R. Etchepare and J. Rubio

ABSTRACT

Raw water clarification by flotation was studied by injecting air into a centrifugal multiphase pump to generate microbubbles (MBs) and nanobubbles (NBs). Measurements of gas dispersion parameters were performed and optimal conditions were obtained using a pump pressure of 4 bar. Values showed a bubble Sauter diameter of 75 μm, an air holdup of 1.2%, a bubble surface area flux of 34 s⁻¹ and an NB concentration of 1×10⁶ NBs mL⁻¹ (measuring 220 nm). Then, a study compared flotation with bubbles formed with the multiphase pump (F-MP) to lamellar settling at the clarification stage of a water treatment plant (WTP), in Brazil. The F-MP showed a higher separation efficiency at high hydraulic loads (9–15 m h⁻¹), even without the use of a polymer, reaching 2 NTU (10–25 NTU raw water feed), which was much lower than the technical goal of the WTP (5 NTU). The results and the technical aspects are discussed, and it is concluded that the employment of MBs and NBs with pumps widens new research lines and applications in modern flotation.

Key words | dissolved air flotation, drinking water, micro- and nanobubbles, multiphase pump

INTRODUCTION

Dissolved air flotation (DAF) is being used extensively as a unitary process for water clarification and has gained wide acceptance in the drinking water treatment industry since the early 1990s. The most recent factor explaining this fact worldwide is the severe decrease in the quality of today’s surface waters, especially regarding the increase in the concentration of organic substances that are dissolved, adsorbed or dispersed in aqueous environments. Moreover, research on DAF has demonstrated that modern installations perform better than conventional systems, with a higher efficiency in lowering raw water turbidity, improved algae and suspended solids removal, less chemical consumption, and shorter flocculation times (Reali & Marchetto 2001; Schofield 2001; Rubio et al. 2007; Edzwald 2010; Gross et al. 2016; Hai et al. 2016). On the other hand, the DAF process also presents some disadvantages, namely a large number of complex process variables, higher operating costs, electrical power required and maintenance (Schofield 2001).

The development of high-rate DAF and new applications arising outside Europe, including emerging countries, have been presented in the last four international conferences on this specific subject (Helsinki, in 2000, Seoul, in 2007, New York, in 2012 and Toulouse, in 2016). Gross et al. (2016) presented the growth of DAF applications in South America, not only the building of new DAF plants but also the upgrading of the existing ones that operate with sedimentation basins. The most outstanding applications are the Rio Grande water treatment plant (WTP), in São Paulo, Brazil (622,000 m³ d⁻¹) and the Laguna del Sauce WTP, in Punta del Este, Uruguay (140,000 m³ d⁻¹).

Advances in the DAF process have been observed with air-saturation and bubble generation techniques, equipment design and major technological developments that have led to an increase in hydraulic loads (HLs). The conventional rate varies between 5 and 15 m h⁻¹, and for a high-rate DAF, values as high as 15–30 m h⁻¹ have been reported (Edzwald 2010). Examples of high-capacity DAF WTPs are New York WTP (12.7 m³ s⁻¹; the biggest DAF WTP in the world) (Crossley et al. 2007); Sangjancon WTP (2.5 m³ s⁻¹) (Sohn et al. 2007), in Korea; and Winnipeg WTP, deployed in Canada (4.6 m³ s⁻¹) (Permitsky et al. 2007).

In DAF, bubbles are formed by reducing the pressure of water previously saturated with air at pressures ranging from 3 to 6 bar. The supersaturated water is forced through constriction devices (e.g., needle valves and venturi) and bubbles are generated downstream, ahead of a flotation tank or column cell (Edzwald 1995; Kiuru & Vahala 2001; Rodrigues & Rubio 2003; Calgaroto et al. 2014). Thus, the process relies on
the buoyancy induced by adding air to a suspension of flocculated water, which drives the flocc-bubble aggregates to the top of the DAF reactor towards the flotation layer, while the clarified water is withdrawn at the bottom of the DAF reactor (Bratby & Marais 1977; Lazaridis et al. 1992). Quite recently, it was discovered that nanobubbles (NBs) are generated together with microbubbles (MBs) in the DAF process (Calgaroto et al. 2014; Azevedo et al. 2016) and their effects on the removal of pollutants from water have been demonstrated (Amaral Filho et al. 2016; Calgaroto et al. 2016; Etchepare et al. 2016).

This paper aims to investigate: (1) the characteristics of MBs and NBs generated by a DAF multiphase pump and the optimization of gas dispersion parameters at the laboratory scale using deionized (DI) water; and (2) the clarification of raw water at pilot scale, at the Rio Branco WTP (R-WTP) installed in Canoas (Brazil), by DAF with the multiphase pump (F-MP), compared with a conventional lamellar settling (LS) process. The main technical goal of the latter was to assess the efficiency of both processes in reducing water turbidity at different HL, evaluating the addition of a polymer flocculant and a coagulant (aluminum sulfate).

**METHODS**

**Characterization of bubbles generated by multiphase pump and gas dispersion parameter measurements**

The bubbles generated by air injection into the suction chamber of a multiphase pump (Edur® EB3) were characterized by their size and concentration using two different techniques: (1) MB characterization using a non-intrusive image analysis technique (LTM-BSizer®) jointly with image analysis software MATLAB® version 5.3.0.10183 (Rodrigues & Rubio 2005); (2) NB characterization using the nanoparticle tracking analysis (NTA) technique (ZetaView® equipment, Particle Metrix, Germany). The experimental setup employed for bubble characterization is shown in Figure 1. This system was operated with DI water recirculation (40 L) under constant temperature (21°C) controlled by a heat exchanger; all experiments were carried out in duplicate.

It is well established that the bubble surface area flux ($S_b$, s⁻¹) plays a key role in the flotation efficiency (Gorain et al. 1997). The apparent linear or near-linear relationship between $S_b$ and collection zone first order rate constant has been documented (Deglon et al. 1999) and debated (Heiskanen 2000).

Because modern instrumentation is not yet capable of measuring the $S_b$ directly, one approach involves measuring the Sauter mean bubble diameter ($D_{32}$) and calculating the $S_b$ from the superficial gas velocity ($J_g$) in Equation (1).

$$S_b = 6 \frac{J_g}{D_{32}}$$

(1)

The $D_{32}$ was obtained using image analysis. The volumetric fraction of air (air holdup) in the flotation column was determined by the differential hydrostatic pressure (pressure transmitter SP98, Sitron®, pressure range 0–0.15 bar) between two points of the column separated by a height of 1.2 m (corresponding to a hydrostatic pressure of 0.118 bar) and calculated by Equation (2),

$$\varepsilon = \frac{0.118 - (P_B - P_A)}{0.118} \times 100 \%$$

(2)

where $\varepsilon$ is the air holdup (%); $P_B$ is the hydrostatic pressure in the point B (bar); $P_A$ is the hydrostatic pressure in the point A (bar). The superficial gas velocity ($J_g$, cm s⁻¹) was obtained by Equation (3),

$$J_g = \frac{Q_g}{A}$$

(3)

where $Q_g$ is the air flux (cm³ s⁻¹); $A$ is the cross-sectional area of the column (cm²).

The samples for NB characterization were collected directly from the column of the LTM-BSizer using a glass beaker and left for 5 min for MB separation (Calgaroto et al. 2015), and then analyzed by the NTA technique to assess their size and numeric concentration.

**Study of raw water clarification at pilot scale**

Table 1 shows the characteristics of the raw water from the R-WTP used during the study. The turbidity of both the raw and treated water was monitored using a portable nephelometer (AP 2000® Policontrol). The pH was measured with a pH meter (Analion® PM 608). All measurements were performed in duplicate.

The reagents used in the pilot studies were the same as those employed in the R-WTP: aluminum sulfate ($Al_2(SO_4)_3$), a non-ionic high-molecular-weight polyacrylamide flocculant (polymer, supplied by PWG Qemifloc AH1020), and a lime solution for pH adjustment.
The pilot plant is shown in Figure 2 and the main equipment design and process data are summarized in Table 2. This rig consisted of three basic units: (1) the aggregation unit, containing stirring tanks with rapid and slow mixing; (2) an F-MP unit, composed of a flotation cell and the same type of multiphase pump characterized in the laboratory.

### Table 1 | Characterization of raw water from the R-WTP, southern Brazil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analysis method (APHA 2005)</th>
<th>Raw water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>pH</td>
<td>Standard methods – 4500 H +</td>
<td>6.8</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>Standard methods – 2130 B</td>
<td>24</td>
</tr>
<tr>
<td>Total solids (TS) (mg L⁻¹)</td>
<td>Standard methods – 2540 B</td>
<td>150</td>
</tr>
<tr>
<td>Total suspended solids (TSS) (mg L⁻¹)</td>
<td>Standard methods – 2540 D</td>
<td>7</td>
</tr>
<tr>
<td>Total dissolved solids (mg L⁻¹)</td>
<td>Difference between TS and TSS</td>
<td>143</td>
</tr>
<tr>
<td>Color (uH)</td>
<td>Standard methods – 2120 C</td>
<td>171</td>
</tr>
<tr>
<td>Alkalinity (mg CaCO₃ L⁻¹)</td>
<td>Standard methods – 2320 B</td>
<td>26</td>
</tr>
</tbody>
</table>
(Edur® EB3); (3) the LS unit, which consisted of a tank with inclined tubes, whereby the flocs settle more rapidly, maximizing the available settling area (Silveira et al. 2009).

The raw water was collected from the R-WTP reservoir using a centrifugal pump operated at different flow rates to achieve adjustable HL values.

Pilot-scale experiments were conducted in two different phases. First, a comparative study of the F-MP and LS techniques was conducted at different HL (2, 3, 4, and 5 m h\(^{-1}\) for LS; 9, 11, 13, and 15 m h\(^{-1}\) for F-MP) using aluminum sulfate (30 mg L\(^{-1}\)) in the coagulation stage (coagulation-F-MP/LS). Second, a non-ionic high-molecular-weight polyacrylamide (PWG Qemifloc AH1020) was added as a polymer after coagulation (coagulation-flotation-F-MP/LS). The same polymer concentration as that applied in the R-WTP (0.06 mg L\(^{-1}\)) was employed in the LS experiments. In the F-MP experiments, the polymer concentration was varied at two different levels (0.03 and 0.06 mg L\(^{-1}\)) during the run of the experiment. Next, the raw and treated water samples (50 mL) were collected at different time intervals during the experiments for turbidity measurement.

### RESULTS AND DISCUSSION

#### Characterization of bubbles generated by the multiphase pump

The generation of MBs and NBs was accomplished by the shearing effect of the pump impellers and hydrodynamic
cavitation through the flow constrictor. In these experiments, the liquid flow rate was 1,000 L h\(^{-1}\) and the air/liquid ratio was set at 7.5%. Under this condition, the liquid superficial velocity was 0.035 m s\(^{-1}\) with a retention time of 2.1 min. Table 3 shows the effect of operation pressure on the gas dispersion parameters. These results indicate that the air holdup increased as the superficial air velocity increased, reaching values close to 1.2%. This effect appears to be due to the greater accumulation of air in the contact zone as more air is fed into the cell.

Ahmed & Jameson (1993) reported that gas holdup favors flotation kinetics because it increases the number of bubbles, and therefore the superficial area available for particle collection and the air/solids ratio. The \(S_b\) was another variable favored by the superficial air velocity and by the smaller bubble size, and reached values of the order of 34 s\(^{-1}\). Furthermore, the mean size of MBs decreased from 130 μm to 75 μm, when the pressure increased from 2 to 5 bar.

Overall, the use of a saturation pressure \((P_{sat})\) equal to or higher than 4 bar generates better results. Thus, the best practical condition, to be implemented at the full scale was a \(P_{sat}\) of 4 bar. This condition guarantees a small size of MBs and high bubble surface area flux, while minimizing energy consumption compared to 5 bar. At this operation pressure, the concentration of NBs measured by the NTA technique was \(1 \times 10^8\) NBs mL\(^{-1}\), and their mean diameter was 220 nm.

### Pilot-plant studies

#### Effect of HL on turbidity reduction by F-MP and LS - Phase 1

The steady state of the F-MP process was determined from the stabilization of residual turbidity values after 60–90 min of operation. The steady state of the LS process was reached after 200 min of operation, due to the lower water flow used in these experiments with low HL (2–5 m h\(^{-1}\)) and hence the higher residence time in this system. Figure 3 depicts an experiment where F-MP was employed and the floated sludge was removed from the top of the flotation cell.

Table 4 shows the turbidity reduction of raw water with F-MP and LS, at pilot scale, at steady state and different HL levels. In all HL levels studied, the residual turbidity obtained with F-MP was lower than that obtained with LS. The residual turbidity values of F-MP were similar at all HL levels studied, ranging from 2.1 to 2.9 NTU, which are much lower than the value used as a target after the LS stage in the R-WTP (5 NTU). Thus, F-MP proved to be effective in clarifying the raw water with turbidity values below 25 NTU under the applied conditions. In the range of influent turbidity (up to 25 NTU) employed here, the residual turbidity after F-MP was not influenced by the raw water turbidity, and the lifting power of bubbles generated by F-MP was sufficient for the separation of suspended solids after coagulation.

These results corroborate the data obtained in our characterization of bubbles; the higher \(S_b\) and air holdup

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**Table 3** | Centrifugal multiphase pump – gas dispersion parameters

<table>
<thead>
<tr>
<th>(P_{sat}) (bar)</th>
<th>MB mean diameter (μm)</th>
<th>Air holdup (%)</th>
<th>(J_g) (cm s(^{-1}))</th>
<th>(S_b) (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>150</td>
<td>0.5</td>
<td>0.017</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>105</td>
<td>0.7</td>
<td>0.025</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>1.2</td>
<td>0.042</td>
<td>34</td>
</tr>
<tr>
<td>5</td>
<td>78</td>
<td>1.2</td>
<td>0.042</td>
<td>33</td>
</tr>
</tbody>
</table>

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**Figure 3** | Treatment of raw water by F-MP at pilot scale. Sequential photography of a coagulation-F-MP trial. (a) Time – 10 min; (b) time – 30 min; (c) time – 60 min; and (d) sludge removed on the top of the flotation cell. Conditions: hydraulic load – 11 m h\(^{-1}\); raw water turbidity – 15 NTU; residual turbidity at 60 min of flotation – 2.5 NTU.
values might lead to an increase in the probability of collision, adhesion and capture of solids, aggregates and particles (Gorain et al. 1997; Deglon et al. 1999; Heiskanen 2000). This appears to indicate that the F-MP process has a high separation kinetics, compared to LS, and might be operated at higher HL and lower retention times in the separation tank.

Reali & Marchetto (2001) obtained similar results with the coagulation–flotation of synthetic raw water (kaolin + humic acids) with a low turbidity (6 NTU), achieving a separation efficiency close to 90%. The sedimentation of the aggregates formed by coagulation with aluminum sulfate was not effective at higher levels of HL (3–5 m h⁻¹), resulting in residual turbidities up to 12 NTU. The polymer, at concentrations of 0.04–0.1 mg L⁻¹, is usually applied at the R-WTP to increase the settling rate of the aggregates and thus avoid particle carryover in the treated water stream.

### Influence of polymer concentration on turbidity reduction by F-MP and LS – Phase 2

The second set of experiments at the pilot scale was conducted during the summer, when raw water turbidity is generally higher (30–40 NTU). Table 5 shows the turbidity values of raw water and treated water by F-MP and LS at different polymer concentrations. The results suggest that the addition of the polymer actually increased the residual turbidity of the treated water by F-MP. Furthermore, an increase in the polymer concentration caused a decrease in the solid–liquid separation efficiency by F-MP. It can be concluded that for this type of polymer, an increase in concentration decreases the separation efficiency, likely due to the size of the flocs and the low lifting power of MBs and NBs. However, the residual turbidity obtained by F-MP at an HL of 9 m h⁻¹ was lower than that obtained by LS at an HL of 2 m h⁻¹, even without polymer.

However, it was observed that, in Runs 1 and 3 (no polymer), with the same HL of flotation (9 m h⁻¹) and under the same conditions of coagulation–flotation, the residual turbidity showed higher values (5.1 and 5.8 NTU) than those obtained during Phase 1. This fact can be explained by the high turbidity values of the raw water in Phase 2 (about

### Table 4 | Treatment of raw water at the pilot scale (coagulation + F-MP or LS) and comparison with full-scale LS. Conditions: pH = 6.2; [Al₂(SO₄)₃] = 30 mg L⁻¹; P_{sat} = 5 bar; recycle ratio of F-MP = 20%; G (rapid mixing) = 1,300 s⁻¹; G (slow mixing) = 80 s⁻¹

<table>
<thead>
<tr>
<th>Process</th>
<th>Hydraulic loading (HL), m h⁻¹</th>
<th>Raw water turbidity, NTU</th>
<th>Residual turbidity, NTU</th>
<th>Turbidity reduction, %</th>
<th>WTP residual turbidity (LS-full scale), NTU</th>
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</thead>
<tbody>
<tr>
<td>F-MP</td>
<td>9</td>
<td>18</td>
<td>2.2</td>
<td>88</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
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<td>25</td>
<td>2.5</td>
<td>90</td>
<td>3.4</td>
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<td></td>
<td></td>
<td>11</td>
<td>20</td>
<td>2.5</td>
<td>88</td>
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<td>13</td>
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<td></td>
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<td>14</td>
<td>2.4</td>
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<td>4</td>
<td>3.8</td>
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<td></td>
<td>13</td>
<td>6.8</td>
<td>50</td>
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<td></td>
<td>4</td>
<td>18</td>
<td>9.5</td>
<td>46</td>
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<tr>
<td></td>
<td></td>
<td>12</td>
<td>9.2</td>
<td>49</td>
<td>1.6</td>
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<td>5</td>
<td>26</td>
<td>12</td>
<td>54</td>
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<td>67</td>
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<td>13</td>
<td>8.9</td>
<td>32</td>
<td>3.8</td>
</tr>
</tbody>
</table>

*Each HL level was studied over 2 days (runs) of operation.

Residual turbidity of treated water from the R-WTP (HL = 2.4 m h⁻¹) after lamellar settling (before sand filtration).

### Table 5 | Treatment of raw water at the pilot scale (flocculation + F-MP or LS). Conditions: F-MP hydraulic load = 9 m h⁻¹; LS hydraulic load = 3 m h⁻¹; pH = 6.2; [aluminum sulfate] = 30 mg L⁻¹; P_{sat} = 5 bar; recycle ratio = 20%; G (rapid mixing) = 1,300 s⁻¹; G (slow mixing) = 80 s⁻¹

<table>
<thead>
<tr>
<th>Process</th>
<th>Run*</th>
<th>[Polyacrylamide], mg L⁻¹</th>
<th>Raw water turbidity, NTU</th>
<th>Residual turbidity, NTU</th>
<th>Turbidity reduction, %</th>
<th>WTP residual turbidity (LS-full scale), NTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-MP</td>
<td>1</td>
<td>0</td>
<td>32</td>
<td>5.1</td>
<td>84</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>35</td>
<td>7.5</td>
<td>78</td>
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<tr>
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<td>41</td>
<td>6.5</td>
<td>84</td>
<td>2.7</td>
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</tbody>
</table>

*Each run was performed over different days of operation. In F-MP experiments the change in the polyacrylamide concentration was made after 2 hours of operation.

Residual turbidity of treated water from the R-WTP (HL = 2.4 m h⁻¹) after lamellar settling (before sand filtration).
40 NTU), compared to Phase 1. Even at high air holdup and $S_b$ values obtained with the F-MP, this process is limited by the air–solids ratio, which is very low in high turbidity waters (Edzwald & Haarhoff 2011).

Compared to LS, these results indicate that F-MP was able to reduce turbidity at higher HL values (9–15 m h$^{-1}$) without the use of a polymer.

Final remarks

The research on flotation with centrifugal multiphase pumps, new applications and installation of several units in the reuse of treated wastewater and drinking water is growing steadily worldwide (Gross et al. 2016). In DAF, the most conventional method for the saturation of water with air is the so-called dead-end saturation, where air is pumped into a pressure vessel to form an air cushion, and water flows through the vessel, dissolving away part of the air (Edzwald & Haarhoff 2011). An increasingly popular alternative is called open-end saturation (Lee et al. 2007; Pioltine & Reali 2011), called F-MP, where an amount of air is continuously injected into the low-pressure suction side of a special centrifugal multiphase pump. Herein, efficient air dissolution and generation of MBs and NBs is attained by hydrodynamic cavitation through the flow constrictors (needle valve or venturi tube).

As the water leaves the pump, the high water pressure and large interfacial area of the bubbles enhance the dissolution of air into the water. The advantages of open-end saturation include: (1) high volumetric efficiency, providing a large mass of air per unit volume of recirculation; (2) elimination of saturation chambers; and (3) air may be supplied from the atmosphere rather than by a compressor (Ross et al. 2000). The performance of these pumps after long periods of operation and the need for maintenance because of the deterioration of pumps caused by forced cavitation may constitute a major issue. Thus, more applied research is needed.

Flotation with MBs and NBs is an upcoming technique for the treatment of water and wastewater, and mineral separation in the industry. The high concentration of NBs generated by hydrodynamic cavitation appears to improve the aggregation and hydrophobization of solids (or macromolecules) present in raw water and enhances the flotation efficiency of particles, and organic and inorganic precipitates (Azevedo et al. 2016; Calgaroto et al. 2016, 2015; Etchepare et al. 2016), leading to more energy efficient processes and cleaner technologies, with less reagent consumption for water and wastewater treatment.

CONCLUSIONS

MB and NB dispersion parameters, affecting their formation, were measured in a well-controlled laboratory system. Increasing the $P_{sat}$ from 2.5 to 4 bar increased the superficial air velocity from 7.9 to 34 s$^{-1}$, enhanced the air holdup from 0.5 to 1.2% and decreased the Sauter diameter of MBs from 130 to 75 μm. Under this condition, the NB concentration and sizes were $1 \times 10^3$ NBs mL$^{-1}$ and 220 nm, respectively. At the pilot plant for raw water treatment, the optimal $P_{sat}$ (4 bar) was applied in an F-MP in parallel with an LS process. The comparative results showed some advantages of F-MP over LS with regard to raw water clarification efficiency, namely: (1) higher HL (9 to 15 m h$^{-1}$) for a smaller footprint, operating at a high process efficiency as evaluated by the low residual turbidity of <3 NTU; (2) no need for a polymer; and (3) high separation efficiency in raw water with moderate feed turbidity (12–25 NTU). It is concluded that the F-MP process has a high potential for the production of drinking water, especially in small communities or regions without treated water (compact DAF units). Another potential application appears to be for the retrofit of large-scale plants that operate using sedimentation, aiming to improve water production and supply.

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