Reverse Osmosis Method for Sulphate Removal from Treated Wastewater of Al-Doura Refinery

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طريقة التناضح العكسي لإزالة الكبريتات من المياه المعالجة لمصفى الدورة

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Abstract

The treated wastewater by industrial Wastewater Treatment Plant (WWTP) which commonly named (INGECO) in Al- Doura refinery suffers from highly sulphate concentrations that exceeding the EPA specified limits of (250 mg/L). Therefore, laboratory water quality historical data have been reviewed and analyzed to determine annual rate, maximum and peak sulphate concentrations that found to be (360 mg/L), (425 mg/L) and (550 mg/L) respectively, and by field inspection which has been done to specify the reasons of highly sulphate concentrations appeared in wastewater of most refinery process units, found that the maximum required sulphate remaining concentration should be not more than (10 mg/L) to use in energy units. In this study, using Reverse Osmosis (RO) system with four stages, the results obtained indicated that the SO4, TDS, and chloride removal efficiencies when direct used with treated wastewater ranged between (95.97% to 98.35%), (95.06% to 97.60%) and (98.38 to 98.93%) respectively, and with five stages were (99.18%, 99.30% and 99.38%) respectively. The major advantage of direct use of RO system was the production of high-quality water, while a major disadvantage is expensive in treatment cost of about (0.4 $US/m3), and production of brine that requires disposal with incurs additional costs. While in pretreatment by chemical precipitation with RO system of one and two membranes for reuse purpose to reduce maximum and peak concentrations to (250 mg/L), it was found that in one membrane (sulphate, chloride and TDS) achieved removal efficiencies of (98.80%, 91.10%, 96.10%) and (97.90%, 92.00% and 96.00%) respectively, and in two membrane achieved of (98.80%, 93.0%, 96.40%) and (98.80%, 95.00%, 96.40%) respectively. As one of the most important additional benefits of this method is to maintain the membranes of osmosis of rapid damage, but one of the most significant disadvantages is the high cost of about (0.59 $US/m3).

Keywords : Sulphate , Wastewater Treatment , Al- Doura Refinery and Reverse Osmosis.

المستخلص

تعاني المياه المعالجة بواسطة محطة معالجة المياه الصرف الصناعية التي تسمى بالانجيكو في مصفى الدورة، من ظهور تراكيز عالية تتجاوز المعايير المحددة من قبل وزارة البيئية العراقية للطرح للأنهار والتي يجب ان لا تتجاوز (250 mg/L). لذلك، تم تحليل البيانات المختبرية لإيجاد المعدل السنوي، الاقصى و ذروة تراكيز الكبريتات في المياه المطروحة الى النهر، حيث وجد بانها (360 550)، (425 mg/L), (mg/L mg/L) على التوالي. وقد اظهرت نتائج التحري الميداني التي اجريت لمعظم وحدات عمليات الانتاج للمصفى بأن الحد الأقصى المسموح به لنوعية المياه المستخدمة يجب ان لا يتجاوز (10 mg/L). في هذه الدراسة، تم استخدام منظومة التناضح العكسي ذات الاربع مراحل، فقد اظهرت النتائج بان كفاءة ازالة الكبريتات, المواد الصلبة الذائبة والكلوريدات عند الاستخدام المباشر للمياه المعالجة تتراوح بين (95.97% الى 98.35%) و(95.06% الى 97.60%) و(98.38 الى 98.93%) على التوالي. اما في حالة استخدامها بخمس مراحل فان كفاءة الازالة المتحققة كانت (99.18%) للكبريتات، و(99.30%) للمواد الصلبة الذائبة، و(99.38%) للكلوريدات,حيث ان من اهم فائدة هذه الطريقة هي انتاج ماء عالي الجودة لإعادة استخدامه في وحدات المصفى، لكن بكلفة معالجة عالية نسبياً تصل لحوالي (0.4 $US/m3)، بالإضافة لإنتاجها لمحلول ملحي يتطلب التخلص منه تكاليف إضافية .وقد وجد من طريقة استخدام الترسيب الكميائي كمعالجة اولية لتقليل اقصى وذروة تركيز للكبريتات الى اقل من (250 mg/L) ثم معالجته بمنظومة التناضح العكسي, وقد وجد باستخدام بغشاء واحد بان كفاءة الازالة المتحققة (للكبريتات, الكلوريدات والمواد الصلبة الذائبة) كانت (98.80%, 91.10% ,96.10%) و(97.90%, 92.00% ,90.00%) على التوالي ، اما عند استخدام غشائيين فكانت (96.40%, 93.00% ,98.80%) و (96.40% ,95.00% ,98.80%) على التوالي.. حيث انه من اهم الفوائد الاضافية لهذه الطريقة هي في الحفاظ على اغشية التناضح من التلف السريع، اما من اهم مساوئها الاضافية هي كلفتها العالية التي تصل الى (0.59$US/m3).

الكلمات المفتاحية: الكبريتات, معالجة المياه الملوثة. التناضح العكسي ومصفى الدورة

Introduction

Sulphate is a naturally occurring substance that contains sulphur and oxygen. It is present in various mineral salts that are found in soil and rocks sulphate forms salts with a variety of elements including barium, calcium, magnesium, potassium and sodium. Sulphate may be leached into water from the soil and is commonly found in most water supplies. Magnesium, potassium and sodium sulphate salts are all soluble in water, calcium and barium sulphate are not very easily dissolved in water. There are several other sources of sulphate in water, decaying plant and animal matter may release sulphate into water, numerous chemical products including ammonium sulphate fertilizers contain sulphate in a variety of forms, the treatment of water with aluminum sulphate (alum) or copper sulphate also introduces sulphate into a water supply. Human activities such as the combustion of fossil fuels and sour gas processing release sulphur oxides to the atmosphere, can give rise to sulfuric acid in rainwater (acid rain) which in turn results in the return of sulphate to surface waters in the environment, as well as the source of sulphate in the water resulting from the addition of sulfuric acid for the purpose ion exchange resin regeneration (INAP, 2010). Although sulphate is non-toxic, except at very high concentrations, it exerts a purgative effect:

1) Precipitation of sulphate can cause damage to equipment through the formation of calcium sulphate scale (Maree el at, 1990).
2) At high concentrations, precipitation of sulphate may affect the efficiency of many industrial processes. The corrosive effect of high sulphate waters, particularly towards concretes, is increasingly becoming a major water quality problem for mining operations (Loewenthal el at, 1986).

3) Sulphate, especially precipitation of gypsum, may impair the quality of treated water. In many arid environments gypsum becomes the dominant contributor to salinity in the vicinity of the discharge (Verhoef, 1982).
4) People consuming drinking water containing sulphate in concentrations exceeding 500 mg/L commonly experience cathartic effects, resulting in purgation of the alimentary canal (WHO, 2004). Dehydration has also been reported as a common side effect following the ingestion of large amounts of sulphate.
5) Saline water can lead to the salinization of irrigated soils, diminished crop yield and changes in biotic communities (Papadopoulos, 2005).

EPA determined sulfate in drinking water currently has a secondary maximum contaminant level (SMCL) of (250 mg/L), based on aesthetic effects (i.e., taste and odor). This regulation was adopted by Iraqi Ministry of Environment (MOE) as enforceable standard for effluent disposal to class (A) streams which was taken as limitation in this study.

Sulphate Removal Methods

Literature studies were conducted to investigate the different generally available methods to remove sulphate from industrial wastewater. These methods can be divided into physical processes such as membrane filtration, chemical treatment such as precipitation methods and biological sulphate reduction (Akcil& Koldas, 2006) (Aube , 2004) :

- Physical Sulphate Removal Methods:
  1) Membrane filtration such as RO (reverse osmosis), SRO (Seeded Reverse Osmosis), SPARRO (Slurry Precipitation and

Recycle Reverse Osmosis), ED (Electro Dialysis) and EDR (Electro Dialysis Reversal).

2) Ion exchange

- Chemical Precipitation Sulphate Removal Methods:
  1) Gypsum precipitation.
  2) Ettringite precipitation such as SAVMIN and CESR (Cost Effective Sulphate Removal).
  3) Barite (barium sulphate) formation.
- Biological Sulphate Removal Methods:
  1) Bioreactors.
  2) Constructed wetlands.

Reverse Osmosis (RO)

The driving force for RO is the difference in pressure across the selective permeable membrane where an external hydraulic pressure is applied on the saline brine side of the membrane; therefore the water is forced through the membrane against osmotic pressure (Fell, 1995) (Strathmann, 2015). A schematic diagram is shown in figure [1].

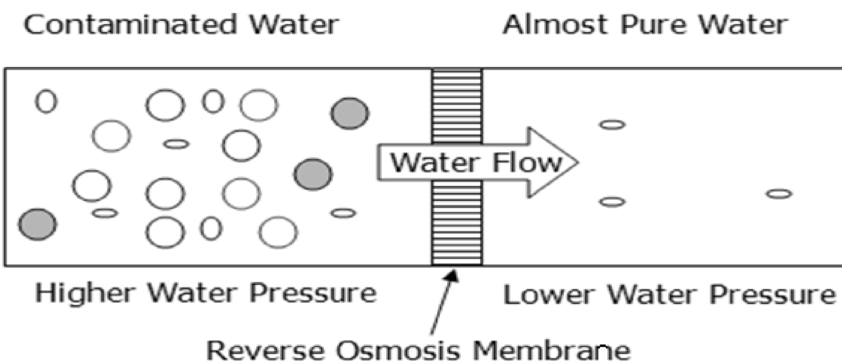

Figure (1): Schematic diagram of RO membrane. After (6)

An RO system consists of four basic stages, namely, pre-treatment, high-pressure pumping, membrane assembly and post-treatment. The pre-treatment prevents membrane fouling from suspended solids, mineral precipitation or microbial growth. It generally involves filtration and/or chemical treatment. A high-pressure pump is required to supply sufficient pressure to force the water through the semi-permeable membrane. This high-pressure pumping is the major contributor to the energy required for this process. Post-treatment involves conditioning of the treated water. This will include pH, alkalinity and hardness adjustments as well as hydrogen sulphide gas removal.

The product water from an RO unit will have a low pH and most probably a high concentration of carbon dioxide. the reason decrease pH depended on the composition of input water source have large or small amounts of gases such as CO2 there is relationship between pH and CO2, CO3 and HCO3 present in feed water, when there is very little CO2, CO3 and HCO3 in feed water, there is a very small pH drop observed in the permeate. RO membranes will reject dissolved ions but not dissolved gases, CO2 will combine with H2O driving reactions that shown in equation, increasing hydrogen ion in water causes decease in pH because pH = - log [H+] .

$$CO_2 + H_2O \rightarrow HCO_3 + H+ \qquad (1)$$

Materials and Methods

After inspection of water quality used in various refinery processes which showed in table (1), it is found that the main highly concentration of sulphate in wastewater reach about (2900 mg/L) coming from blowdown water of energy units. But when it reach the WWTP, the concentration reduced to less than (600 mg/L) by using ion exchange process, then decreased to average level when mixed with other lesser concentration wastewater into WWTP influent collection basin. There wasn't any specific process to control or remove sulphate to reach the effluent disposal limit in WWTP. Laboratory test results for five years (2008 to 2013) have been analysis as shown in figure (2) to determine annual rate and maximum sulphate concentration which found to be (360 mg/L) and (425 mg/L) respectively. Also, peak concentration which possible to reach WWTP for more than (15) days per year considered to be (550 mg/L).

Table (1): Sulphate concentration in various refinery processes

Water treatment unit	SO4 (mg/L)	
	Influent	Effluent
sedimentation basins	(190 – 320)	283
After DMF and ACF		272
After storage tanks when adding chemical substances		300
RO unit	300	(4 – 6)
Water resulting from RO unit (reject)		980
Energy unit – 1	15	15
Energy unit – 1 (reject)		1000
Energy unit – 2 and energy unit – 3	15	0
Energy unit – 2 and energy unit – 3 (reject)		2900
Chiki units (one and two)		120
Hydrogenation units (one and two)		530
Grease unit – 1		155
Grease unit – 2		185
Grease unit – 3		270
WWTP (INGECO) unit	300	360

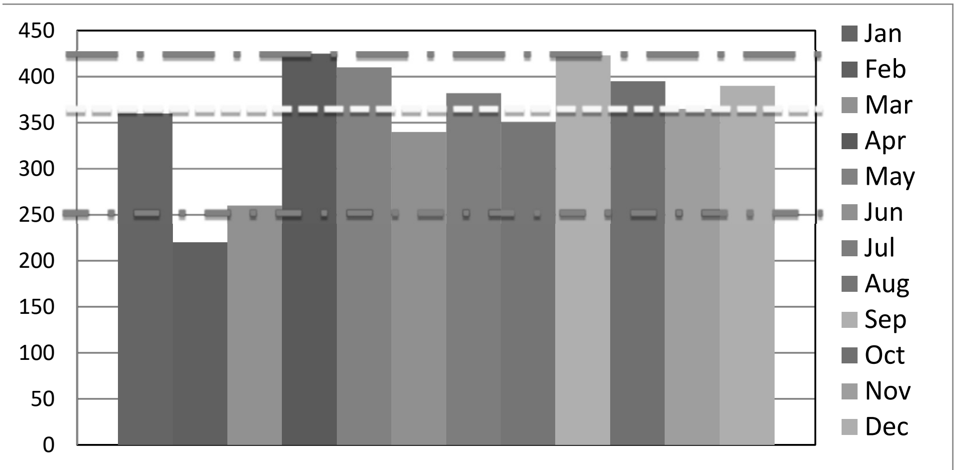

Figure (2): Mean monthly rate of treated water sulphate concentration

A pilot plant was designed, built and operated in home. It consists of a collection tank No.1, water pump No.1, P.P.5 micron (Polypropylene sediment filter), GAC (Granular Active Carbon) filter, P.P.1 micron (Polypropylene sediment filter), water pump No.2, 1 R.O. (reverse osmosis) membrane, collection tank No.2, water pump No.3, 2R.O. (reverse osmosis) membrane, and collection tank No.3, as shown in figure (3).

Figure (3): Pilot Plant

1. Raw Water Collection Tank No. 1:

It is a plastic tank has a capacity of (35) liters as shown in figure (4). The treated water used in the experiments was collected from the effluent of Al Doura refinery wastewater treatment plant.

Figure (4): Raw water collection tank

2. Water Pumps No. 1:

It is used to pump the water from the collection tank to the P.P.5 micron (Polypropylene sediment filter) as shown in figure (5), the specifications of this pump are:

Type pump	**booster pump**
Model	**CR – 004**
Open flow	**1.35L / min**
Pressure	**70 – 125 psi**
Booster	**24 V DC**
Ampere	**0.21 A**
Max operation Temperature	**55 C°**

Figure (5): Pump and transformer

3. P.P. 5 micron (Polypropylene Sediment Filter 5 micron) :

It removes the big particles which is bigger than 5 micron such as dirt, hair, sand and etc. The main function of this filter is to prevent big particles to block the RO membranes, which can extend the lifetime of the RO membrane, as shown in figure (6) (Average lifetime: 3 months).

Figure (6): P.P.5 micron filter

4. GAC (Granular Active Carbon) Filters :

It removes the chlorine, color, odor, bad test and organic chemicals from the feeding water, as shown in figure (7) (Average lifetime: 6 months).

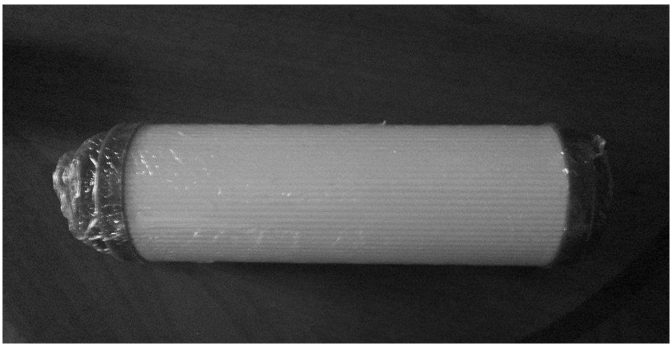

Figure (7): GAC filter

5. P.P.1 micron (Polypropylene Sediment Filter) :

It removes the big particles which is bigger than 1 micron such as dirt, hair, sand and etc. The main function of this filter is to prevent big particles to block the RO membranes, which can extend the lifetime of the RO membrane, as shown in figure (8) (Average lifetime: 3 months).

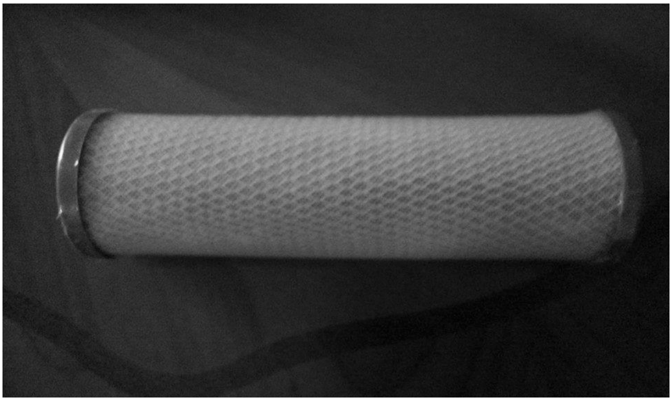

Figure (8): P. P.1 micron filter

6. Water Pump No. 2

It is used to pump the water from P.P.1 micron (Polypropylene sediment filter) to 1 R.O. (reverse osmosis) membrane as shown in figure (5), the specifications of this pump like water pump No.1 specifications.

7. Reverses Osmosis Membrane (1) :

A thin film composite (TFC) high quality membrane can process 50 – 100 gallon per day. It removes 85% - 95% of the particles in the water including the left over chemicals such as: cooper, lead, mercury, sodium and etc, to make it close to pure water, as shown in figure (9) (Average lifetime: 1 – 1.5 years).

Figure (9): Reverses osmosis membrane

Operation Limits :

- Membrane type: thin-film composite.
- Membrane material: Polyamide (PA).
- Maximum operating temperature: 113°F (45°C).
- Maximum operating pressure: 150 psig (10 bar).
- Maximum feed flow rate: 2gpm (7.6 lpm).
- Operation pH range: (2-11).
- Maximum Feed Silt Density Index (SDI): 5.
- Maximum chlorine concentration: < 0.1 ppm

8. Collection Tank No. 2 :

It is rectangular plastic tank used to collect the product water from (RO), with dimensions (60 cm*20 cm*30 cm), as shown in figure (10).

Figure (10): Collection tank

9. Water Pumps No. 3 :

It is used to pump the water from 1 R.O. (reverse osmosis) membrane to 2R.O. (reverse osmosis) membrane as shown in figure (5), the specifications of this pump like Water pump No.1 and No.2 specifications.

10. Reverse Osmosis Membrane (2) :

A thin film composite (TFC) high quality membrane can process 50 – 100 gallon per day. It removes 85% - 95% of the particles in the water including the left over chemicals such as: cooper, lead, mercury, sodium and etc, to make it close to pure water, the same as figure (9) (Average lifetime: 1 – 1.5 years)

11. Collection Tank No. 3 :

It is rectangular plastic tank used to collect the product water from (RO), with dimensions (60 cm*20 cm*30 cm), the same figure (10).

12. Chemical Treatment with Reverse Osmosis (RO) Method by Using Barium Chloride Material (BaCl2) :

In this method sulphate removal from treatment wastewater of Al-Doura refinery by using chemical precipitation using barium chloride material (BaCl2) and after that is entered water to the reverse osmosis unit. In the first chemical water treatment that has been placed in the collection tank before enter reverse osmosis unit by using barium chloride material (BaCl2) as shown in figure (11), the dosage (BaCl2) added to the water depended on:

1) The amount of flow.
2) Sulphate concentration.

3) Residence time of water.

4) Mixing speed.

In the case specifications of water that has been placed in collection tank (required water treated chemical) before enter reverse osmosis unit:

- Volume water = 15 L
- Sulphate concentration in water = 425 mg /L

So that the dosage (BaCl2) added to the water to reduce sulphate form (425 mg/L to 250 mg/L) = (1.2 g/L (BaCl2) * 15 L) = 18 g/15L with mixing speed = 120 rpm and residence time = 15 min.

In the case specifications of water that has been placed in collection tank (required water treated chemical) before enter reverse osmosis unit:

- Volume water = 15 L
- Sulphate concentration in water = 550 mg /L

So that the dosage (BaCl2) added to the water to reduce sulphate form (550 mg/L to 250 mg/L) = (1.8 g/L (BaCl2) * 15 L) = 27 g/15L with mixing speed = 120 rpm and residence time = 15 min.

After that the water treated by (BaCl2) enters to the reverse osmosis unit consisting of three primary filters and then enters the first reverse osmosis membrane (1RO) and then enters the second reverse osmosis membrane (2RO).

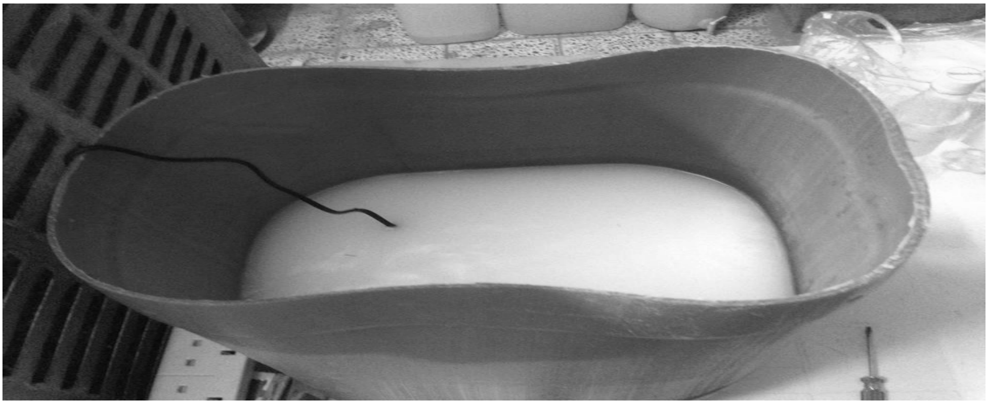

Figure (11): Chemical water treatment by using (BaCl2) before treated water by RO

Results and Discussion

About (24) runs have been done to test the efficiency of using one and two RO membranes for direct removing sulphate of refinery treated water, and before pretreatment with chemical precipitation process by using BaCl2 substance of lesser dosage and retention time.

1. Direct Operating by Using One Membrane

Ten samples of treated water with variable SO4, TDS, Cl, pH and temperatures have been run directly into pilot plant. Test results obtained of initial concentrations; moderate pH ranged from (7.2 to 7.6) and temperatures of (18 – 22°C) with sulphate, TDS and Cl removal efficiency are shown in Figures (A.1-1) to (A.1-6). Obviously observed that using of one RO membrane was sufficient in removing each of SO4, TDS, and chloride concentration in ranged between (95.97% to 98.35%), (95.06% to 97.60%) and (98.38 to 98.93%) respectively. RO system removes TDS from water passing it with high pressure because RO membrane have very tiny micro pores that only let pass the molecules that were smaller than 0.001 micron. As the salts or other metallic dissolved molecules were comparatively bigger than water molecules, the metals and salts will be filtered. This was indicated that RO system can be considered as efficient process in removing chloride and sulphate from water and so reducing TDS concentrations. It is found that with the same SO4 concentration as (360 mg/L), SO4, TDS and Cl removal efficiency increased when TDS and chloride concentrations increased, and the higher removal efficiency occurred with a highest TDS such as a highest sulphate removal of (97.86) occurred when SO4 concentration was (360 mg/L) and TDS was (1572 mg/L), and (98.35%) when SO4 was (425 mg/L) and TDS was (1591). Another conclusion could be declared was pH decreased with increasing of removal efficiency, the reason of decreasing pH depended on the composition of input water source have large or small amounts of gases such as CO2 there was a relationship between pH and CO2, CO3 and HCO3 present in feed water, when there was very little CO2, CO3 and HCO3 in feed water, there was a very small pH drop observed in the permeate. RO membranes would reject dissolved ions but not dissolved gases, CO2 would combine with H2O driving reactions that shown in equation (1), increasing hydrogen ion in water causes a decrease in pH because pH= - log [H+].

2. Direct Operating by Using Two Membrane

Effluent water from one membrane runs into the RO second membrane. The results obtained as shown in Figures (A.2-7) to (A.2-12) indicated the same conclusions which mentioned previously in using one membrane. Where, the highest sulphate removal efficiency of (57.89%) occurred when TDS was (70 mg/L). In addition of that, the highest TDS removal efficiency of (71.79%) occurred with highest influent pH value of (7.8), while influent pH in range of (5.8 to 7.8) tended to be more acidic in range of (5.5 to 7.6) in the effluent.

Figures (A.3-13) to (A.3-18) shows that maximum SO4, TDS and Cl removal efficiencies were (99.18%, 99.30% and 99.38%) respectively. This indicated that the second RO membrane increased removal efficiencies ranged from (0.26% to 2.09%), (1.27% to 3.26%) and (0.40 to 0.71%) for SO4, TDS and Cl respectively. Thus, it can be concluded that there was no need to use more than one RO membrane in case of reuse of treated water in refinery process.

3. Indirect Operating

To increase operation time of RO membranes by reducing harmful effects of highly sulphate in water of (550 and 425 mg/L) to (250 mg/L), pretreatment by chemical precipitation using ($BaCl_2$) in dosage and mixing time with test results obtained as shown in Tables (2) and (3).

Table (2): Test results of maximum sulphate concentrations by using pretreatment with RO system

Parameters	Unit	Initial Value	After (BaCl2)	RO	
BaCl2	g/L	0.0	1.2	1 membrane	2 membrane
tmix	min	0.0	15		
N	rpm	0.0	120		
Ph		7.3	6.75	6	5.9
Tc	°C	23.7	24.4	28.9	28.9
TDS	mg/L	1880	1950	77	70
SO4 (max)	mg/L	425	250	3	3
Cl	mg/L	100	672	60	48

Table (3): Test results of peak sulphate concentrations by using pretreatment with RO system

Parameters	Unit	Initial Value	After (BaCl2)	RO	
BaCl2	g/L	0.0	1.8	1 membrane	2 membrane
tmix	min	0.0	15		
N	rpm	0.0	120		
pH		7.3	7.3	6.3	6.4
Tc	°C	25.2	26.7	29	29.1
TDS	mg/L	2936	2744	110	100
SO4 (peak)	mg/L	550	240	5	3
Cl	mg/L	140	988	80	48

From table (2) it was found that by using one RO membrane (98.8%, 91.1% and 96.1%) removal efficiencies have been achieved for each sulphate, chloride and TDS respectively, and (98.8%, 93% and 96.4%) by using of two membranes. While from table (3) it was found that removal efficiencies achieved of (97.9%, 92% and 96%) and (98.8%, 95% and 96.4%) for one and two membrane respectively. This indicated that using of one RO membrane was sufficient to remove sulphate for reuse purpose. And by comparison the removal efficiencies reused from indirect process with direct process, it can be concluded that there was no valuable increasing obtained. The only reason that insists to use RO system was to reduce TDS and chloride concentrations which valuable increased when using both of chemical precipitation methods as mentioned previously from the results obtained.

Conclusions

1. The inspection of refinery water quality used in various processes that showed in table (1) before indicated that the main highly concentration of sulphate in wastewater that reach about (2900 mg/L) was coming from blowdown water of energy units, because of using sulfuric acid for resin regeneration in ion exchange process.
2. The analysis of WWTP effluent water quality historical data indicated that the annual rate, maximum and peak sulphate concentrations are found to be (360 mg/L, 425 mg/L and 550 mg/L), and pH ranged from (7.0 to 7.6).
3. When was used with pretreatment by (P.P.5 micron, GAC and P.P.1 micron filter) and one RO membrane, it was sufficient in removing each of SO4, TDS, and chloride concentrations in the range between (95.97% to 98.35%), (95.06% to 97.60%) and (98.38 to 98.93%) respectively. This was indicated that RO system can be considered as efficient process in removing chloride and sulphate from water and so reducing TDS concentrations.
4. When was used with pretreatment by (P.P.5 micron, GAC and P.P.1 micron filter) and two RO membrane, the (SO4, TDS and Cl) removal efficiencies were (99.18%, 99.30% and 99.38%) respectively. This indicated that the second RO membrane increased removal efficiencies ranged from (0.26% to 2.09%), (1.27% to 3.26%) and (0.40 to 0.71%) for SO4, TDS and Cl respectively. Thus, it can be concluded that there was no need to use more than one RO membrane to ruse of refinery treated water.

5. While in pretreatment by chemical precipitation with RO system of one and two membranes for reuse purpose to reduce maximum and peak concentrations to (250 mg/L), it was found that in one membrane (sulphate, chloride and TDS) achieved removal efficiencies of (98.8%, 91.1%, 96.1%) and (97.9%, 92% and 96%) respectively, and in two membrane achieved of (98.8%, 93%, 96.4%) and (98.8%, 95%, 96.4%) respectively.
6. The major advantage of direct use of RO system was the production of high-quality water, while a major disadvantage is expensive in treatment cost of about (0.4 $US/m3), and production of brine that requires disposal with incurs additional costs.

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Reverses Osmoses System

A.1 First Membrane

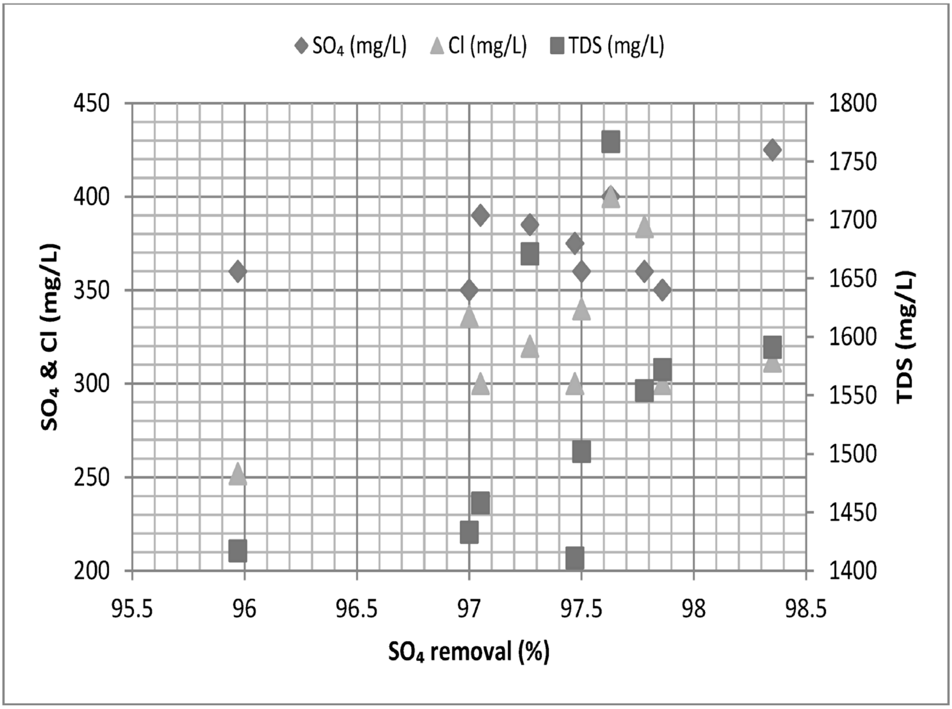

Figure (A.1–1): SO4, TDS and Cl concentrations with SO4 removal efficiency.

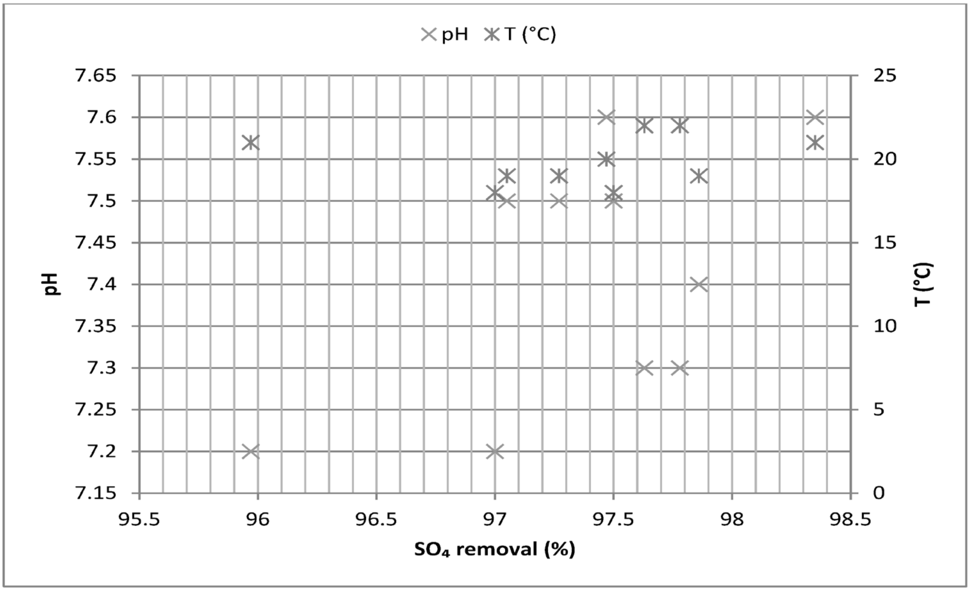

Figure (A.1–2): pH and temperature values with SO4 removal efficiency.

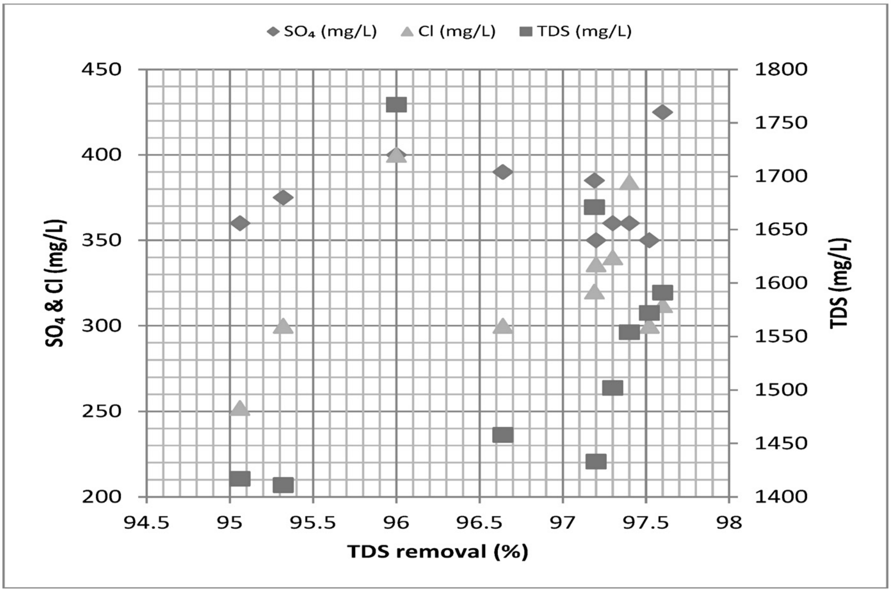

Figure (A.1–3): SO4, TDS and Cl concentrations with TDS removal efficiency

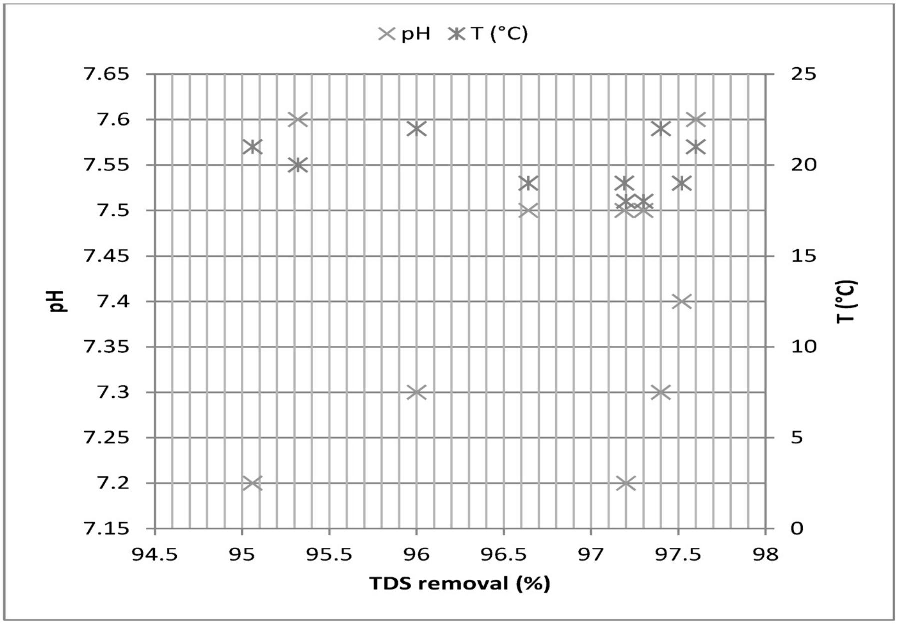

Figure (A.1–4): pH and temperature values with TDS removal efficiency.

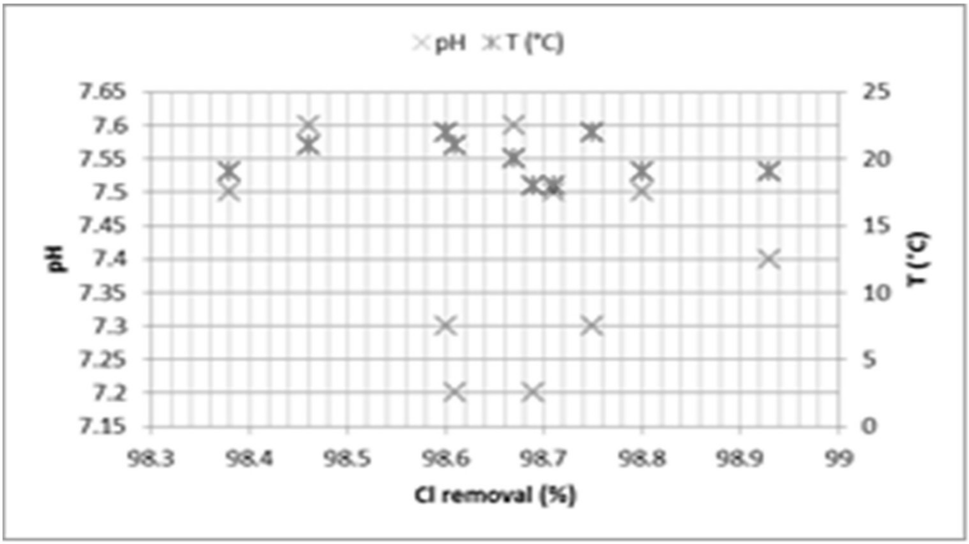

Figure (A.1–5): SO4, TDS and Cl concentrations with Cl removal efficiency.

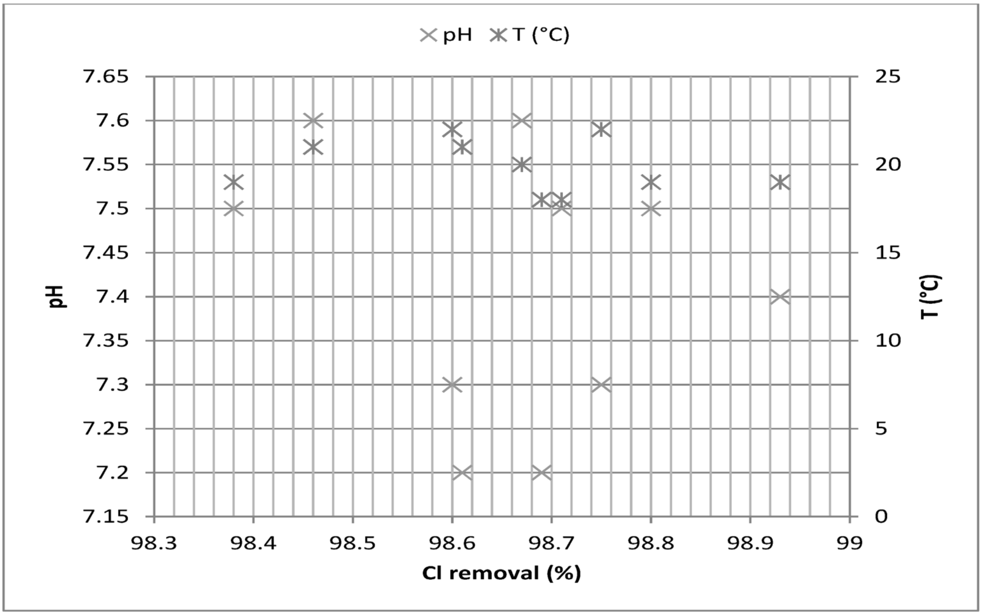

Figure (A.1–6): pH and temperature values with Cl removal efficiency

Reverses Osmoses System

A.2 Second Membrane

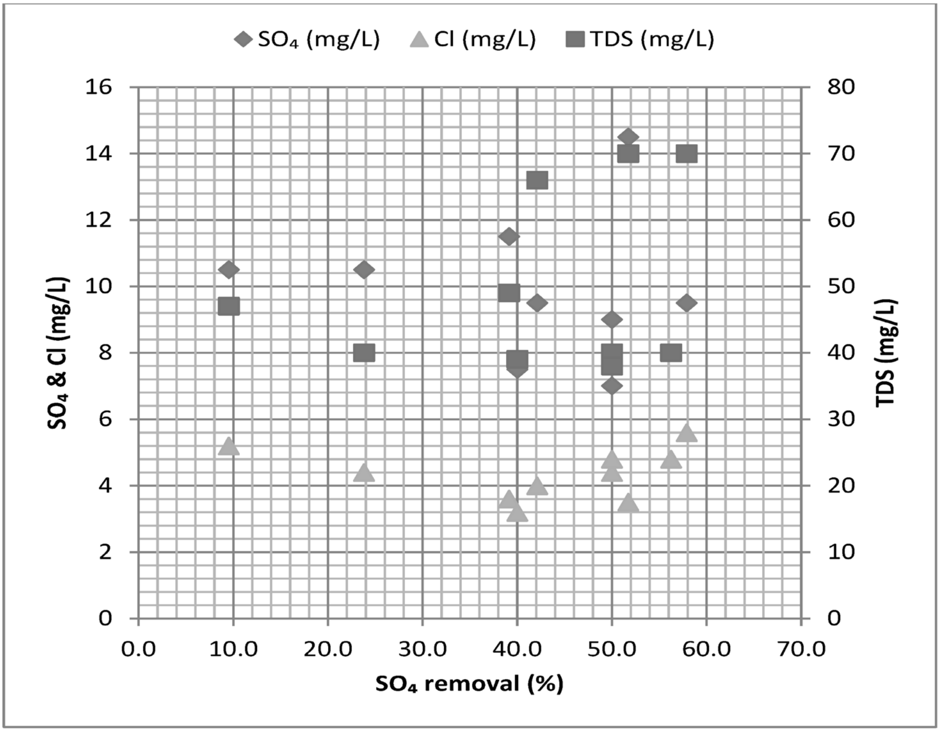

Figure (A.2–7): SO4, TDS and Cl concentrations with SO4 removal efficiency..

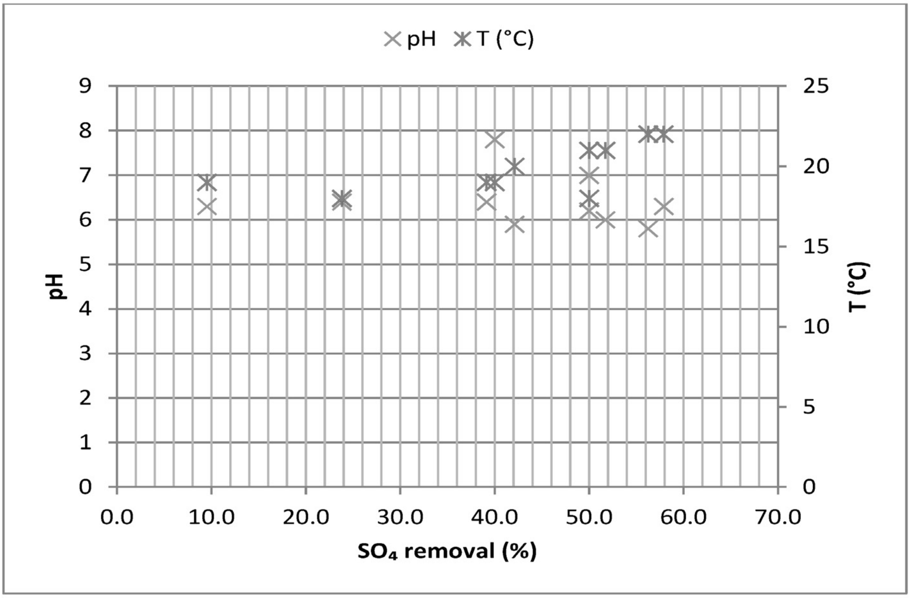

Figure (A.2–8): pH and temperature values with SO4 removal efficiency

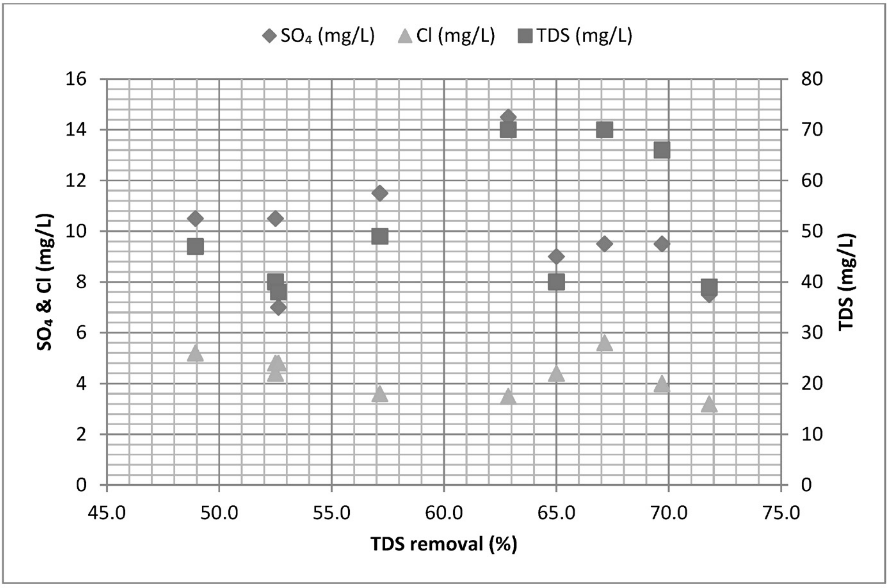

Figure (A.2–9): SO4, TDS and Cl concentrations with TDS removal efficiency.

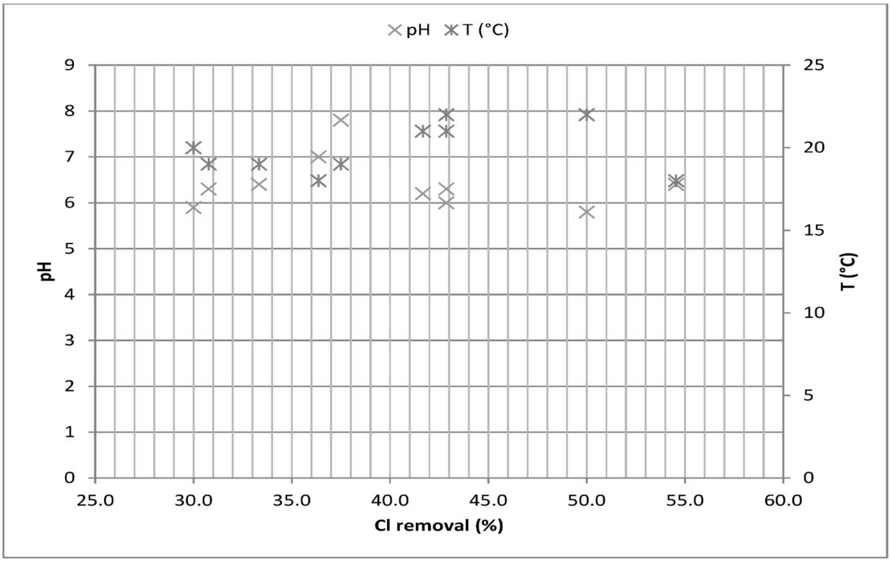

Figure (A.2–10): pH and temperature values with TDS removal efficiency

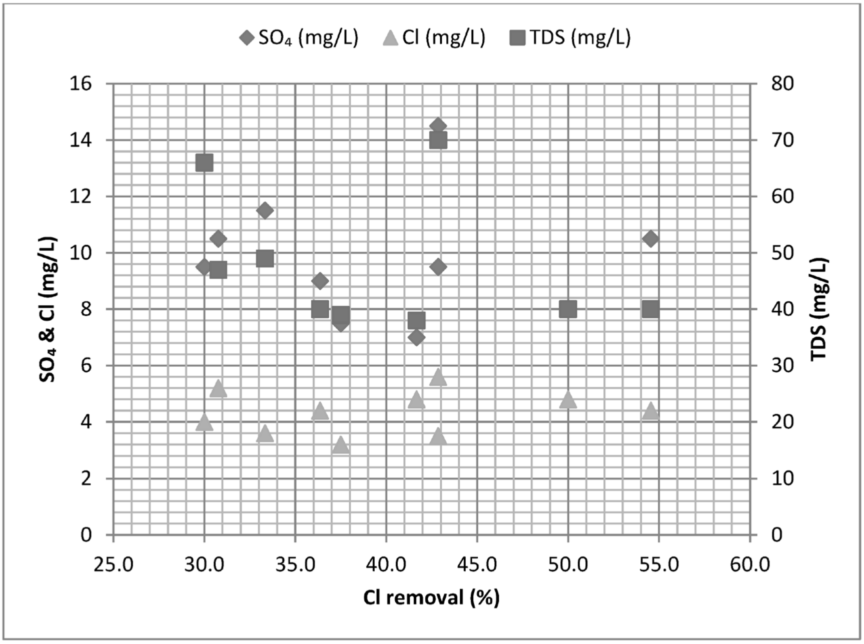

Figure (A.2–11): SO4, TDS and Cl concentrations with Cl removal efficiency. .

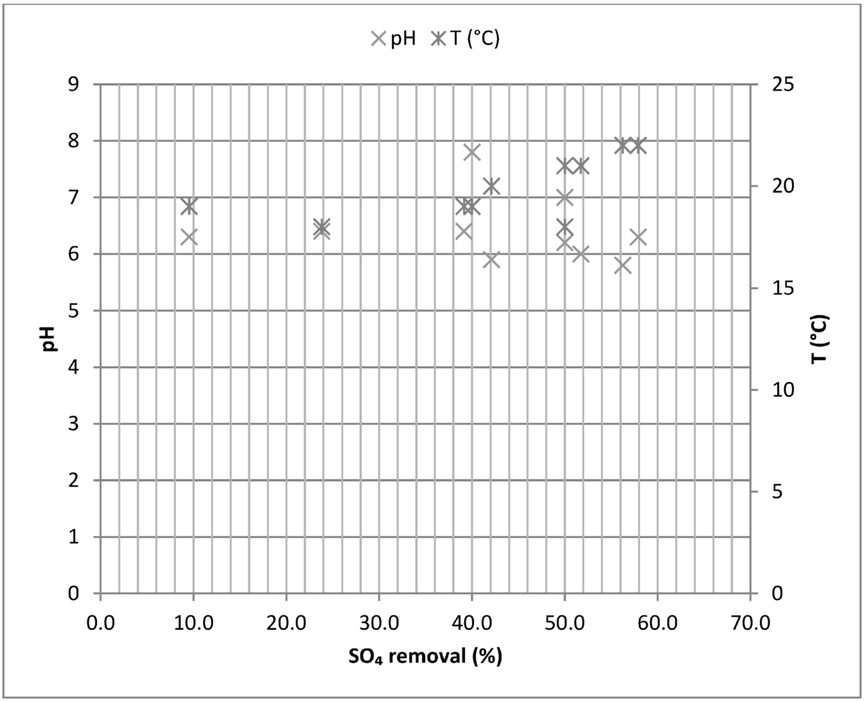

Figure (A.2–12): pH and temperature values with Cl removal efficiency

Reverses Osmoses System

A.3 Overall System

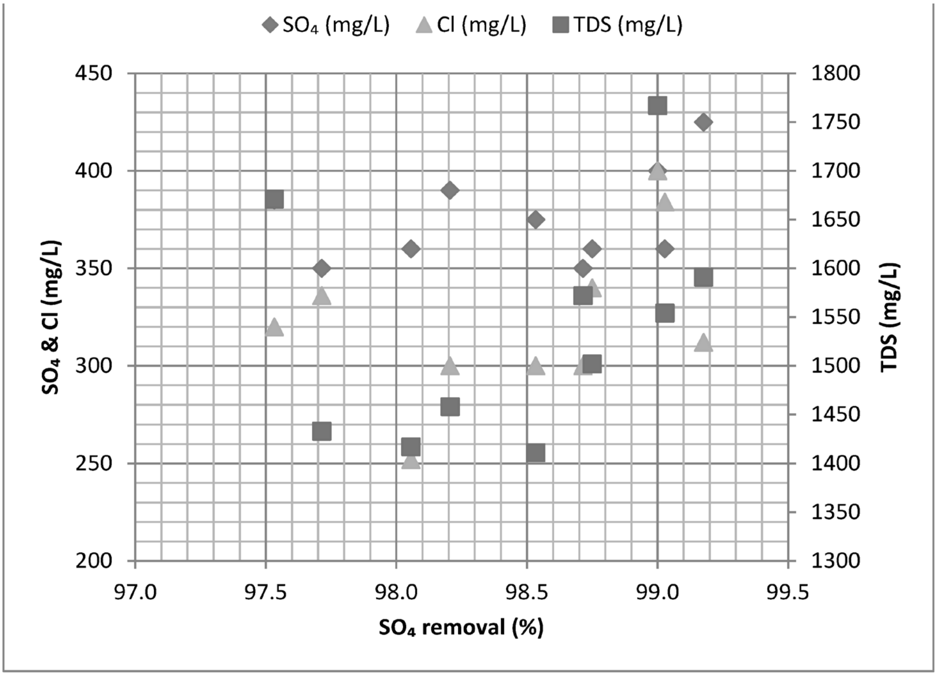

Figure (A.3–13): SO4, TDS and Cl concentrations with SO4 removal efficiency..

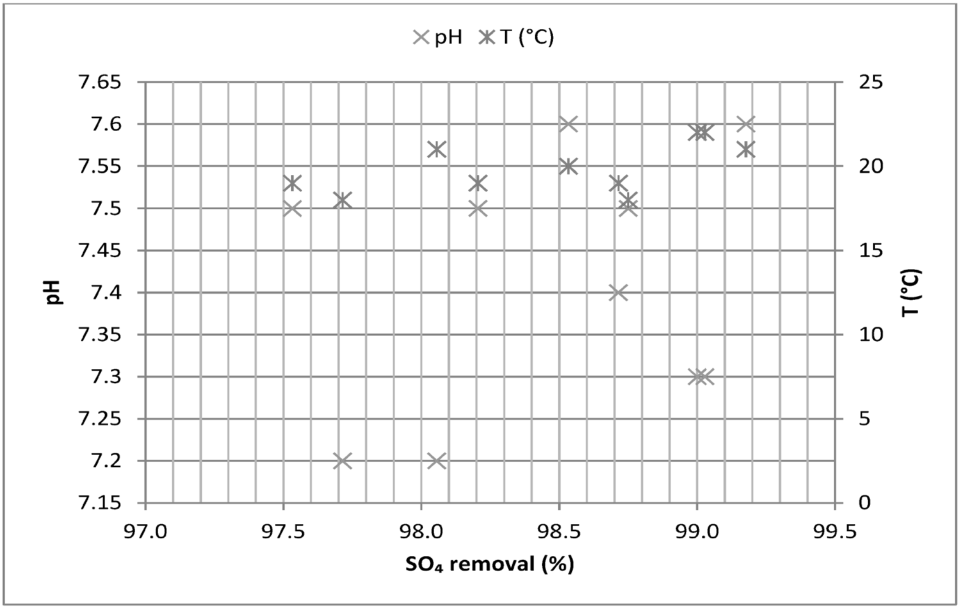

Figure (A.3–14): pH and temperature values with SO4 removal efficiency

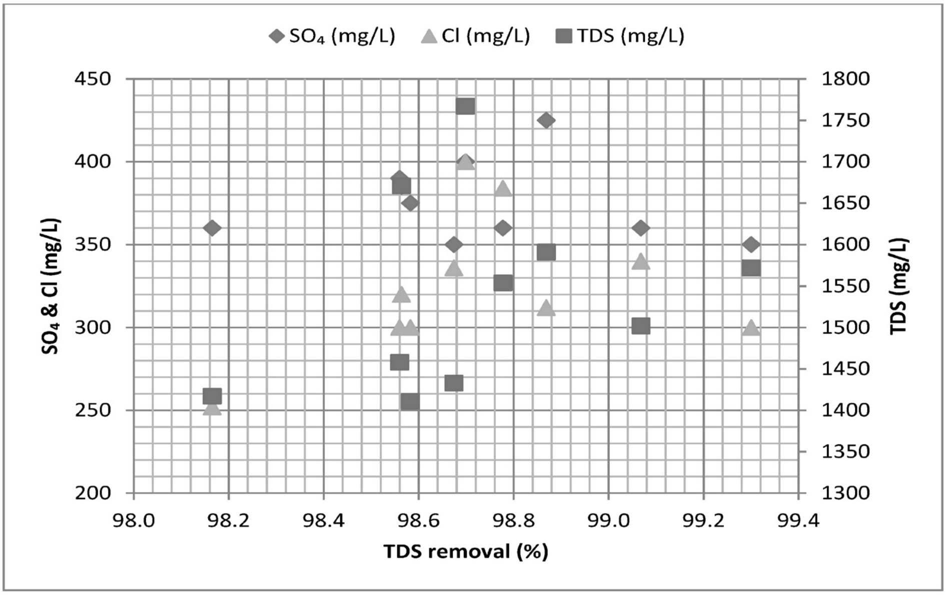

Figure (A.3–15): SO4, TDS and Cl concentrations with TDS removal efficiency.

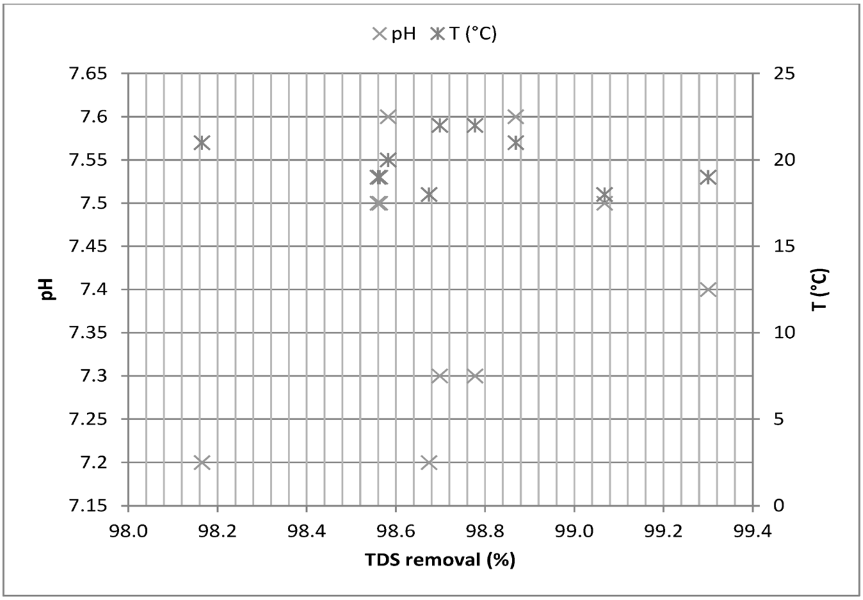

Figure (A.3–16): pH and temperature values with TDS removal efficiency.

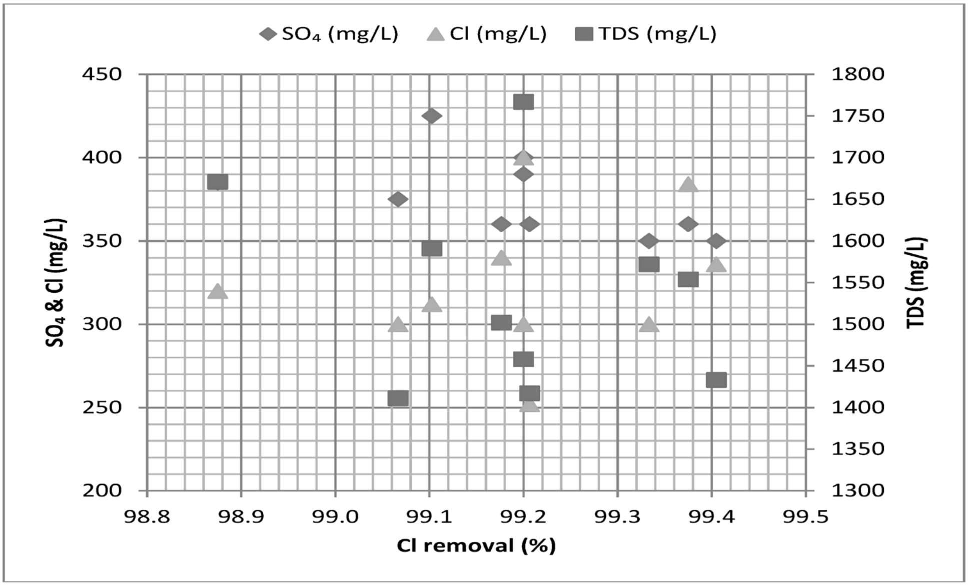

Figure (A.3–17): SO4, TDS and Cl concentrations with Cl removal efficiency.

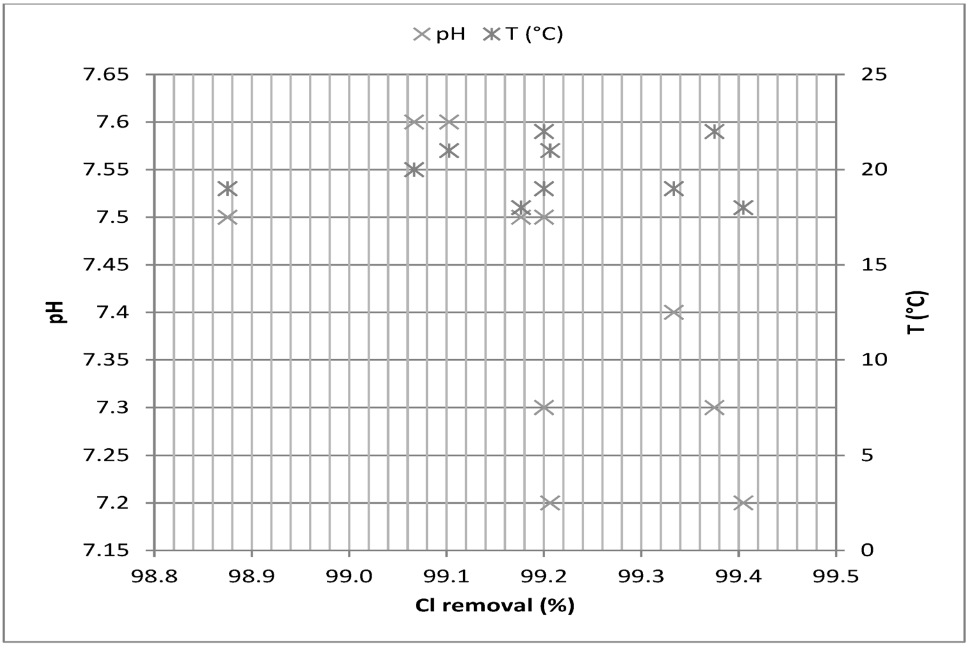

Figure (A.3–18): pH and temperature values with Cl removal efficiency.