Coagulation/ Flocculation, Microfiltration and Nanofiltration for Water Treatment of Main Outfall Drain for Injection in Nasiriyah Oil Field

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Abstract

The present work aims to study the efficiency of coagulation/ flocculation as 1st stage, natural gravity water filter or microfiltration (MF) as 2nd stage and nanofiltration (NF) technology as final stage for treatment of water of main outfall drain (MOD) for injection in Nasiriyah oil field. Effects of operating parameters such as coagulant dosage, speed and time of slow mixing step and settling time in the 1st stage were studied. Also feed turbidity and total suspended solids (TSS) in the 2nd stage were studied. Also feed concentration, temperature and operating time, in the final stage were studied. The results showed that the optimum dosage for alum was 35, 40 and 50 ppm. While, for ferric chloride it was 15, 20 and 30 ppm and for polyelectrolyte 4, 8 and 10 ppm for 11.8, 30 and 100 NTU initial turbidity respectively. The optimum speed for the 2nd step was 25 rpm for each of alum 35 ppm, ferric chloride 15 ppm and polyelectrolyte 4 ppm. While the optimum time for the 2nd step was 30 min for each of alum 35 ppm, ferric chloride 15 ppm and polyelectrolyte 4 ppm and settling time was 30 min for each of alum 35 ppm, ferric chloride 15 ppm and polyelectrolyte 4 ppm. It was found that turbidity and TSS increases by increasing the inlet turbidity and TSS.

Also it was found that salts concentration in product increases by increasing feed concentration and temperature. Rejection percentages were (94.475 – 95.631 %), (88.088 – 90.714 %), (83.33 – 93.2 %), (85.116 – 92.727 %) and (65.385 – 72.727 %) for sulphate, total hardness (TH), Ca^{2+}, Mg^{2+} and Cl^- respectively and recovery percentage of product water was (11.429 – 38.143 %) for polyamide membrane (TFC). In the case of concentrate recirculation, feed concentration, permeate concentration and volume of permeate increases with increasing in operating time and 12.69 liter of water valid for injection in oil field was recovered from 25 liter feed after 180 minute.

Introduction

Water injection is used in the petroleum industry to Enhanced Oil Recovery (EOR) by maintaining the reservoir pressure and to sweep oil towards the production wells [1]. Although the suspended solids must be reduced in the injection water to ensure no blockage of the reservoir rock, the sulphate must be removed from it because Barium and Strontium in the formation water will react with the injected water sulphate ions causing a supersaturated Barium and/ or

Strontium Sulphate scale formation in the production tubing and/or plugging of reservoir rock around the production well. The industry recognized solution is to remove sulphate from water before injection. This also helps prevent well souring by controlling sulphate reducing bacteria where there is simply a reduced source of sulphur that can be converted to hydrogen sulfide by thermophilic sulphate reducing bacteria. Consequently, well souring does not occur [2-4].

Water consumption has become an increasingly important factor in conventional and unconventional crude oil production. The petroleum industry has begun to emphasize water management practices and look for alternative water sources to reduce freshwater consumption, particularly in regions where water resources are scarce. Saline water, brackish water, and even desalinated seawater are being used for oil Exploration & Production (E&P) [5]. The choice of which treatment to use from the great variety of available processes depends on the characteristics of the water, the types of water quality problems likely to be present, and the costs of different treatments [6].

Coagulation is a process used to neutralize charges and form a gelatinous mass to trap (or bridge) particles thus forming a mass large enough to settle or be trapped in the filter. Coagulation comes from the Latin word (coagulare) which means to agglomerate. Coagulation is the step where colloidal particles (similar to spheres of a diameter of less than 1 micrometer) are destabilized [7]. Flocculation is the step where destabilized colloidal particles (or the particles formed during the coagulation step) are assembled into aggregates. Flocculation is gentle stirring or agitation to encourage the particles thus formed to agglomerate into

masses large enough to settle or be filtered from solution [8]. During the coagulation, when adding the coagulant (alum and ferric chloride) to water occur the following reactions [9]:

$$Al_2(SO_4)_3.18H_2O + 6H_2O \rightarrow 2Al(OH)_3 +6H^+ +3SO_4^{2-} +18H_2O$$

$$\dots (1)$$

$$FeCl_3.18H_2O + 3H_2O \rightarrow Fe(OH)_3 +3H^+ +3Cl^-$$

$$\dots (2)$$

$$Al_2(SO_4)_3.18H_2O + 3Ca(HCO_3)_2 \rightarrow 2Al(OH)_3 +3CaSO_4 +6CO_2 +18H_2O$$

$$\dots (3)$$

$$2FeCl_3 + 3Ca(HCO_3)_2 \rightarrow 2Fe(OH)_3 + 3CaCl +6CO_2$$

$$\dots (4)$$
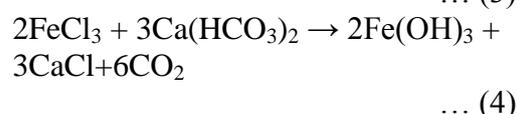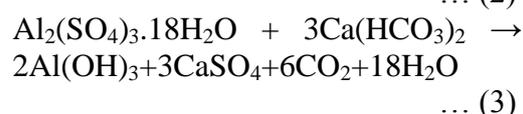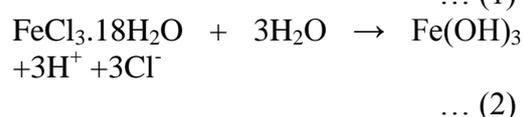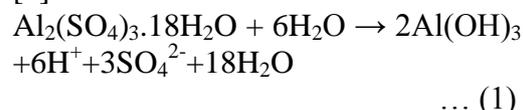
Natural gravity water filter is multi-media filters, in which water flows by gravity through a porous bed of multi layers of granular media. The top layer is anthracite coal, and the bottom layer is sand. Filters are operated until one of two criteria is exceeded the effluent turbidity standard or the allowable head loss through the filter. The filter is cleaned by backwashing to remove the particles that have been collected on the filter media [10 - 11]. Either natural gravity water filter or MF membrane can be used in through the treatment operation. Microfiltration (MF) is the process of removing particles or biological entities in the 0.025 μm to 10 μm range from fluids by passage through a micro porous medium such as a membrane filter [12].

Nanofiltration (NF) has always been a difficult process to define and to describe. Frequently NF and reverse osmosis (RO) are considered as one process, because of similarities of the basic principles used. The history of NF technology began in the 1970s when efforts started to develop RO membranes with reasonable water flux at relatively low pressures. The high pressures used in RO resulted in

considerable energy cost but the quality of permeate was very good, and often too good. Thus a search for membranes with lower rejections of dissolved components but with higher permeability encouraged the development of NF membranes [12-13]. NF is a membrane separation process which uses thin porous membranes with pore sizes between 0.5 and 2 μm. NF processes typically operate at pressures from 0.3 to 1.4 MPa. NF thus represents a process that functions between ultrafiltration (UF) and RO, and is often termed 'loose reverse osmosis' [14-15].

Theoretical Aspect
Water and Solute Fluxes

The Water and salt Fluxes through NF membrane can be described by two models: solution-diffusion model and irreversible thermodynamics models. The two models are selected based on the credibility they have among the researchers as well their domination in practical applications. The two models are conceptually different.

The expressions for water and salt (solute) fluxes through the membrane are given by the following equations [16]:

$$J_W = A_P(\Delta P - \Delta \pi) \qquad \dots (5)$$

$$J_S = \left(\frac{D}{K\delta}\right)\Delta C \qquad \dots (6)$$

Where J_w is the product water flux, A_P is the pure water permeation, ΔP is the operating pressure, $\Delta \pi$ is the difference in the osmotic pressure across the membrane, J_S is the flux of salt permeating the membrane, $(D/K\delta)$ is the salt permeability coefficient, and ΔC is the difference in salt concentration across the membrane. The salt permeability coefficient takes into account the diffusivity coefficient of the salt through the membrane, D, the partitioning of salt concentration between the bulk solution and the membrane, K, and the membrane thickness, δ. The model considers (D/Kδ) as an intrinsic parameter, which is not calculated by dividing the diffusivity coefficient to the product of the partitioning coefficient times the membrane thickness [17 – 18].

Recovery

The recovery is the percentage of the feed flow that passes through the membrane and becomes the permeate stream. It is an estimation of the performance of a membrane system. It measures the volumetric fraction of permeate to the feed showing how much of permeate is recovered from the feed. It is also called separation efficiency.

$$R_w = \frac{Q_p}{Q_f} \times 100\% \qquad \dots (7)$$

Where R_w is the recovery percentage, Q_p is the permeate (or product) flow rate and Q_f is the feed flow rate [13 – 19].

Salt Rejection Percentage

Membrane salt rejection is a measure of overall membrane system performance, and membrane manufacturers typically state a specific salt rejection for each commercial membrane available. Salt rejection through an NF membrane (cross flow operation) is nominally given by:

$$R_s = \left(1 - \frac{C_{permeate}}{C_{feed}}\right) \times 100\% \qquad \dots (8)$$

Where R_s is the rejection percentage, C_{feed} is the concentration of a specific component in the feed solution to the membrane process and Cpermeate is the concentration of the same specific component in the cleaned discharge stream leaving the membrane system. RO membranes achieve NaCl rejections of 98 – 99.8 %, while NF membranes exhibit rejection values greater than 90 % for multivalent ions and between 60 and 70 % for

monovalent ions. NF salt rejection, particularly for monovalent ions, is highly dependent on the total dissolved solid (TDS) concentration and the presence of other ions [18].

Concentration Factor:

The concentration factor (CF) is the ratio of the concentrate TDS concentration in the concentrate or reject stream to its concentration in the feed stream [20]:

$$CF = \frac{C_{concentrate}}{C_{feed}} \qquad \dots (9)$$

Experimental
Main Outfall Drain (MOD)

Main Outfall Drain is a drainage channel, conveying to the Shatt Al Arab the drainage water (soil wash water) of most of the irrigation projects in the medium reaches of the Tigris and Euphrates rivers. At present, the MOD carries large amount of water with relatively low levels of nutrients, pesticides and other chemical components and with a moderate concentration of dissolved salt that must be treated anyway prior to any possible reutilization. The MOD could be therefore a very interesting water resource that, if coupled with proper treatment facilities, could provide water for industrial (including oil fields), domestic, agriculture and environment (marshland) uses. Table 1 shows the specification of water from MOD. In this research, Main Outfall Drain water treatment will be in three stages: Coagulation and flocculation process, natural gravity water filter or microfiltration (MF) membrane, and nanofiltration process.

Coagulation and Flocculation

In coagulation and flocculation process using three initial turbidity contents is 11.8, 30 and 100 NTU. The first sets of tests were to find the efficiency of turbidity removal using alum, ferric chloride and polyelectrolyte as individual coagulants. The second set of experimints was to test speed and time of slow mixing and settling time with the above coagulants for the removal of turbidity. The Jar test apparatus was performed as rapid mixing at 100 rpm for 2 min. During experiments, samples were withdrawn from the supernatant of each beaker for turbidity measurement. Turbidity was measured by using the HACH (2100 N) turbidimeter.

Natural Gravity Water Filter and Microfiltration (MF) Membrane

The water produce from coagulation and flocculation process was fed into natural gravity water filter 5 μm MF membrane and 1 μm MF membrane severally then the turbidity and TSS of outlet was measured. The natural gravity water filter consisted of five layers with the following specifications from top to bottom as shown in Figure 1. First layer consists of activated carbon and its shape is an upside down cone lump head and has circular two bases areas, while the other layers were similar in shape which was cylinder, but they have different contents. Second layer consists of tourmaline stones, third layer consists of calcium stones, fourth layer consists of activated carbon, and Fifeth layer consists of sand. MF membrane is polypropylene cartridge type which has an exceptionally good chemical compatibility and excellent resistance to micro-organism.

Nanofiltration (NF) Membrane

An experimental rig of nanofiltration membrane (Axeon NF4-1812) was constructed in the laboratory as shown in Figure 2. Feed solution was prepared in a 25-liter vessel and then the outlet valve of the feed vessel was opened to let the solutions fill the entire pipes of the system. The feed

water was drawn from the vessel by means of a centrifugal pump to pass through microfiltration membrane, and then the water introduced into the NF elements by means of a high-pressure pump. Through NF element, water transports from the inlet stream across the salt rejecting membrane and into the product stream. In some experiments, the rejected stream is recycled to the feed vessel and the reading was recorded for known periods of time. The Gravimetric Method is used to determine the sulphate ions in the feed permeate and reject streams while the titration was used to determine the total hardness, calcium, magnesium and chloride ions in the feed permeate and reject streams [21 – 23].

Table 1: Specification of MOD Water

Test	Range Value	Test	Range Value	Test	Range Value
pH	7.9 – 8.69	Ca^{2+}	240 – 500 mg/l	COD	12 mg/l
Temp.	15.1 – 33.7 ^{o}C	Mg^{2+}	290 – 430 mg/l	BOD	2.4 mg/l
TSS	6343 mg/l	O & G	31.5 mg/l	DO	7 mg/l
TDS	5310 – 9630 mg/l	NO_3	1.6 – 0.86 mg/l	PO_4	0.02 – 0.29 mg/l
Cl^-	1400 – 2343 mg/l	Alk	180 – 296 mg/l	Na^+	1367 mg/l
SO_4^{2-}	631 – 1796 mg/l	Acid	Nil	K^+	8.8 mg/l
COND.	7930 – 12150 µs/cm	Turbidity	0.45 – 101 NTU	Ba	0.138 mg/l
TH	1920 – 3400 mg/l	NaCl %	16.622 %	Sr	0.0916 mg/l
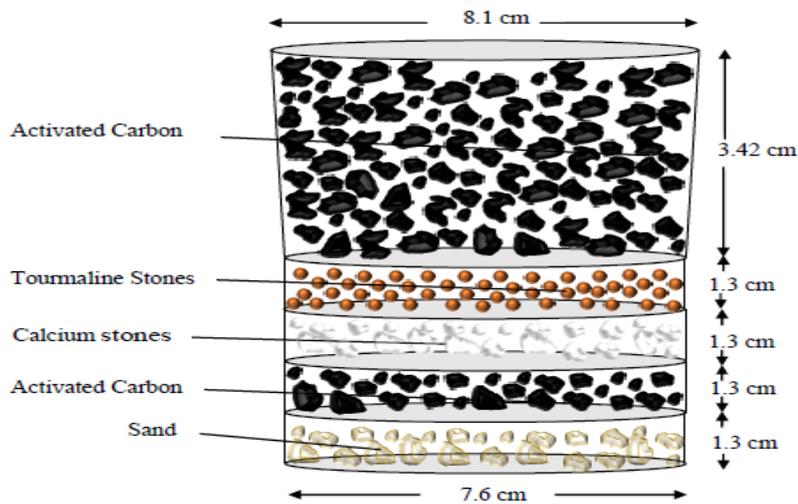
Fig. 1: Schematic Diagram Represents Layers of Natural Gravity Water Filter
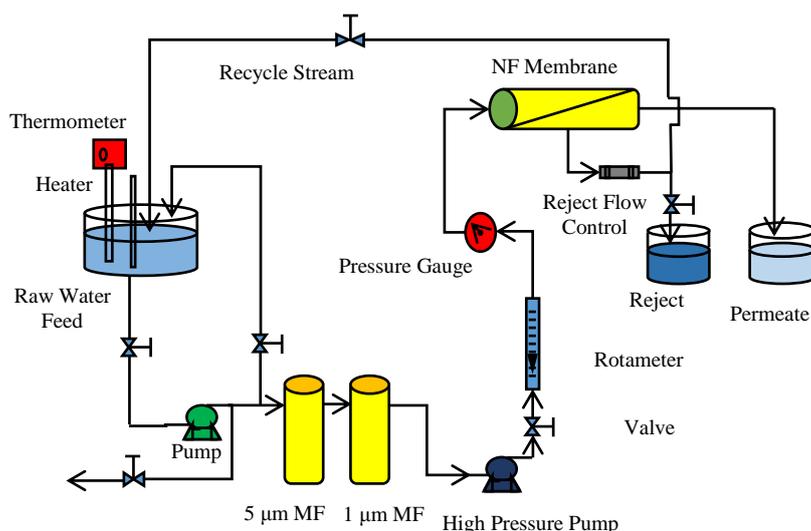
Fig. 2: Schematic Diagram of Nanofiltration (NF) Separation Process

Results and Discussion
Coagulation and Flocculation

Effect of Coagulant Dosage on Turbidity Removal

The effect of different coagulants dosages (Alum, FeCl$_3$ and Polyelectrolyte) on turbidity removal from water of MOD is shown in Figures 3, 4 and 5 for initial turbidities of 11.8, 30 and 100 NTU respectively. These figures show that the optimum dose for alum was 35, 40 and 50 ppm for 11.8, 30 and 100 NTU initial turbidity respectively. While, for ferric chloride it was 15, 20 and 30 ppm and for polyelectrolyte 4, 8 and 10 ppm for 11.8, 30 and 100 NTU initial turbidity respectively. Similar observation was noticed by Hasan et al., and Kadhum et al., [24 – 25].

Colloidal particles in nature normally carry charges on their surface, which lead to the stabilization of the suspension. By addition of some chemicals dose, the surface property of such colloidal particles can be neutralized and precipitated so as the turbidity can be decreased until the colloidal particles are neutralized and precipitated where the minimum turbidity can be obtained. Any more addition of the chemicals dose leads to increase the turbidity because there

were no charged colloidal particles to be neutralized. These excess amounts of chemicals remain in the water as suspension and increase turbidity.

Effect of Agitation Speed and Contact Time on Turbidity Removal

Figures 6, 7 and 8 show the effect of the agitation speed of 2nd step (flocculation step), time of 2nd step and settling time on turbidity removal respectively for the same initial turbidity concentration (11.8 NTU) of water from MOD. In these experiments, the optimum speed of 2nd step was (25 rpm) for both of alum (35 ppm), ferric chloride (15 ppm) and polyelectrolyte (4 ppm). While the optimum time of 2nd step was (30 min) for both of alum (35 ppm), ferric chloride (15 ppm) and polyelectrolyte (4 ppm) and of settling was (30 min) for both of alum (35 ppm), ferric chloride (15 ppm) and polyelectrolyte (4 ppm). A similar observation was noticed in the experimental study of James [26].

It has been found that for high solids concentrations and relatively low doses, flocculation occurs rapidly, but the flocs are not stable and can be broken at moderate stirring rates so high values of turbidity are obtained. Increased mixing speed of 2nd step

leads to low values of turbidity. Increased agitation more leads to the production of smaller flocs and the turbidity increased. By reducing the rate of stirring shortly after dosing, floc size (and settling rate) can be held at plateau levels, without subsequent decline. Incomplete mixing of the flocculant may result in local overdosing and restabilization of a small number of particles, giving rise to a persistent haze in the water so high values of turbidity are obtained. Increased mixing time of 2nd step

decreases values of turbidity. By continuity, the restabilization state appears for small number of particles and the turbidity increased.

Decreases settling time, allowing much higher flow rates to be treated. The electrostatic repulsive forces do not constrain the particles from approaching each other because the suspension is characterized as instable; therefore, short time period was required for settling. After this time there is no change in turbidity recorded.
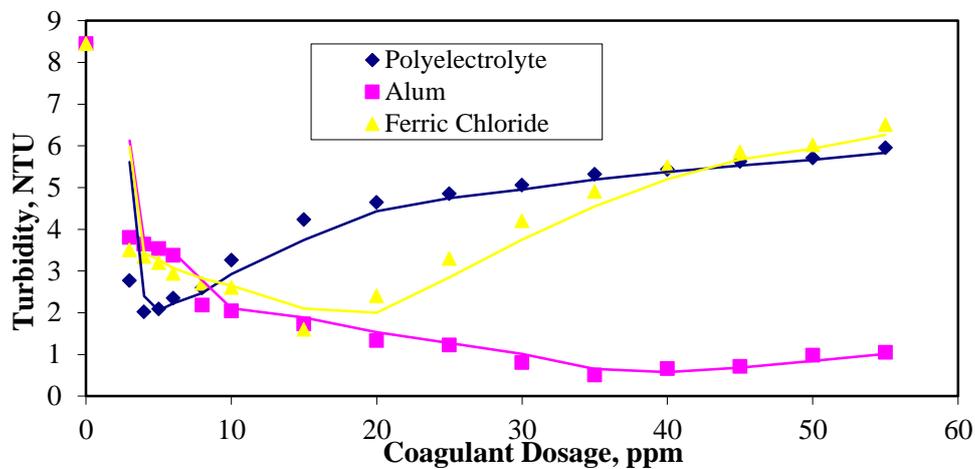
Fig. 3: Effect of Coagulant Dosage on Turbidity removal (Coagulation Time 2 min (100 rpm), Flocculation Time 30 min (25 rpm), Settling Time 30 min, Initial Turbidity = 11.8 NTU, pH = 8.2)
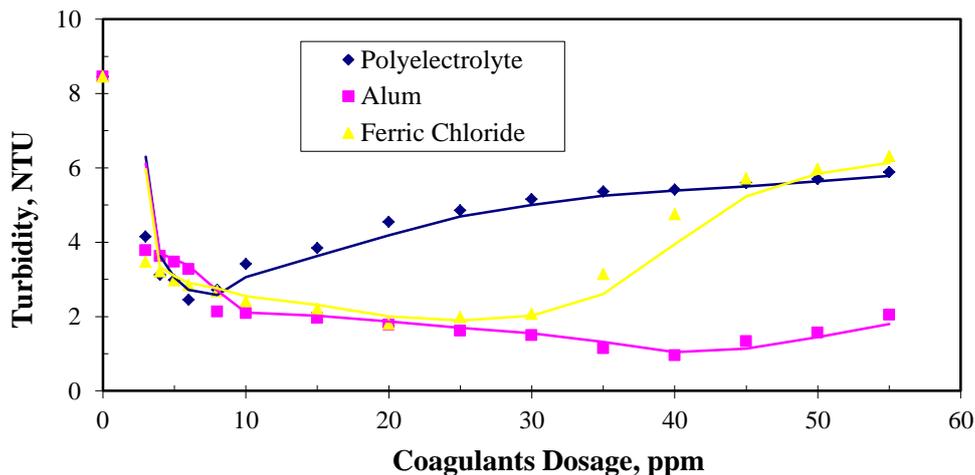
Fig. 4: Effect of Coagulants Dosage on Turbidity Removal (Coagulation Time 2 min (100 rpm), Flocculation Time 30 min (25 rpm), Settling Time 30 min, Initial Turbidity = 30 NTU, pH = 8.2)
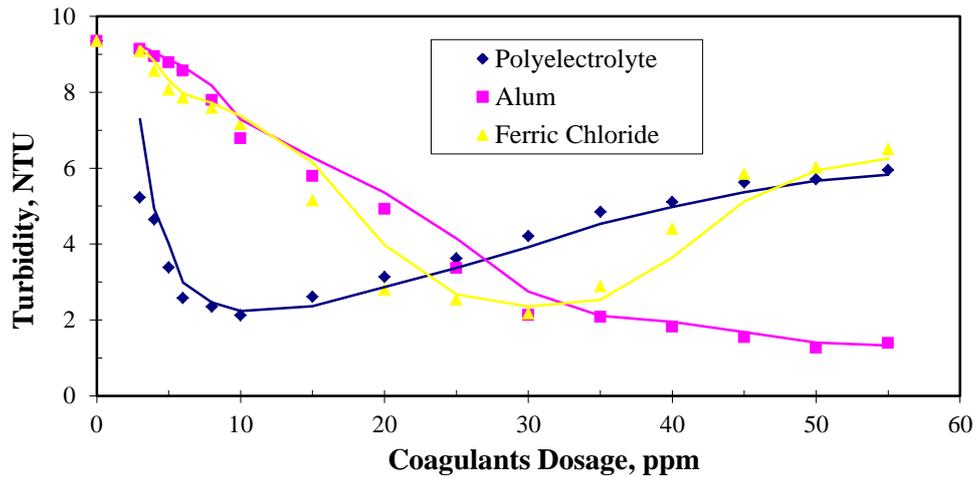
Fig. 5: Effect of Coagulants Dosage on Turbidity Removal (Coagulation Time 2 min (100 rpm), Flocculation Time 30 min (25 rpm), Settling Time 30 min, Initial Turbidity = 100 NTU, pH = 8.2)
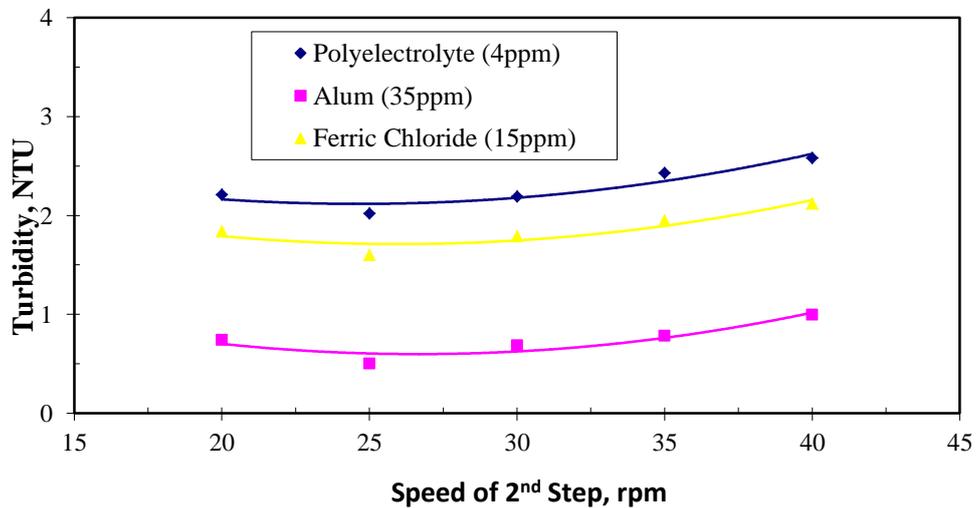
Fig. 6: Effect of Speed of 2nd Step on Turbidity (Coagulation Time 2min (100 rpm), Flocculation Time 30 min, Settling Time 30 min, Initial Turbidity = 11.8 NTU, pH = 8.2)
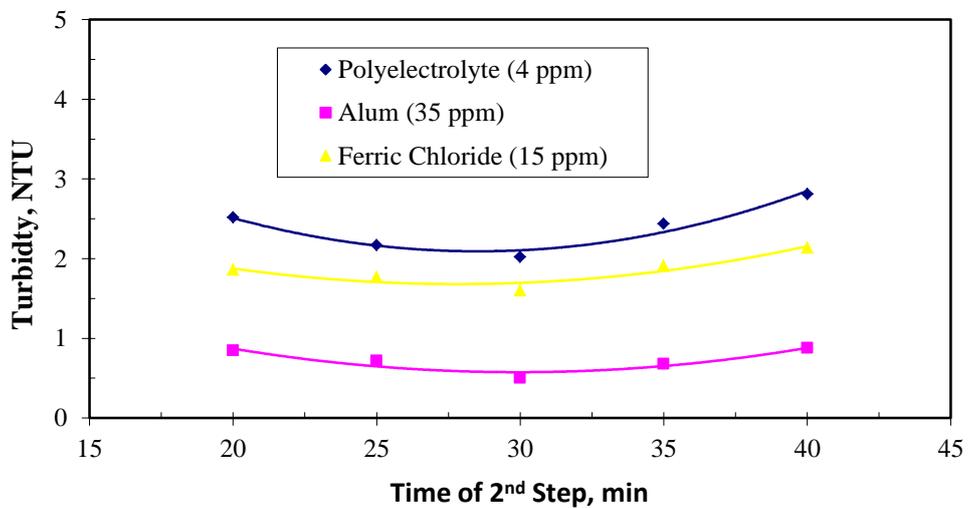
Fig. 7: Effect of Time of 2nd Step on Turbidity (Coagulation Time 2min (100 rpm), Flocculation Speed 25 rpm, Settling Time 30 min, Initial Turbidity = 11.8 NTU, pH = 8.2)
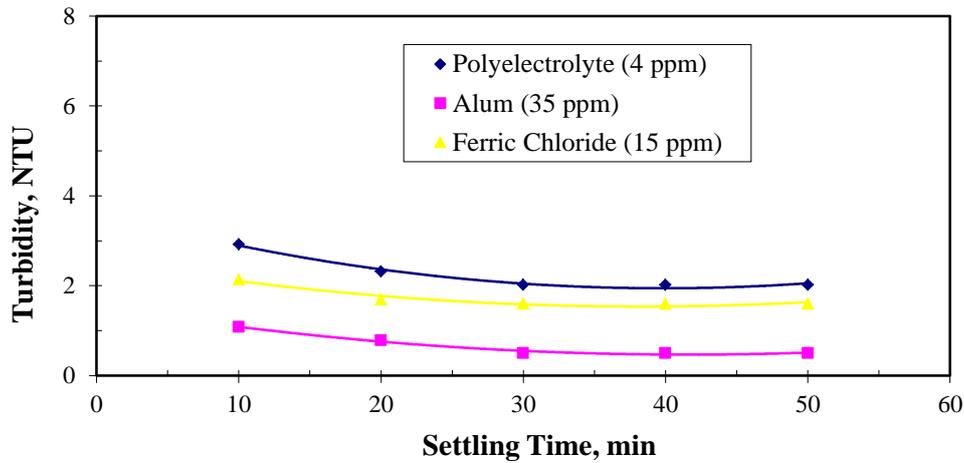
Fig. 8: Effect of Settling Time on Turbidity (Coagulation Time 2 min (100 rpm), Flocculation Time 30 min (25 rpm), Initial Turbidity = 11.8 NTU, pH = 8.2)

Natural Gravity Water Filter and Microfiltration Membranes

Either natural gravity water filter or microfiltration (MF) membranes (5 & 1 μm) was used to remove the turbidity and TSS from water. The same feed water inlet into sand filter and MF membranes (5 & 1 μm) and the results was arranged progressively as the following:

Natural gravity water filter → 5 μm MF → 1 μm MF.

When the pore size of membrane was small, the quality of the production was better and the operating pressure was high, see Figures 9 and 10.
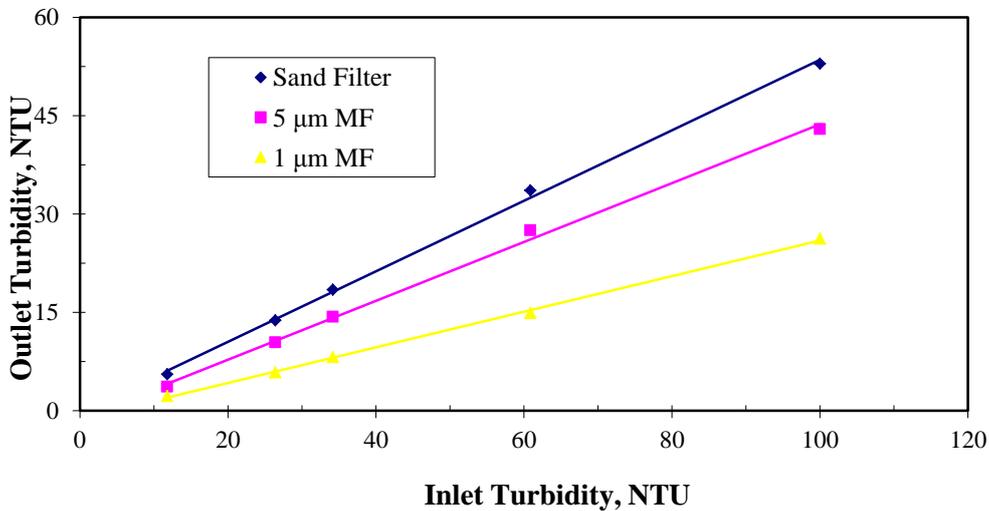
Fig. 9: Effect of Feed Turbidity Change on Product Turbidity
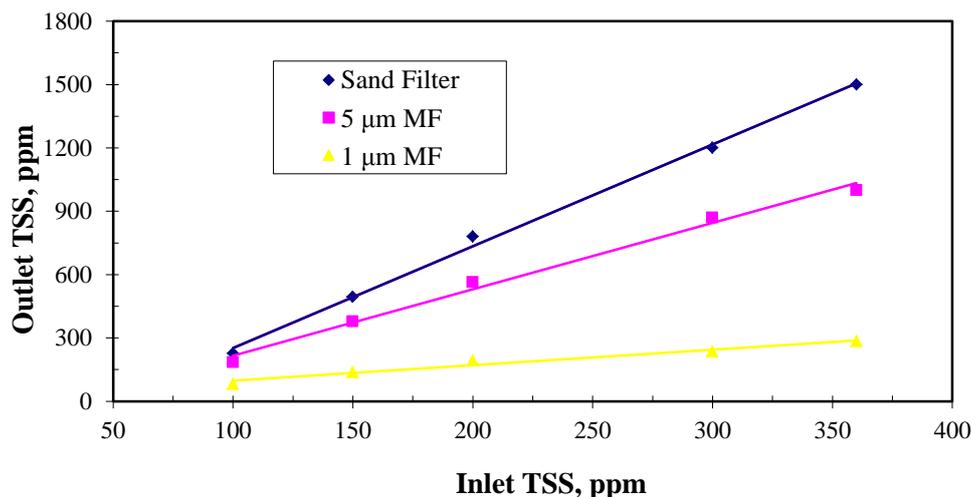
Fig. 10: Effect of Feed Total Suspended Solids (TSS) Change on Product TSS

Nanofiltration Membrane
Effect of Feed Solute Concentration

By increasing concentration of solute feed from MOD, osmotic pressure increases, then driving force ($\Delta P - \Delta \pi$) decreases. This appears as a decrease of water flow through the membrane to 4.8 l/h at feed concentration 9630 mg/l. This is shown in Figure 11. Also, Figure 11 show the effect of feed concentration of water from MOD on recovery where upper value of recovery percentage was 38.143 % at feed concentration 1800 mg/l and by increasing the concentration of water feed from MOD, the recovery percentage decrease until reaching to lower value 11.429 % at feed concentration 9630 mg/l according to equation 7. By increasing feed concentration from MOD, solute flux increases according to the equation 6, this appears as an increase of solute concentration in the product as shown in Figures 12 and 13.
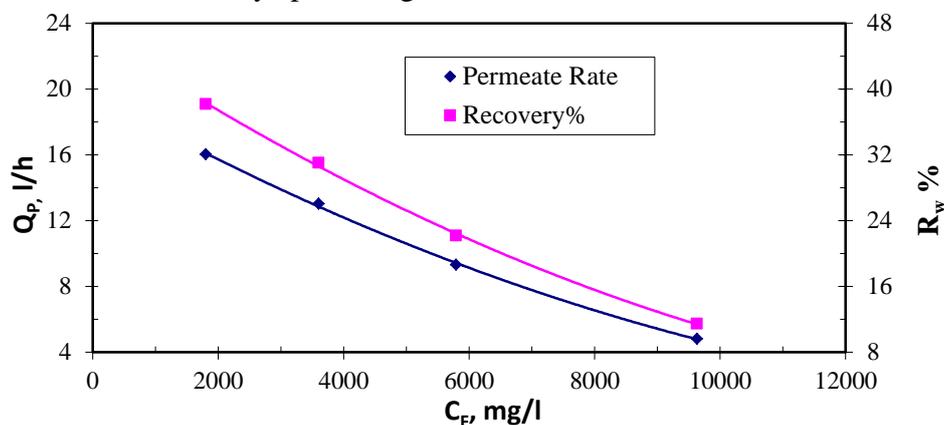
Fig. 11: Effect of Feed Concentration Change on Permeate Rate and Recovery Percentage (at T = 25 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)
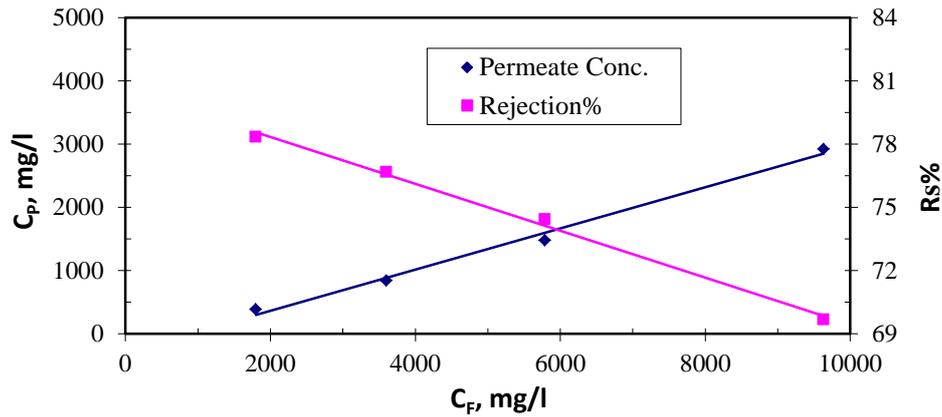
Fig. 12: Effect of Feed Concentration on Permeate Concentration and Rejection Percentage (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)
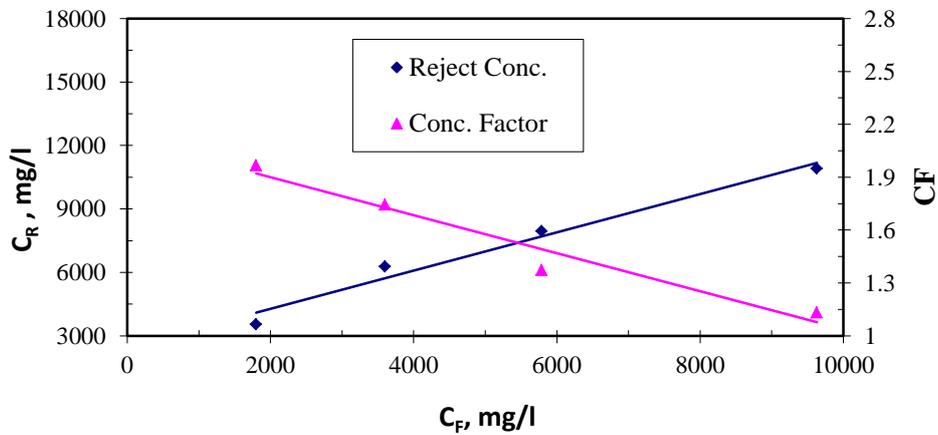
Fig. 13: Effect of Feed Concentration on Reject Concentration and Concentration Factor (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)

Figures 14, 16, 18, 20, and 22 show that increasing in feed concentration from MOD leads to increase sulphate ion concentration (SO_4^{2-}) (14.85 – 49.38 mg/l), TH (65 – 405 mg/l), Ca^{2+} (10 – 34 mg/l), Mg^{2+} (8 – 64 mg/l), and Cl^- (159.75 – 639 mg/l) in the permeate respectively because by increasing the feed, solute flux increases according to equation 6, this appears as an increase of solute concentration in the permeate. Therefore, using nanofiltration membranes to remove ions (especially sulphate) and produce water within the allowable limits of ions in order to be injected into the oil field.

Also these figures show the change in rejection percentage. The salts which have high molecular weight such as SO_4^{2-} and Ca^{2+} pass through the membrane with rejection percentage higher than salts which have low molecular weight such as Mg^{2+} for the same values of valence. For different values of valence, the salts which have high valence such as Ca^{2+} pass through the membrane with rejection percentage larger than salts which have low valence such as Cl^- for the same or approaching molecular weights. This relation was contingent with equation 10. Figures 15, 17, 19, 21, and 23 show that the increasing in feed concentration of water from MOD leads to increase sulphate ion concentration (SO_4^{-2}) (518.468 – 1011.757 mg/l), TH (1775 – 5000 mg/l), Ca^{+2} (190 – 730 mg/l), Mg^{+2} (260 – 635 mg/l), and Cl^- (887.5 –

2786.75 mg/l) in the reject respectively because pure water transfer from feed side to the permeate side across the membrane and this leads to concentrate of solute in the reject. By increasing solute concentration for sulphate, TH and Mg^{2+} in the feed, their solute fluxes increase. This caused much increase in the permeate concentration for these ions. Then their values of $C_{permeate}/C_{Feed}$ increase and their rejection percentages decrease according to equation 8 see figures 16, 18 and 22. Figures 20 and 24 show different effect for Ca^{2+} and Cl^- because the increasing of solute flux leads a little increase the permeate concentration for these ions. Then their values of $C_{permeate}/C_{Feed}$ decrease and their rejection percentages increase according to equation 8.
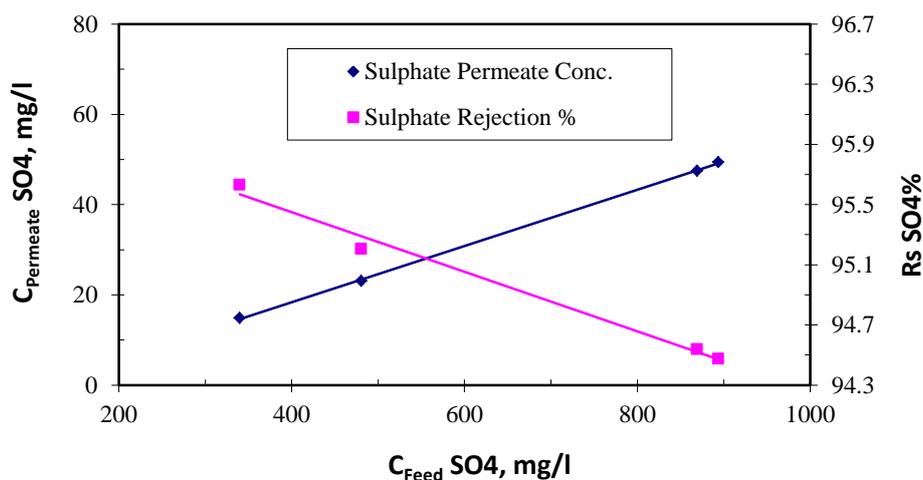
Fig. 14: Effect of Sulfate Feed Concentration on Sulfate Permeate Concentration and Sulphate Rejection Percentage (at T = 27 °C, P = 85 psi, pH = 8, Q_F = 42 l/h
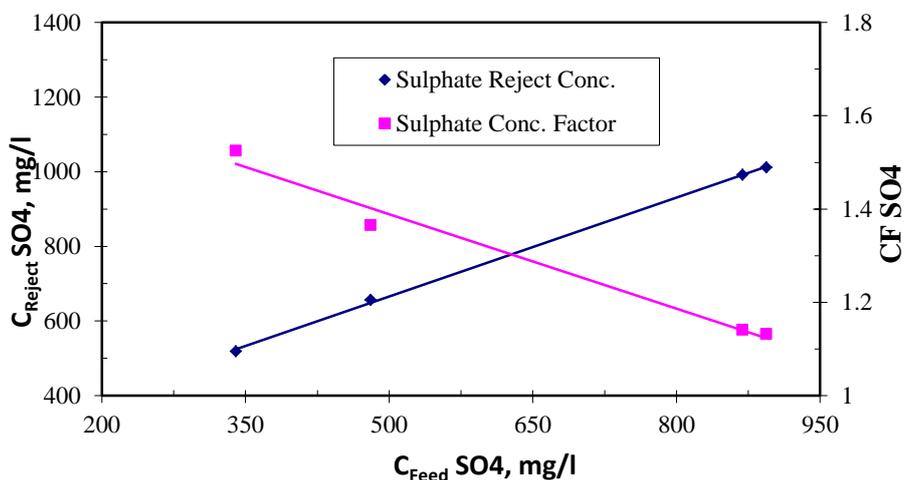
Fig. 15: Effect of Sulfate Feed Concentration on Sulfate Reject Concentration and Sulphate Concentration Factor (at T = 27 °C, P = 85, pH = 8, Q_F = 42 l/h)
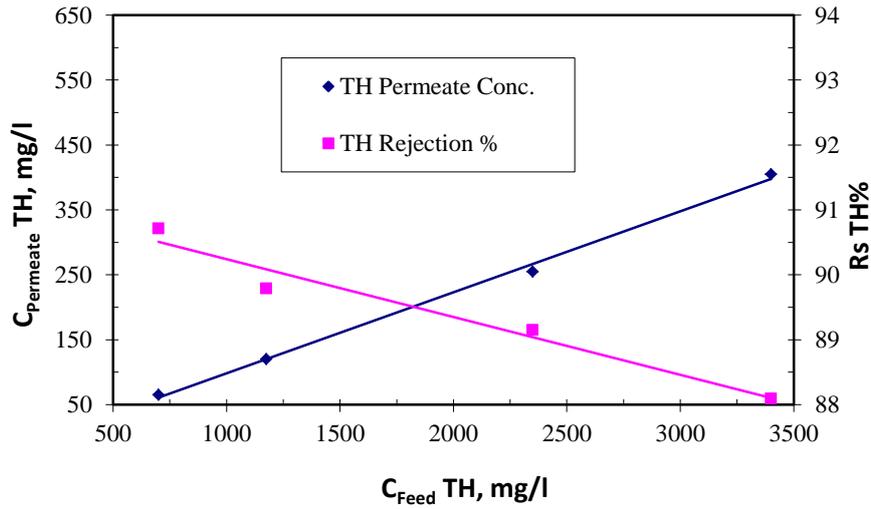
Fig. 16: Effect of Total Hardness Feed Concentration on Total Hardness Permeate Concentration and Total Hardness Rejection Percentage (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)
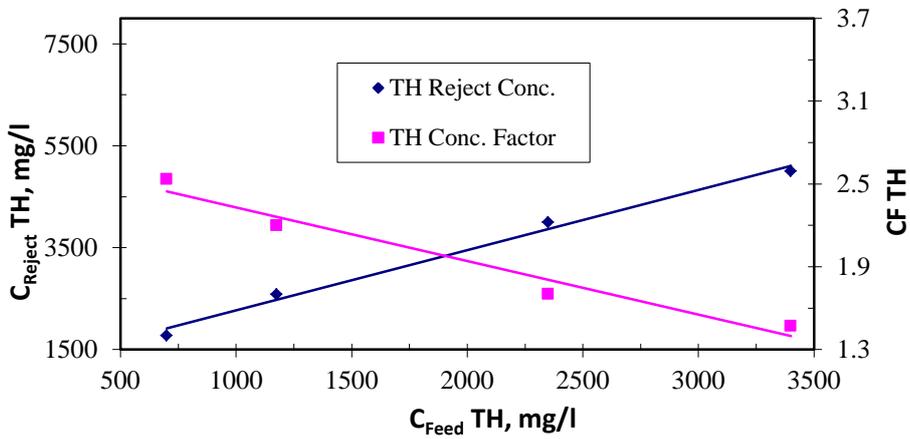
Fig. 17: Effect of Total Hardness Feed Concentration on Total Hardness Reject Concentration and Total Hardness Concentration Factor, (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)
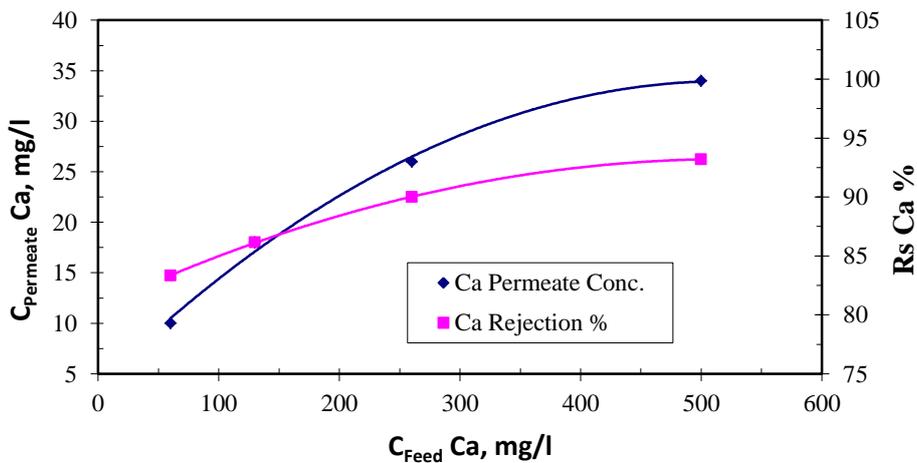
Fig. 18: Effect of Calcium Feed Concentration on Calcium Permeate Concentration and Calcium Rejection Percentage (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)

Fig. 19: Effect of Calcium Feed Concentration on Calcium Reject Concentration and Calcium Concentration Factor (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)

Fig. 20: Effect of Magnesium Feed Concentration on Magnesium Permeate Concentration and Magnesium Rejection Percentage (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)

Fig. 21: Effect of Magnesium Feed Concentration on Magnesium Reject Concentration and Magnesium Concentration Factor (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)

Fig. 22: Effect of Chloride Feed Concentration on Chloride Permeate Concentration and Chloride Rejection Percentage (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)

Fig. 23: Effect of Chloride Feed Concentration on Chloride Reject Concentration Chloride Concentration Factor (at T = 27 ^{o}C, P = 85 psi, pH = 8, Q_F = 42 l/h)

Effect of Operating Temperature

Increasing of inlet operating temperature within the range of 20 – 37 ^{o}C will increase the product rate to the range of 12.72 – 18.6 l/h and recovery percentage of water of range 30.286 – 44.286 %. This is shown in Figure 24. A change in operating temperature of feed water from MOD changes (1) the densities and viscosities of the feed, and (2) the osmotic pressure of the system. An increase of temperature increases the osmotic pressure of feed water from MOD, resulting in a decrease in the driving force (ΔP – Δπ). Thus while change (1) above increase the relative

flow of the pure water through the membrane with increase in temperature; the change in the osmotic pressure has the opposite effect. A similar observation was noticed in the experimented study of Mohammed and Mattheus [20, 27].

The increase of operating temperature for feed water from MOD within the range of 20 – 37 ^{o}C leads to increase the flux; this appears as an

increase of salts concentrations in the product to the range of 580 – 840 mg/l. The effect of operating temperature on salts concentrations, can be explain the decreasing of rejection percentage with increase in

operating temperature, see Figure 25. While Figure 26 show that the reject concentration and concentration factor increases with the ranges of (6280 – 6630 mg/l) and (1.794 – 1.894) respectively with increasing temperature because the increasing of pure water passed through the membrane leads to increase the salts concentration in the reject. A similar observation was noticed in the experimented study of Mohammed [20].

Recirculation of Concentrate

In the nanofiltration (NF) membrane technology experiment with recirculation mode, the permeate was removed and the concentrate stream was recycled back to the feed vessel in order to recover high quantity from pure water. The operating time taken to

180 min, in this time the difference between operating pressure and osmotic pressure became very small then the process is stopped. At time equal to zero, for recirculation of concentrate the operating conditions for the water from MOD with 8390 mg/l concentration were V_F = 25 l, Q_F = 50 l/h, T = 27 ^{o}C, P = 185 psi.

Figure 27 shows the effect of time on volume of permeate and recovery percentage. As the time increased the product rate decreased. This leads to decrease the recovery percentage according to the equation 7. Due to the increase of the feed concentration with time in the recirculation mode, the salts concentration in the product increased with the increase in operating time. This means that the rejection percentage decrease, see Figure 28.
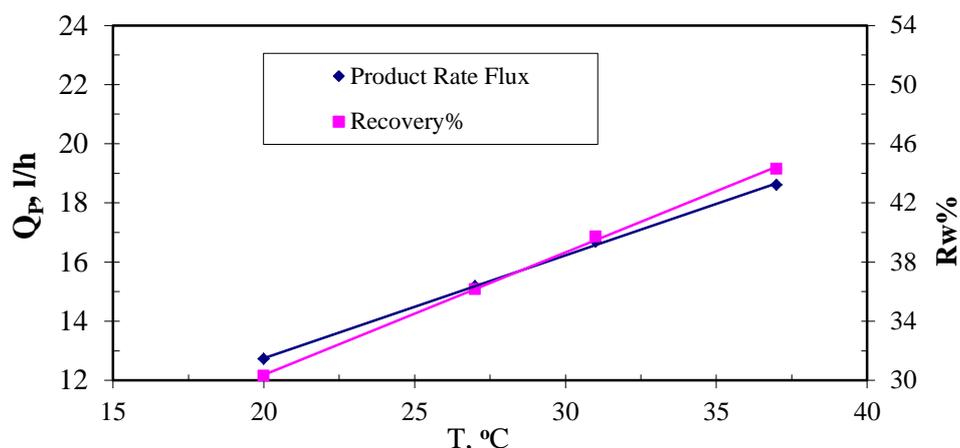
Fig. 24: Effect of Operating Temperature on Product Rate Flux and Recovery (at C_F = 3500 ppm, P = 85 psi, pH = 8, Q_F = 42 l/h)
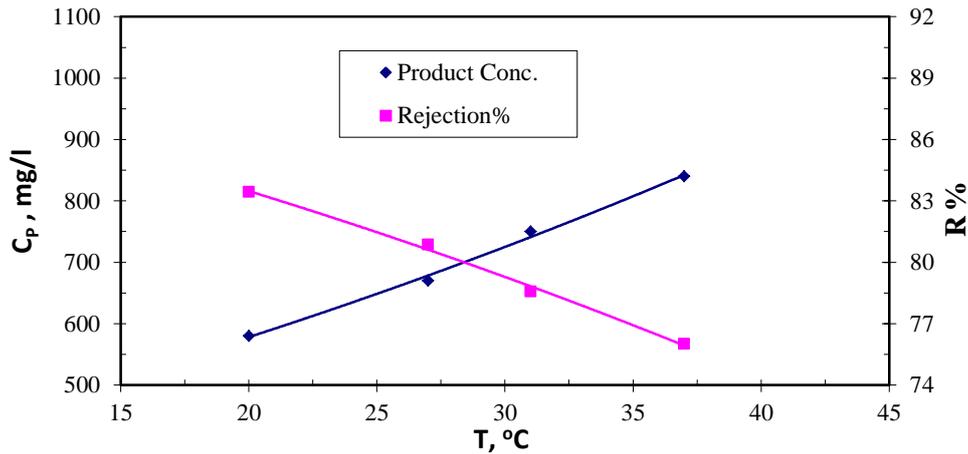
Fig. 25: Effect of Operating Temperature on Product Solute Concentration and Rejection Percentage, (at C_F = 3500 ppm, P = 85 psi, pH = 8, Q_F = 42 l/h)
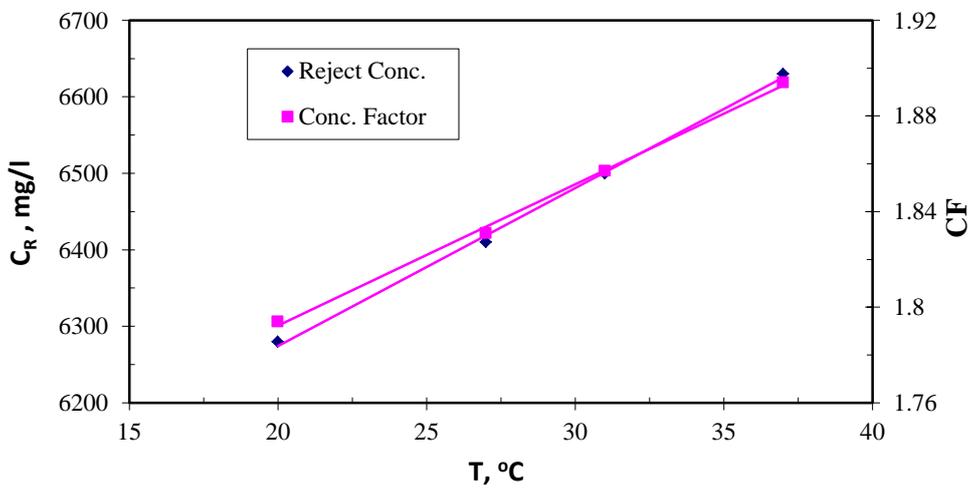
Fig. 26: Effect of Operating Temperature on Reject Concentration and Concentration Factor (at C_F = 3500 ppm, P = 85 psi, pH = 8, Q_F = 42 l/h)
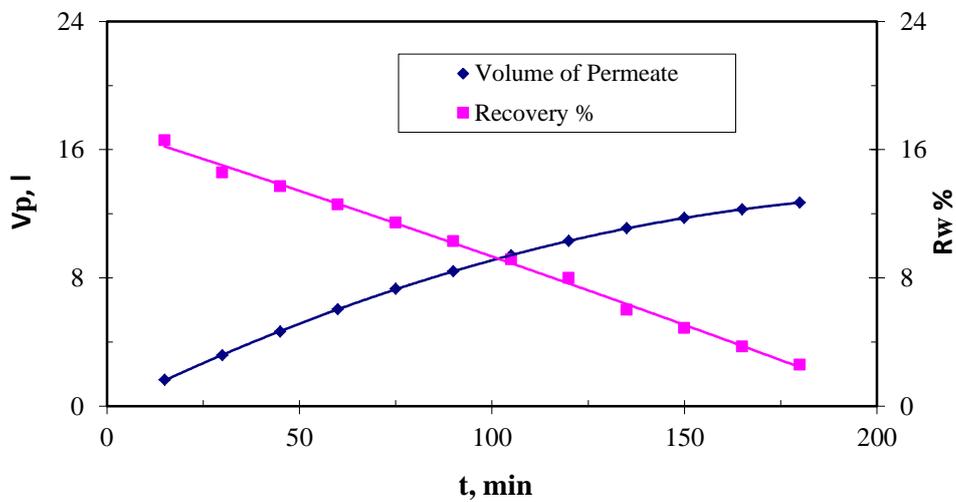
Fig. 27: Effect of Operating Time on Volume of Permeate and Recovery Percentage (Recirculation of Concentrate, V_F = 25 l, Q_P = 42 l/h, T = 27 ^{o}C, pH = 8 and P = 185 psi)

Fig. 28: Effect of Operating Time on Permeate Concentration and Rejection Percentage (Recirculation of Concentrate, V_F = 25 l, Q_P = 42 l/h, T = 27 °C, pH = 8 and P = 185 psi)

Conclusion

Produced water appropriate for injection in the oil field from MOD, using conventional methods and nanofiltration membranes. In coagulation/ flocculation process, optimum dosage for alum was 35, 40 and 50 ppm for 11.8, 30 and 100 NTU initial turbidity respectively. While, for ferric chloride it was 15, 20 and 30 ppm and for polyelectrolyte 4, 8 and 10 ppm for 11.8, 30 and 100 NTU initial turbidity respectively. The optimum speed of 2nd step was 25 rpm. While the optimum time of 2nd step was 30 min and of settling was 30 min. For the same dosage, the ability of alum, ferric chloride and polyelectrolyte to remove the turbidity is arranged progressively as the following:

Polyelecrolyte → Ferric chloride → Alum.

For the same feed, the ability of the filters to remove the turbidity and TSS from water was arranged progressively as the following: Natural gravity water filter → 5 μm MF → 1 μm MF.

Microfiltration can be used to reduce the turbidity, TSS, and the particle size to the demand limits. Nanofiltration membrane can be used to reduce the sulphate to the demand limits. The product rate of the membrane decreases with increasing feed concentration. The maximum recovery percentage (38.143 %) was at C_F = 1800 mg/l for P = 85 psi, Q_F = 42 l/h, T = 25 °C and pH = 8. Maximum component rejection percentage at P = 85 psi, Q_F = 42 l/h, T = 27 °C and pH = 8 95.631 %, 90.714 %, 93.2 %, 92.727 %, 72.727 % for sulphate, TH, Ca^{2+}, Mg^{2+} and Cl^- respectively. In recirculation of concentrate process, maximum value of volume of permeate is (12.69 liter) from feed vessel (25 liter) after 180 min.

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