Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1038732

57 (2016) 6106–6115
March

Taylor & Francis
Taylor & Francis Group

The effect of suspended matter concentration on the coagulation–flocculation and decantation process for low brackish water $C_{(NaCl)}$ = 3 g/L

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Received 12 February 2014; Accepted 29 March 2015

ABSTRACT

This work fits within the pretreatment of brackish water before treatment by reverse osmosis. Our objective was to study the influence of coagulation–flocculation and decantation technique on suspended matter concentrations in brackish water. Tests were conducted in jar tests by varying the coagulant dose, the flocculant dose, and the pH of the medium. A first jar test series conducted on brackish water samples of low salt concentration with different initial concentrations of suspended matter has shown that aluminum sulfate remains the most interesting compound for the suspended matter removal, and determining the optimum dose of coagulant is very difficult for low turbidity water. Then, a second jar test series carried out with a mixture of aluminum sulfate and the polymer showed the influence of molecular weight and the degree of cross-linking polymers on treatment efficacy. In fact, a phase of study was conducted focusing on determined optimal concentration of coagulant and flocculant which aims to evaluate the pH effect on the removal of suspended matter. Finally, some tests have been carried out on the pilot "TE 600", and then, we compared the given results within those found in the jar test.

Keywords: Brackish water; Coagulation–flocculation; Jar test; Pilot

1. Introduction

A geological study in the United States has found that 96.5% of water on earth is located in the seas and oceans, while 1.7% is located in the ice caps. Approximately, 0.8% is considered as freshwater. The remaining percentage consists of brackish water, slightly salty water found as surface water in estuaries and as groundwater in salty aquifers [1].

In 2006, Maurel predicted that 1.4 billion inhabitants will not have access to freshwater. He has estimated that this number will increase to 2.3 milliards

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Presented at the 3rd Annual International Conference on Water (CI.EAU 2013), 18–20 November 2013, Algiers, Algeria

1944-3994/1944-3986

in 2031 [2]. The increasing need is linked to the population growth but also to the economic development (industry), widely dominated by agricultural field (irrigation, development).

In fact, the water desalination constitutes one of the ultimate possible answers to slowdown the cresses and lack of water. In many regions, the intensive and large demand for freshwater lead the managers and responsible to the coming back to brackish water resources for the freshwater production [3]. This brackish water can have a wide range of TDS (1,000–10,000 mg/L) and is typically characterized by low organic carbon content and low particulate or colloidal contaminants [4].

Some brackish water components, such as boron and silica, have concentrations that can vary widely from source to source; an important factor in brackish water reverse osmosis (RO) system optimization is accurate characterization of the specific feed water [4]. In brackish water treatment, the limiting recovery factor is mainly attributed of a chemical nature (e.g. precipitation and scale formation by compounds such as calcium carbonate or calcium sulfate). The biofouling potentiality is another limiting factor in brackish water treatment and reclamation. Among brackish water; industrial and municipal wastewaters have a wide variety of organic and inorganic constituents may be present. Thus, limiting factors are sometimes governed by additional characteristics of feed waters, for example organic matter or phosphate scaling potential [5].

Desalination processes used in the treatment of brackish water are generally based on RO [3]. But the major disadvantage of RO membranes is their clogging sensitivity, especially in particular clogging by colloids. In the twenty-first century, RO membrane processes are among the most important, widely commercialized and versatile water treatment technologies [6]. This worldwide technology is used for the ultrapure, freshwater production with the resource recovery [7].

The RO systems can be used to remove soluble ions, dissolved solids, and organic materials from high tertiary effluent quality to final polish effluents for reuse or for groundwater recharge [8].

Accordingly, the pretreatment is an important step primordial in RO, intended mainly to reduce the clogging potential of wastewater and to provide a pretreated satisfactory quality of water, which is necessary to the successful implementation of desalination processes.

The conventional pretreatment, widely and currently used in desalination plants operation, is based on physicochemical separations (coagulation/flocculation, decantation, depth filtration, etc.) [9]. For this fouling, coagulation and adsorption are widely used as pretreatments options. Baek and Chang [10] experimental results showed that membrane filterability was enhanced, respectively, by the alum and ferric sulfate addition which has been attributed to the effective destabilization of colloidal particles, as confirmed by particle size measuring distribution. During treatment, soluble foulants present in secondary effluents were entrapped to coagulated flocs and removes the colloidal particle responsible for fouling. Their results further showed that the hydrophobic membrane showed higher flux decline than the hydrophilic membrane and flux enhanced significantly in the later than initial one. For these reasons, they recommended that for controlling membrane fouling, a pretreatment using coagulation is more efficient for hydrophobic against hydrophilic [10].

Coagulation–flocculation facilitates the removal of suspended solids and colloids, by gathering them as flocs whose separation is carried out by decantation, flotation and/or filtration. This is a physical treatment which eliminates all or part of the effluent pollutants, including particulate inert or living fractions, flocculatable fractions of organic materials and certain heavy metals, suspended matter associated to micropollutants and colloidal macromolecules [11].

Prior to treatment by RO, the study aim was to observe the suspended matters influence on coagulation–flocculation and brackish water decantation. Jar test experiments were performed on brackish water samples of low salt concentration (C_{NaCl} = 3 g/L) and different initial concentrations of suspended matters. Various reaction parameters were varied namely pH, coagulant dose, and flocculant dose.

After coagulant optimization and flocculant concentration, tests have been realized using coagulation–flocculation and decantation pilot «TE 600». We then compared the obtained results from pilot with those found by the jar test.

2. Materials and methods

2.1. Reagents and solutions

The water samples were prepared in the laboratory from the tap water permeate and whose conductivity does not exceed 200 μS. Commercial lime and salt were used.

2.2. Preparation of coagulant

As coagulant salt, powdered aluminum sulfate [$Al_2(SO_4)_3 \cdot 18H_2O$] was used. A stock solution of 10 g/L was prepared by dissolving periodically this powder in distilled water. The dosages of ferric chloride used ranged between 10 and 70 mg/L.

2.3. Preparation of flocculant

As flocculant, a cationic polymer (polyamide) has been chosen which is used by "Sakak" dam station as a coagulant aid. The dosages of ferric chloride used ranged between 1 and 8 mg/L.

2.4. Description of flocculation tests

One used the jar test at the first time to find the optimal amounts of coagulant and of flocculating used agent then we used the jar test flocculator mark 11197, comprises 4 agitators were the number of rotations can vary between 0 and 200 rev/min. The blades have propellers type and the volume of the beakers is of 1 l. Then, we carried out tests on the pilot of coagulation–flocculation and decantation "TE 600".

The used jar test protocol is as follows:

- Preparation of 1 l of sample, with pH adjustment,
- fast stirring at 200 rev/min for 2 min, during the introduction of coagulant,
- slow stirring at 30 rev/min for 20 min,
- stopping the stirring, raising stirring blades, and decantation for 15 min,
- sample of 30 ml decanted water from each beaker (Fig. 1).

The coagulant used is aluminum sulfate $[Al_2(SO_4)^3{\cdot}18H_2O]$, while the coagulant aid (polymer) is a non-ionic (cationic polymer; polyamide). The aluminum sulfate dosages used ranged between 10 and 70 mg/L, whereas polymer dosage varied between 1 and 8 mg/L. A four beaker jar test was set up at room temperature for each trial. Each beaker contained 1 l of the water. The coagulant or polymer was added into the beakers.

The results are expressed in terms of turbidity reduction percentage (yield) to overcome any variation of it.

$$\%\text{ reduction} = \frac{\text{initial turbidity} - \text{residual turbidity}}{\text{initial turbidity}} \times 100 \tag{1}$$

Then, tests on coagulation–flocculation and decantation «TE 600» pilot have been carried out.

2.5. Experimental installation of pilot

The pilot is regarded as a small station; therefore, for carrying out the tests on this pilot, it is always necessary to find the optimal amounts of coagulant and the flocculating agent used on the level of jar test.

Considering our work, we have found the optimal amounts of coagulant and flocculating agent on the level of jar test, taking into account our experiments depending on the pilot TE 600 considered as a small

Fig. 1. The jar test (flocculator 11197) (Hydraulics Laboratory Department, Tlemcen University).

station; this pilot allows studying two types of treatments: coagulation–flocculation and decantation. One can easily study both separately or simultaneously.

The experimental installation used for coagulation–flocculation and decantation tests of brackish water is shown in Figs. 2 and 3.

(1) The food suspension tank, out of PVC transparent, cylindrical, service output 300 l, with sluice drainage of the cylindrical type spherical;
(2) the supply line of the PVC suspension with control valve to chrome brass punch;
(3) the food coagulant tank, service output 30 l, with drainage sluice of the type to spherical plug out of PVC;
(4) the food tank of the flocculating agent, service output 1 l, with drainage sluice of the spherical plug type out of PVC;
(5) the mixture suspension engine and the chemical reagents, of cylindro-conical type out of glass borosilicate, service output 20 l, with drainage sluice of the spherical plug type out of PVC;

Fig. 2. Pilot of coagulation–flocculation and decantation (TE 600) (Hydraulics Laboratory Department, Tlemcen University).

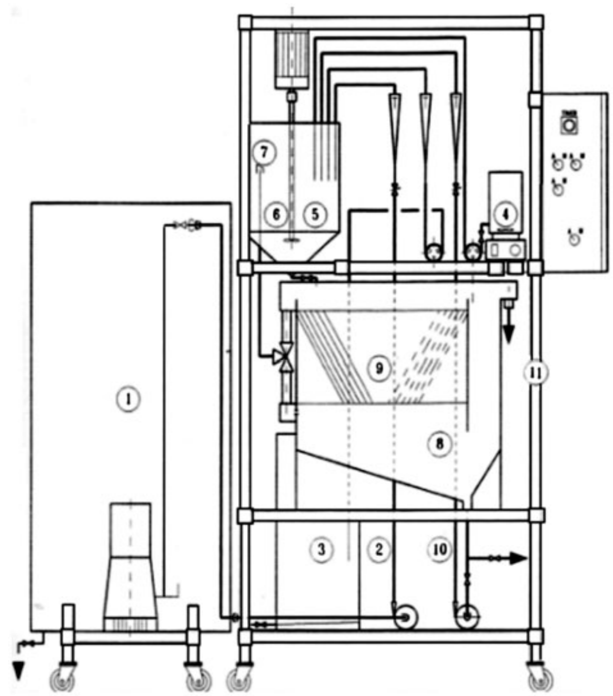

Fig. 3. Experimental device of the “TE 600” pilot.

(6) the engine agitator;
(7) taking away overflow of the suspension leaving PVC engine, adjustable in height;
(8) the static decanter of rectangular section with recovery cone of the mud’s elutriated out of plexiglass:

(a) the feeder valve of the type three ways in “L” with spherical plug out of PVC;
(b) the passage baffle of the clarified liquid;
(c) evacuation of the higher clarified liquid;
(d) the removable evacuation baffle of the liquid clarified for operation with counter-current;
(e) the removable evacuation baffle of the liquid clarified for operation with co-current;
(f) the drainage sluice of mud’s decanter of the spherical plug type out of PVC.

(9) plates of decantation, removable, for operation with counter-current and co-current, in altuglas, with disassembling and inversion rapids (slope of the plates 30°);
(10) the possible drain recycling of the decanter mud’s toward the engine with gate valve of the spherical plug type out of PVC;

(11) the frame of self-supporting quality out of tube squares out of stainless steel.

The product is prepared in the input tray (1) under continuous stirring with an immersed centrifugal pump and is then fed through a flow meter and a control valve (2) in the reactor (5) via a centrifugal pump.

The coagulant is stored in a specific tray (3) and then fed the reactor through a second peristaltic pump. The flocculant is also stored in a specific tray (4) and then fed the reactor through a second peristaltic pump. The reactor is maintained under constant agitation (6) by a propeller stirrer with variable speed. The reactive product is withdrawn through overflow (7) and then fed to the static decanter (8) provided with adjustable slats (9). A portion of the decanted products can be recycled using a circuit (10) with centrifugal pump, control valve, and flow meter.

2.6. *Methods of physicochemical analysis*

Experimental study and analyses were performed using equipments, a 2100N turbidimeter and a PHM220 pH meter.

The turbidity was measured by Naphelometric method using turbidimeter Model 2100 as described in Turbidimeter Instruction Manual Laboratory (HACH, 2000) (Fig. 4).

The pH is measured for the concentration in H^+ ions of water. It translates the balance between acid and bases on a scale from 0 to 14 (7 being pH of neutrality). This parameter characterizes a great number of physicochemical balances and depends on multiple factors, where it belongs to the origin of water.

We measured the potential hydrogenates pH by the pH meter measures (PHM220) This measuring device made up of an electrode of pH which we plunge in the solution and where we want to know acidity, then its pH posts on the screen. The electrode must be rinsed well with tap water, then in the distilled water, after with the analyzed water before each measurement, and the apparatus must be regularly calibrated so that these measurements will be right (Figs. 5–8).

3. Results and discussion

3.1. *Influence of the coagulant dose*

The coagulation–flocculation assays were conducted on synthetic solutions containing increasing concentrations of lime in brackish water ($C_{NaCl} = 3$ g/L) (unadjusted pH). Increasing concentrations of aluminum sulfate were added to the different solutions (Tables 1 and 2).

Essentially, insufficient dosage or overdosing would result in the poor flocculation performance. Therefore, it is significant to determine the optimum dosage in order to minimize the dosing cost, sludge formation, and also to obtain the optimum treatment performance [12].

From Fig. 6, it is noted that the addition of 10 mg/L of coagulant has caused the yield increase of the suspended removal matter and with the increased coagulant concentration; the yield reaches a maximum and then decreases. This is due to the fact that coagulant particles destabilize the negatively charged colloids present in the treating water, by neutralizing charges that generate repulsion forces between the colloids [13,14]. Reaching, respectively, coagulant concentrations of 46, 50, and 60 mg/L for lime-charged water (1, 1.5, and 2 g/L), we appallingly noticed that the yield increases and reaches a maximum value. So we can say that these values are the optimal concentrations of the coagulant. Captions

Fig. 4. The turbidimeter (Hydraulics Laboratory Department, Tlemcen University).

Fig. 5. pH measures (PHM220) (Hydraulics Laboratory Department, Tlemcen University).

Table 1
Effect of coagulant dose on lime removal

	1 g/L of lime			1.5 g/L of lime			2 g/L of lime		
	Turbidity (NTU)		R (%)	Turbidity (NTU)		R (%)	Turbidity (NTU)		R (%)
C_c (mg/L)	Before	After		Before	After		Before	After	
10	10.3	10.03	2.62	11.4	4.16	63.50	13.5	6.96	48.44
20	10.3	9.95	3.39	11.4	3.44	69.82	13.5	5.5	59.25
30	10.3	7.85	23.78	11.4	3.38	70.35	13.5	5.28	60.88
40	10.3	5.75	44.17	11.4	3.28	71.22	13.5	3.46	74.37
42	10.3	6	41.74	11.4	3.2	71.92	13.5	3.02	77.62
46	10.3	4	61.16	11.4	2.45	78.50	13.5	2.85	78.88
50	10.3	4.26	58.64	11.4	0.89	92.19	13.5	1.68	87.55
54	10.3	4.7	54.36	11.4	2.3	79.82	13.5	0.62	95.40
60	10.3	4.88	52.62	11.4	3.44	69.82	13.5	0.58	95.70
70	10.3	7.67	25.53	11.4	4.55	60.08	13.5	1.8	86.66

Note: C_c = coagulant concentration (mg/L); R (%) = the yield (%).

Table 2
Effect of brackish water turbidity on coagulation–flocculation

		Turbidity (NTU)		
Lime concentration (g/L)	C_c (mg/L)	Before	After	R (%)
1	46	10.3	4	61.16
1.5	50	11.4	0.89	92.19
2	60	13.5	0.58	95.7

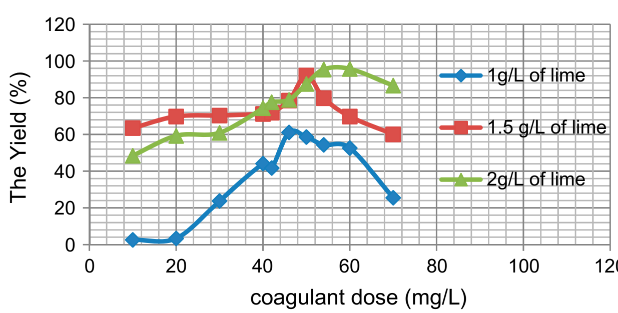

Fig. 6. Effect of the coagulant dose on lime removal.

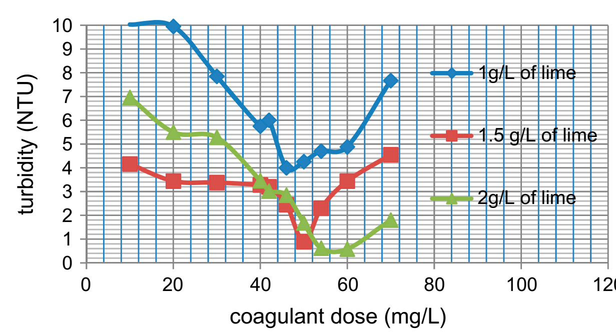

Fig. 7. Effect of the coagulant dose on lime removal.

provided by the coagulant have almost encompassed the totality of colloidal suspensions in the liquid which leads to a better clarity. Increasing suspended matter causes increased turbidity (10.3 NTU for 1 g/L up to 13.5 NTU for 2 g/L). These amounts are included to the fact that a content of suspended matter indicates the presence of suspended particles which exert between them repulsion forces causing a greater turbidity. For a given suspended matter value, adding coagulant produces the decrease of turbidity until the optimal dose, and then slightly increases beyond this dose. From here, we understand that overdoses of coagulant causes the restabilization of the colloidal particles and the availability of their sites decrease then prevent the formation of inter particular bridges [15] after it will be coagulant laden

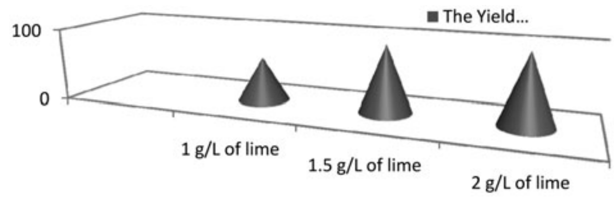

Fig. 8. Effect of brackish water turbidity on coagulation–flocculation.

water with poor clarification. However, from results and from Fig. 8, we see that more the suspended matter increase, more the coagulation effect on turbidity is important, thus for 1 g/L of suspended matter, the maximum decrease is only 4 NTU (R = 61.16%), whereas it is 0.58 NTU for 2 g/L of suspended matter. So we can conclude that the coagulation process is more difficult at low concentrations of colloids because the rate of inter particular contact is probably down.

3.2. Influence of the flocculant dose

Taking into account basically the optimum coagulants concentrations previously determined, a series of tests is performed to approach the optimum flocculant concentration. Figs. 9 and 10 show the final results (Table 3).

From Fig. 9, we see that when we added the flocculant, the turbidity removal is more efficient and at the optimal dose, the yield reached 87.76% for 1 g/L, 94.82% for 1.5 g/L, and 97.33% for 2 g/L of lime. The flocculant addition causes the colloidal agglomeration particles. Thereafter, this colloidal cluster called floc has sufficient mass to settle. Indeed, the micro-flocs formed by agglomeration of previously discharged particles by the effect of the added mineral

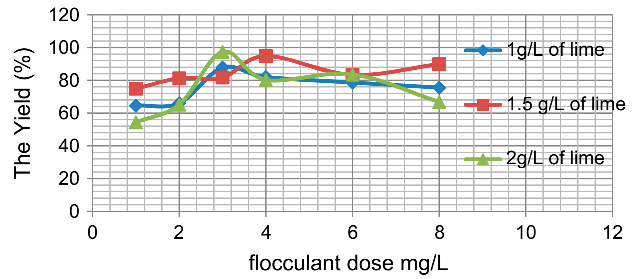

Fig. 9. Effect of the flocculant dose on lime removal.

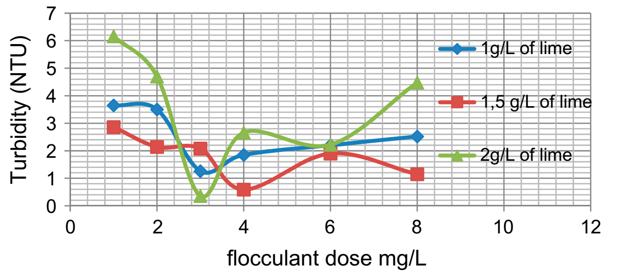

Fig. 10. Effect of the flocculant dose on lime removal.

coagulant are further supported by the macromolecules of added flocculant.

In fact, micro-flocs formed by aggregate particles discharged by the effect of added mineral coagulant are more strengthened by the macromolecules of added flocculant [16,17].

Various studies have shown that the cationic polymers are effective to the removal of suspended matter. Narkis and Rebhun found that cationic flocculant reacts first and preferentially with the dissolved organic matter. Moreover, the characteristics (molecular weight and charge density) of the used cationic polymer are important [18].

Table 3
Effect of the flocculant dose on lime removal

	C_c = 46 mg/L Turbidity (NTU)		R (%)	C_c = 50 mg/L Turbidity (NTU)		R (%)	C_c = 60 mg/L Turbidity (NTU)		R (%)
C_f (mg/L)	Before	After		Before	After		Before	After	
1	10.3	3.65	64.56	11.4	2.86	74.91	13.5	6.16	54.37
2	10.3	3.5	66.01	11.4	2.14	81.22	13.5	4.7	65.18
3	10.3	1.26	87.76	11.4	2.08	81.75	13.5	0.36	97.33
4	10.3	1.85	82.03	11.4	0.59	94.82	13.5	2.66	80.29
6	10.3	2.2	78.64	11.4	1.9	83.33	13.5	2.22	83.55
8	10.3	2.52	75.53	11.4	1.15	89.91	13.5	4.48	66.81

Note: C_f = Concentration of flocculant (mg/L).

The impact of the flocculating agent can be influenced by an important parameter in order to know “the stirring velocity” [19], where a high gradient speed can produce the shearing of the flocs and is likely to destroy them, and consequently one will have a turbidity increase again; in our experiment one used a fast agitation 200/min turns during 2 min in continuation to 20 min of agitation to 30 turns/min, not to precisely dissociate the formed flocs.

3.3. Influence of pH on coagulation–flocculation

From the optimal concentrations of coagulant and flocculant, as determined above, an operational phase is conducted in order to overcome the influence of pH on the lime elimination. The pH adjustment (generally from 2 to 11) was performed during the rapid stirring phase, with solutions of NaOH and HCl (2N).

We present in Figs. 11 and 12, the evolution of lime elimination yields depending on the initial pH of the solutions (Table 4).

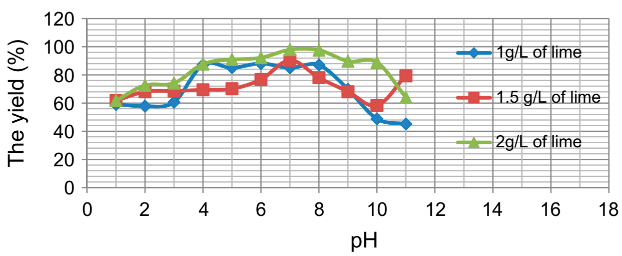

Fig. 11. Effect of pH on coagulation–flocculation.

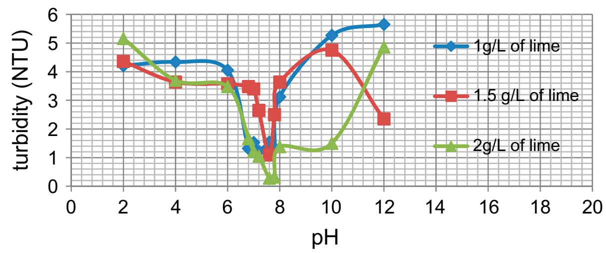

Fig. 12. Effect of pH on coagulation–flocculation.

The effectiveness of alum, commonly used as a coagulant, is severely affected by low or high pH. In optimum conditions, the white flocs were large and rigid, and settled well in less than 20 min. The reduction of turbidity and other parameters were observed to be good at pH 7. The results were in correlation with the studies done by Bina et al. [20].

From Fig. 11, we can observe that the optimum removal of suspended matter and turbidity corresponds to a pH ranging between 6.80 and 7.80. The results confirm the bibliographic data on the removal of colloidal compounds for pH ranging generally between 6 and 8 according to the coagulant nature [21–23]. The aluminum specification depends on pH, aluminum concentration, stirring conditions, and especially inorganic or organic present anions. These anions are indeed considered as ligands complexing the aluminum. During the metal chelation, the most required anions are firstly OH^- ions that determine the pH and some organic groups such as carboxyl, carbonyl, or amines groups [24–26].

Table 4
pH Effect on coagulation–flocculation

pH	C_c = 46 mg/L C_f = 3 mg/L Turbidity (NTU)		*R* (%)	C_c = 50 mg/L C_f = 4 mg/L Turbidity (NTU)		*R* (%)	C_c = 60 mg/L C_f = 3 mg/L Turbidity (NTU)		*R* (%)
	Before	After		Before	After		Before	After	
2	10.3	4.21	59.12	11.4	4.36	61.75	13.5	5.16	61.77
4	10.3	4.34	57.86	11.4	3.64	68.07	13.5	3.7	72.59
6	10.3	4.05	60.67	11.4	3.58	68.59	13.5	3.48	74.22
6.8	10.3	1.32	87.18	11.4	3.48	69.47	13.5	1.66	87.70
7	10.3	1.53	85.14	11.4	3.4	70.17	13.5	1.22	90.96
7.2	10.3	1.22	88.15	11.4	2.65	76.75	13.5	1.05	92.22
7.6	10.3	1.54	85.04	11.4	1.09	90.43	13.5	0.28	97.92
7.8	10.3	1.33	87.08	11.4	2.5	78.07	13.5	0.32	97.62
8	10.3	3.12	69.70	11.4	3.64	68.07	13.5	1.38	89.77
10	10.3	5.27	48.83	11.4	4.75	58.33	13.5	1.5	88.88
12	10.3	5.65	45.14	11.4	2.35	79.38	13.5	4.86	64

In our study, removal of suspended matter and turbidity is greater at pH 7.20 for brackish water loaded with 1 g/L of lime and pH 7.6 for brackish water loaded with 1.5 and 2 g/L.

So for this pH range (7.2–7.6), soluble forms of aluminum are available, in the other side at pH >7.6 and pH <7.2 we have a weak interaction between hydrolyzed forms of aluminum and suspended matter. Finally, we note that pH may itself be influenced by the medium temperature, which have an impact on the solubility of aluminum forms and the dissociation of organic substances [27]. The influence of pH was not systematically investigated because several studies show that the range of pH favorable for coagulation with aluminum sulfate lies between 5.5 and 6.5 or even between 5.0 and 7.0 [28,29].

3.4. Coagulation–flocculation and decantation on the pilot

From Table 5, we note that the obtained value for turbidity after coagulation–flocculation, in the pilot for each type of decantation is greater than that obtained by Jar test, although we used the obtained optimal doses of reagents. The defect hides between several parameters such as the water flow, the decanter shape, the type of the stirring speed, and the decantation time.

From Fig. 13, we see that the lamellar decantation is more effective than the classic one and even in the lamellar settling, the co-current decantation is better. The inclination and the succession of slats in the upper part of the decanter allow reducing the surface of the floor occupancy and increasing the decantation surface. Human waste and fats are generally flocculated before being admitted to decantation. Water and "sludge" by density effect, circulate in opposite directions: the water rises along the lamellae and sludge accumulates in the background.

Table 5
Effect of decantation type (dose of lime = 1.5 mg/L) (optimal concentration of coagulant = 50 mg/L) (optimal concentration of flocculant = 4 mg/L)

Physico-chemical parameters Decantation type	Turbidity (NTU) Before	Turbidity (NTU) After	*R* (%)
Lamellar decantation			
Co-current	11.4	3.32	70.87
Counter-current	11.4	4.45	60.96
Classic decantation	11.4	4.74	58.42

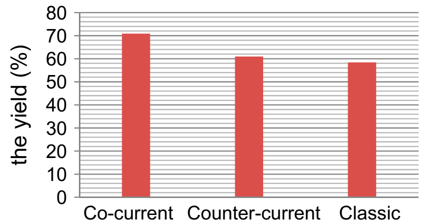

Fig. 13. Percentage of turbidity reduction depending on the decantation type.

4. Conclusions

The experimental conducted study was devoted to the elimination of lime from brackish water by coagulation–flocculation with aluminum sulfate, and to determine the influence of suspended matter on the pretreatment process. The process of coagulation–flocculation has revealed a variety of mechanisms, often complex. This process is more difficult at low colloidal concentrations since the rate of inter particular contact is probably down.

Various tests have been conducted for coagulation–flocculation of brackish water with cationic polymer to improve the quality of treated water and reduce the decantation time.

The influence of pH showed the best performance at pH ranged between 5 and 7 when the compounds are not dissociated, favoring the adsorption on aluminum hydroxide flocs.

Treatment by coagulation–flocculation and decantation on the TE 600 pilot is very effective to improve and promulgate an idea about direct application of the obtained conditions in the jar test on a treatment plant.

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