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Original Article

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Dissolved Air Flotation for Fiber Removal from Clear Water

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ABSTRACT

We investigated the use of dissolved air flotation (DAF) to treat clear water effluent from the paper industry in order to remove fibers. The dosage of polyaluminium chloride (PAC) was varied in the following concentrations: 0, 75, 100, 125, 150 and 175 mg/L; as well as bubble rise velocity of 18 and 9 cm/min for two types of paper wastewater: print and gloss. Data were statistically analyzed through factorial arrangement 6x2x2. The treatment of the print paper effluent showed better performance in removing the analyzed parameters with an optimal dosage of 100 mg/L PAC, whereas the gloss paper effluent treatment had satisfactory removal of analyzed parameters with an optimal dosage of 150 mg/L of PAC. This led to the observation that the high efficiency directly obtained with the DAF in conjunction with the use of PAC coagulant was an excellent primary treatment option for effluent resulting from the paper industry.

Keywords: fiber recovery, paper industry, total suspended solids.

1. INTRODUCTION

Three forces are currently driving the wastewater treatment market: increasing industrialization, which requires stricter standards for the disposal of effluent to preserve the environmental characteristics of the site; increasing water costs, encouraging water-saving measures and, where possible, its reuse and recycling; and the production and recovery of increasingly advantageous value-added by-products (Pires et al., 2013).

In recent decades, the pulp and paper industry has tended to adapt its productive and operational processes with the main objective of reducing costs and waste, as well as improving its environmental performance. In the Kraft process, even factories with best production practices in terms of water use have a consumption varying from 40 to 55 m^3/tsa, resulting in considerable volumes of effluent for treatment (Brazilian Technical Association of Pulp and Paper, 2011).

In the paper machine, an effluent called white water is generated during the process of forming, pressing and drying the sheet, mainly consisting of a high concentration of cellulosic fibers, mineral filler, settling solids, suspended solids, starch, glue, and fine fibers which increases organic matter content, color and turbidity of the effluent (Sousa et al., 2011).

In the forming part of a sheet of paper in the production process, the white water is collected in channels, located just below the screen. After collection, white water passes through fiber recovery equipment, with both clear water and fibers being reusable in the system in different ways, depending on the quality of recovery of both (Lan et al., 2009).

In the papermaking process, pulp represents the largest percentage of mass and cost. Cellulose constitutes about 80% of the paper composition and contributes approximately 50% to the total cost. This makes the minimization of fiber losses from paper machines a desirable outcome (Belosinschi & Bobu, 2007).

The recovery and reintroduction of cellulose fibers present in the white water from the production process has a number of advantages: it allows for substituting a great part of the treated water use, reduces unit costs, reduces solid waste generation, minimizes the need for landfill sites for final disposal, and reduces fiber overload at the industrial effluent treatment plant, which causes a number of operational problems at the station when present (Foelkel, 2007).

As a basic principle, fiber recovery seeks to prevent it being lost during the process. There are several fiber recovery techniques, such as filters, sieves, decanters, and clarifiers including dissolved air flotation (DAF), which present different recovery percentages (Foelkel, 2007).

DAF technology consists of a three-phase process in which solid particles (flakes) suspended in the liquid medium (water) are separated by the action of gas (air) microbubbles. These air microbubbles adhere to the surface of the flakes, increasing the intensity of the thrust acting on them, which causes them to rise to the surface of the floatation tank where the sludge accumulates over a period of time until collected by the appropriate mechanisms on the surface of the float (Reali, 1991).

DAF has been widely used in the petrochemical, mining, food processing, drinking water treatment and paper and pulp industries (Miranda et al., 2009). The most common application of DAF in the pulp and paper industry is mainly in primary treatment to clarify raw effluent, with an efficiency of up to 98% for suspended solids removal (Costanzi & Daniel, 2002).

This study investigated the use of DAF to treat clear water effluent from the paper industry, aiming to remove fibers lost in the production process.

2. MATERIAL AND METHODS

The present study was developed in a medium-sized paper factory in the mid-west region of Parana, which produces a total of 115,000 tons per year of offset and kraft paper, with an estimated wastewater production of approximately 500 m^3/day and concentration of suspended solids in the effluent from 350 to 500 mg/L.

It is a case study in which the company already had a disc filter for fiber recovery, but the efficiency was around 60% due to operational and technical problems, resulting in fiber losses and an increase in the generation of primary sludge at the end of the treatment system.

The volume of white water generated in the process that was not reused passed through the disk filter for recovery of the fibers and clearing the water for reuse, resulting in an effluent called clear water. The clear water effluents characterized and analyzed in the present study come from two types of offset paper produced by the company: gloss and print.

Preliminary characterization of the clear water effluent and the analyzed parameters were: pH, temperature, chemical oxygen demand (COD), turbidity, total suspended solids (TSS) and apparent color. All analyses were performed according to Standard Methods for the Examination of Water and Wastewater 21st edition (APHA, 2005).

The effluent was heated to 37°C in order to obtain a temperature in the same operating conditions during the industrial process, and it was subsequently submitted to treatment, in triplicate, by means of coagulation/flocculation/flotation in laboratory bench equipment with batch operation according to the methodology proposed by Di Bernardo & Centurione (2003). The coagulant dosage range of polyaluminium chloride (PAC) of 0 (without addition of coagulant) 75, 100, 125, 150 and 175 mg/L was tested, and rise velocity of the air bubbles of RV1 (18 cm/min) and RV2 (9 cm/min) was also tested to verify which of the configurations would behave best in terms of treatment efficiency, to optimize the process.

In order to evaluate the fiber removal capacity and efficiency during treatments, concentrations of TSS, COD, apparent color and turbidity were determined.

PAC is a high molecular weight mineral polymer which, due to the characteristic of its molecular structure, has advantages in flocculation compared to other non-prepolymerized inorganic coagulants whose efficacy is on average 2.5 times higher than the others, as well as having advantages such as the use of a large pH range, the formation of large, rigid and heavy flakes, as well as the ability to remove organic and inorganic fillers (Zouboulis & Tzoupanos, 2010).

The physicochemical characteristics of the PAC used are listed in Table 1.

The parameters set for the DAF assays were chosen from values of the area-specific literature (Pioltine & Reali, 2011; Quartaroli et al., 2014) and are listed in Table 2.

Table 1. Physicochemical characteristics of the PAC coagulant used.

Physical state	Liquid
Solids concentration percentage	36.86%
Density at 25°C	1.260 g/cm^3
pH	2.00 to 3.20

Table 2. Settings of DAF tests.

Parameter	Configuration
Velocity gradient for rapid mixing	500 s^{-1}
Detention time for rapid mixing	60 s
Velocity gradient for flocculation	50 s^{-1}
Residence time for flocculation	5 min
Recirculation	20%
Saturation pressure	5 bar
Saturation time	15 min

3. STATISTICAL ANALYSIS

The statistical analysis performed for the research consisted of a 6 x 2 x 2 factorial arrangement with a completely randomized design. Six different dosages of PAC coagulant were tested, two different types of paper effluent and two rise velocities of the air bubbles tested. The response variables chosen were: apparent color, turbidity, COD and TSS.

The statistical analyses and graphs generated were obtained using Statistica® software version 7.0. Data were transformed (log) to adhere to gaussianity of residue, verified by the Shapiro-wilk test, and homogeneity of variance verified by Bartlett's test at 5% significance. After analysis of variance, multiple mean comparison tests were performed for each parameter using the Tukey test with a significance level of 5%.

4. RESULTS AND DISCUSSION

4.1. Characterization of the effluent clear water

In Table 3, the data with the physicochemical characterization of the clear water effluents for the types of print and gloss paper are presented.

Characterization of the clear water effluent (Table 3) showed a high concentration of fibers in the evaluated industry effluent, which could be removed. This effluent containing high fiber and organic matter loads went directly to the company's wastewater treatment plant, generating fiber waste and making it difficult to treat the final effluent, justifying the need to introduce a more efficient primary treatment system.

By specifically analyzing the parameter related to the fibers (total suspended solids), even after the effluent had gone through the process of recovering fibers from the paper machine, the values were still high: 545 mg/L and 410 mg/L (Table 3) for effluents from the production of print and gloss paper, respectively. Fiber removal in the disk filter system in the paper machine was around 60%; this is not satisfactory, since Foelkel (2007) establishes that a simple filter can recover between 85 and 95% of the fibers.

For common filters, usual characteristics for clear waters are low suspended solids (50 to 80 mg/L), and these suspended solids consist of fibers, mineral fillers, etc. The COD levels of these clarified waters are low, ranging from 40 to 100 mg/L, due to the presence of small or diluted organic compounds (fibrils, fine fibers, starch, etc.). It can be observed that the COD concentration of the studied effluent is up to 81% above the usual values found in the literature for waters that have already undergone a fiber recovery process. Another characteristic of the effluent is the high temperatures, which vary from 30 to 40°C due to the production process and the use of steam in paper drying (Foelkel, 2007).

Table 3. Physicochemical characterization from print and gloss paper clear water.

Parameter	Print	Gloss
Color (Pt–Co units)	1,104	1,760
Turbidity (NTU)	812	544
COD (mg/L)	446	570
TSS (mg/L)	545	410
Temperature (°C)	37	37
pH	7.8	7.8

4.2. Efficiency of removing the studied parameters

Tables 4 and 5 show the efficiency for removing the main response variables studied, calculated on the basis of the values of the two raw clear waters in relation to the residuals after DAF treatment.

In analyzing Tables 4 and 5, it is possible to observe that the rise velocities 1 and 2 presented similar performances in removing the studied parameters. In general, satisfactory removal efficiency was obtained for the print paper effluent (Table 4): apparent color 96.7%, turbidity 99.5% and TSS 98.6%. High efficiency

Table 4. Removal efficiency of DAF for apparent color, turbidity, chemical oxygen demand (COD) and total suspended solids (TSS) parameters in the treatment of print paper clear water.

Print	Apparent color (%)		Turbidity (%)		COD (%)		TSS (%)	
CD (mg/L)	RV1	RV2	RV1	RV2	RV1	RV2	RV1	RV2
0	94.1	94.7	91.9	92	35	33.9	96.7	97.5
75	75.5	89.3	98.8	99.1	11.7	11.1	95	96.2
100	92.6	93.9	99.3	99.4	17.8	10.9	98.2	98.2
125	94.9	94.8	99.5	99.5	23.3	21.9	98.3	98.6
150	92	93.7	98.9	99.4	12.6	12	96.7	97.3
175	95.4	96.7	99.4	99.5	21.1	24.1	93.6	96.8

Where: CD = Coagulant Dosage; RV1 = 18 cm/min; RV2 = 9 cm/min.

Table 5. Removal efficiency of DAF for apparent color, turbidity, chemical oxygen demand (COD) and total suspended solids (TSS) parameters in the treatment of gloss paper clear water.

Gloss	Apparent color (%)		Turbidity (%)		COD (%)		TSS (%)	
CD (mg/L)	RV1	RV2	RV1	RV2	RV1	RV2	RV1	RV2
0	90.5	90.6	87.9	90.3	70.1	70.9	93.2	94.1
75	90.1	93.4	93.4	96.8	50.8	64	81.4	88.4
100	90.6	93.1	91.4	94.9	43.3	46.2	85	88.3
125	94.4	93.4	85.7	94.4	92.5	89.8	86.3	90.7
150	91.2	91.4	92.5	95.5	92.5	92.6	90.9	90.7
175	92.6	94	98	98.2	82.4	88.1	87.5	89.4

Where: CD = Coagulant Dosage; RV1 = 18 cm/min; RV2 = 9 cm/min.

was also observed with DAF for paper gloss effluent, with removal of apparent color of 94.4%, turbidity 98.2% and TSS 94% (Table 5).

This result can be explained due to the composition of each paper type; print (Table 3) has higher fiber content and loads in the inlet production and throughout the system. Theoretically more fibers/fillers are lost during the paper-forming process in print paper, which in turn facilitates the formation of denser flakes, which favor flotation (Di Bernardo et al., 2011).

The concentration of fibers in the inlet in the gloss paper production process is 0.5 to 0.7% and 0.7 to 1.4% in the print. This was confirmed by characterizing the effluent (Table 3) from the TSS concentration, which is directly correlated with the presence of fibers in the effluent (Foelkel, 2007).

Regarding the removal of the COD parameter, which corresponds to the organic matter content dissolved in the effluent, the best performance was observed for the gloss paper effluent (Table 5) whose COD removal was 92.6% compared to the highest COD removal percentage (35%) for the effluent of print paper (Table 4).

The color of a water sample is directly associated with the degree of light reduction intensity that it undergoes due to the presence of dissolved solids, mainly organic and inorganic colloidal material (Di Bernardo et al., 2011). In this case, both the origin of the color and the high COD concentration may arise from effluents from paper and cellulose industries, and contain lignin, cellulose, starch, calcium carbonate, etc. (Sousa et al., 2011).

4.3. Apparent color

The variation in apparent color can be seen in Figure 1.

In Figure 1 it is indicated that the print paper effluent presented the highest index of apparent color removal. We can affirm that there was no statistical difference between the rise velocities tested for the print paper effluent.

In the gloss paper effluent, the rise velocity 2 was better at removing the apparent color at the dosage of 100 and 75 mg/L. There was no statistical difference between the two velocities in the other dosages.

The maximum removal value was 96.7% for print paper effluent (Table 4) at a dose of 175 mg/L (Figure 1), which was statistically similar to the other dosages.

For gloss paper effluent, all dosages allowed more than 90% color removal, with 125 mg/L being the best dosage, and with a maximum removal efficiency

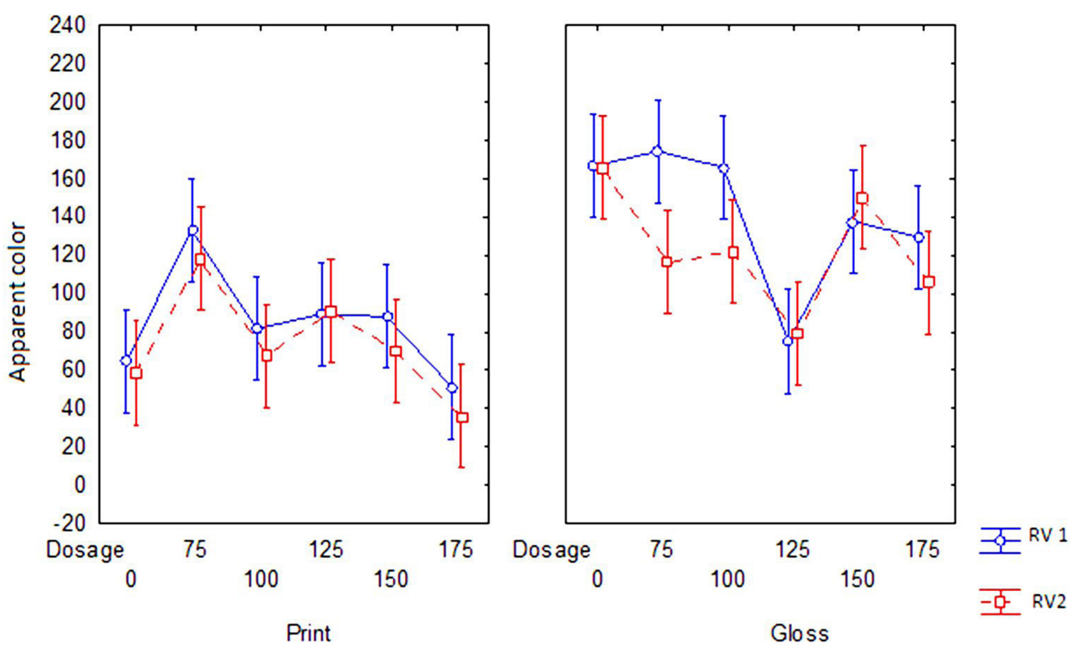

Figure 1. Interaction between: dosage x rise velocity x paper type for apparent color.

of 94.4% (Table 5) without statistically differing from the 175 mg/L (Figure 1). It is important to note that the apparent color of the gloss paper effluent is higher than that of the print, surpassing it by 656 Pt–Co units, and yet it still satisfactorily removed the parameter.

Clarification by means of flotation can be adopted when the raw water has a relatively high color in relation to the turbidity since it facilitates the removal of light flakes, usually produced after coagulation and flocculation (Di Bernardo et al., 2011). This can be observed in Table 3 in which the apparent color of the print and gloss paper effluents were respectively 1,104 and 1,760 Pt–Co units, compared to the turbidity of 812 NTU for print and 544 NTU for gloss.

4.4. Turbidity

The variation in turbidity can be seen in Figure 2.

Figure 2 shows that there was no statistical difference between rise velocities 1 and 2 for print paper effluent. For the gloss paper effluent, velocity 2 (9 cm/min) was statistically the best performance for turbidity removal at dosages 0, 75, 100 and 150 mg/L.

In the interaction between the three studied factors (Figure 2), it is possible to conclude that turbidity presented the highest removal efficiencies for the print paper effluent at the 125 mg/L dosage with 99.5% removal (Table 4), being statistically equal to the other three dosages (100, 150 and 175 mg/L).

For the gloss paper effluent, a maximum of 98% turbidity removal (Table 5) was obtained for the 175 mg/L dosage during the interaction of paper type, dosage and rise velocity factors (Figure 2).

Lima & Reali (1997) obtained similar results with paper-based effluents using DAF as treatment, varying the dosage of PAC (0 to 400) and the pH of the sample (5.5 to 8.0). The highest removal efficiencies were obtained for pH 8 at the dosage of 200 mg/L, with remaining turbidity values of 43 and 32 NTU at the rise velocities of 22 and 8.89 cm/min, respectively.

4.5. Chemical Oxygen Demand (COD)

The variation in COD can be seen in Figure 3.

Figure 3 shows that there was no statistical difference between the rise velocities for the print paper effluent, independent of the interactions between the paper type and the dosages. For gloss paper effluent, rise velocities are statistically similar for all dosages except for the 75 mg/L dosage, in which velocity 2 (9 cm/min) represented a better performance to remove the COD parameter.

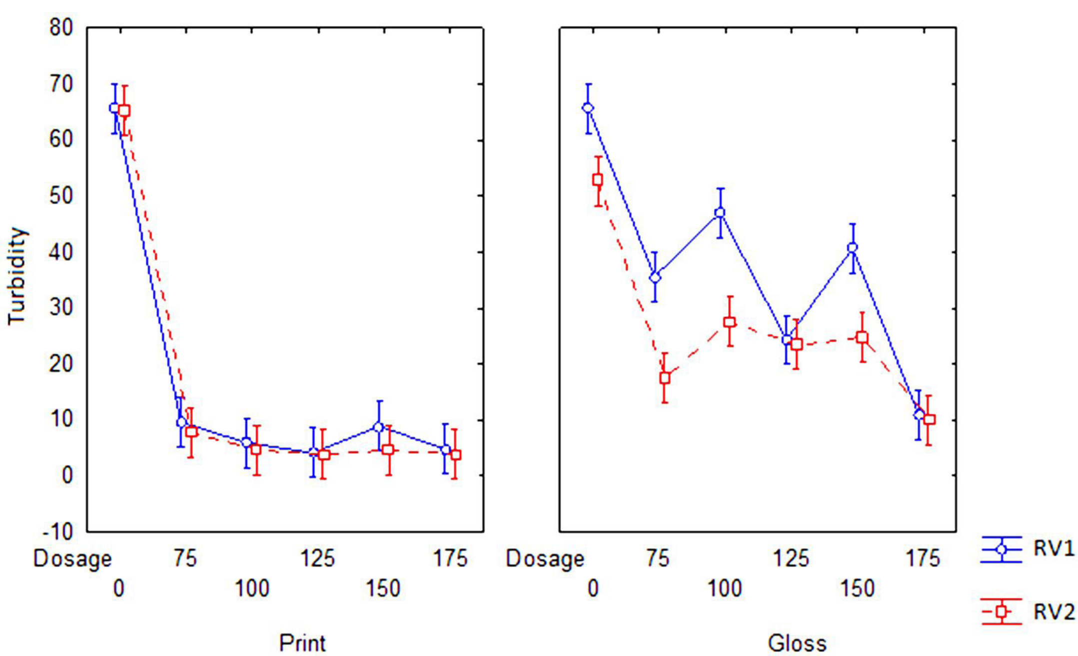

Figure 2. Interaction between: dosage x rise velocity x paper type for turbidity.

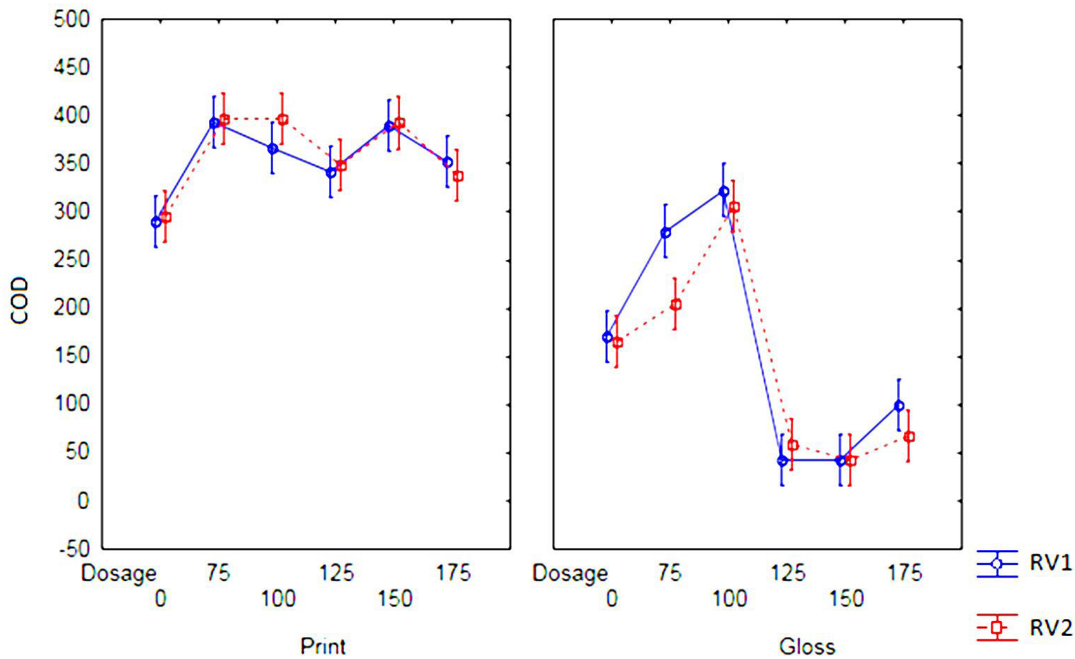

Figure 3. Interaction between: dosage x rise velocity x paper type for COD.

For the print paper effluent, the best dosages statistically were 0, 125 and 175 mg/L. For the gloss paper effluent, the dosages 125, 150 and 175 mg/L, which are statistically similar, are highlighted (Figure 3).

Based on Figure 3, we can see that the gloss paper effluent had the highest COD reduction, with maximum removal efficiency of 92.6% for the 150 mg/L dosage (Table 5). The best removal (35%) was obtained for the print paper effluent without coagulant addition (Tables 4).

Kaya & Kurama (1999) state that treatment by DAF equipment should generally have COD removal efficiency between 80-89%. However, Kuhn et al. (1996) reported removal of COD from 30 to 40% using DAF technology, proving that the percentage of removal can vary according to the composition of each treated effluent.

In the case of the print paper clear water, where the removal efficiencies of the COD parameter were statistically the same for the dosages of 125 and 175 mg/L, and in the absence of coagulant addition, this could possibly be attributed to the remaining COD being in the form of organic matter dissolved in the effluent. Physical and chemical processes such as DAF remove lignin, high molecular weight chlorinated hydrocarbons, color, toxic substances and suspended solids. Compounds of soluble organic matter and low molecular weight such as dissolved solids however, are not efficiently removed (Sharma et al., 2014).

4.6. Total suspended solids (TSS)

TSS variation can be seen in Figure 4.

Based on Figure 4, we can see that the rise velocities tested did not statistically differ for all the analyzed factors, except for the 75 mg/L dosage in the gloss paper effluent, where velocity 2 represented the best results in TSS removal.

In the print paper effluent treatment, the best overall fiber removal (TSS) was obtained (Figure 4) with a maximum value of 98% for the dosages of 100 and 125 mg/L. The removal efficiency for all other dosages tested was above 93% (Table 4). All can be considered statistically similar, demonstrating that this is a highly effective treatment for the removal of the TSS parameter.

DAF technology is very useful when light flakes are to be floated, as this is a process for removing suspended insoluble materials present in waste water (Costanzi & Daniel, 2002), such as the short fibers present in the print paper effluent.

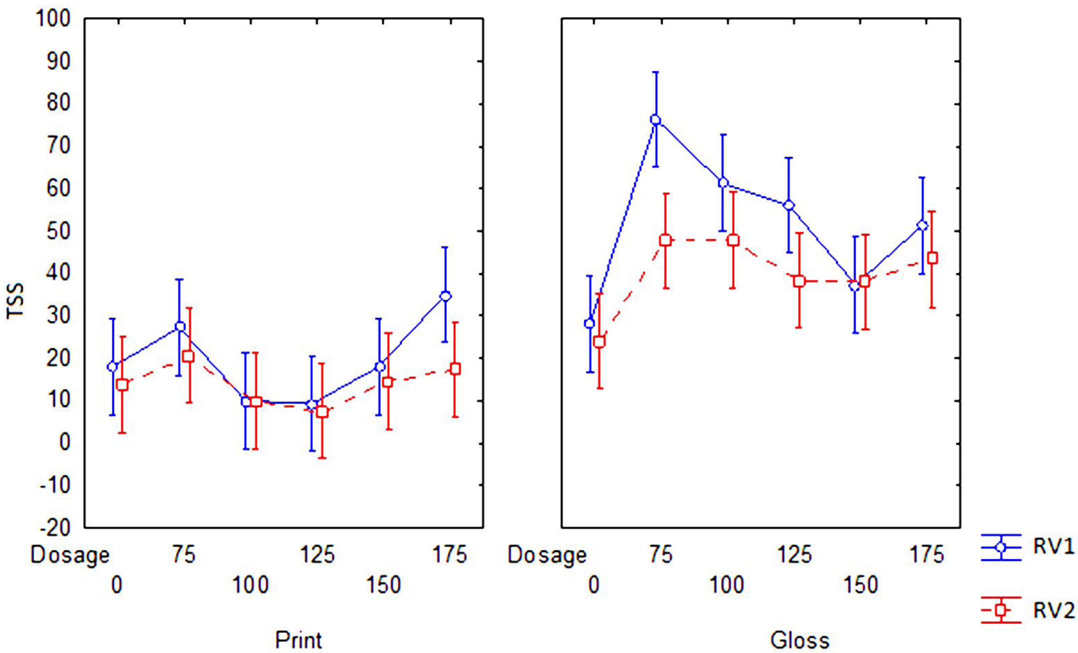

Figure 4. Interaction between: dosage x rise velocity x paper type for TSS.

For the gloss paper effluent treatment, good TSS removal results were also obtained with 94% without the addition of coagulant, being statistically similar to the dosages 125, 150 and 175 mg/L with 90.9% maximum removal. The lowest value obtained for TSS removal was for the dosage of 75 mg/L, with 81.4%. These values are accepted within the range of 70-98%, as described by Ben et al. (2004) as typical for the removal of suspended solids using DAF as the primary treatment. The use of coagulants is generally recommended to achieve greater removal efficiency.

Lima & Reali (1997) obtained good results using DAF in paper machine effluent without the aid of coagulant, attributing this behavior to the use of starch, cationic polymer and other additives used as retention aids that contribute to the formation of the paper sheet in the machine.

4.7. Optimal configuration

Taking into account the flow rate, rise velocity 1 (18 cm/min) is the most indicated because it showed good removal performance of the parameters, and in most cases it was statistically similar to velocity 2. Thus, the volume of effluent treated per amount of time will be higher, which implies an industrial scale in a more compact unit, maintaining the same removal efficiency.

The optimal dosage was chosen hierarchically based on the statistics and the best removal efficiencies of TSS, COD, turbidity and apparent color parameters. In opting for the best treatment efficiencies and the lower applied dosages, the dosages of 100 and 150 mg/L were chosen for the print and gloss paper effluents, respectively.

With the possibility of a compact flotation tank, low operating costs and good energy efficiency, DAF proved to be especially suitable for primary treatment applications in pulp and paper effluents due to its high hydraulic capacity and advanced performance, and when specifically applied to recover suspended solids which contain fibers, fines, and fillers.

5. CONCLUSIONS

The results indicate that the addition of a primary treatment by DAF with the aid of the PAC coagulant improves the characteristics of the clear water effluent, facilitating flotation of the suspended material.

The total suspended solids, which represent the fibers contained in the clear water effluent, presented excellent removal efficiency in relation to the PAC coagulant dosage used in DAF treatment, reaching 98% of TSS removal and with a minimum of 81.7%.

The optimal configuration of the DAF treatment of the gloss paper effluent presented an efficiency of more than 90% for all analyzed parameters, with the dosage of 150 mg/L of PAC and a rise velocity of 18 cm/min.

The optimal configuration of the DAF treatment of the print paper effluent reached removal efficiency values above 92% for all parameters, except for COD (17.8%), for the dosage of 100 mg/L of PAC and rise velocity of 18 cm/min.

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