# Experimental and Theoretical Study of the Effect of Adding Ion Exchange Bed to RO Desalination System

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Abstract- In the present work, a novel hybrid reverse osmosis (RO) system with ion exchange (IX) bed is designed and studied experimentally and theoretically. This is done by adding a new IX bed before conventional RO system. Natural zeolite is chosen as a cheap adsorbent for IX process. The present work investigates IX process in continuous water flow bed. The effect of natural zeolite mass, water flow rate, bed diameter and natural zeolite grain size on the performance of IX bed is studied. Moreover, water recovery, permeate water and membrane flux of RO system are studied and compared with the conventional RO system. The results showed that the proposed system water recovery, permeate water and membrane flux is higher than that for conventional RO system by 9% to 27.1%, 8.5% to 29 % and 30% respectively at different inlet water concentrations for zeolite bed with 250 g weight. Finally, a good agreement between theoretical and experimental results is performed.

*Keywords*: Desalination, Reverse osmosis, Ion exchange, Membrane recovery

## I. INTRODUCTION

Salinity of water is a significant problem in many parts of the world. Desalination system, as a method of producing drinking water; is predicted to spread and become more applicable in the world. The most important method that used in desalination process is reverse osmosis (RO). This desalination method, however; suffers from a number of disadvantages as it requires high pressures in order to overcome the natural osmotic pressure of saline Water. Also, precipitation of salts from the input saline solution can form deposits on RO membranes causing a reduction in membrane efficiency and high expenses of energy.

To enhance the water permeability of an RO system, the work in [1] investigated experimentally the effect of using a highly porous microstructured support membrane. They found that their proposed system water permeability was surpassing commercial RO membranes and thin-film nanocomposite membranes. In [2], Atab et al. studied numerically the performance of a new hybrid reverse osmosis with adsorption desalination system. This hybrid system was succeeded to produce large amount of water for irrigation and high quality water for drinking. Moreover, their proposed system can produce water air-conditioning. Therefore, this system may be considered as the optimum solution for countryside areas. In [3], Parlar et al. compared between conventional reverse osmosis (RO) system with reverse osmosis (RO) integrated nanofiltration. They found that the permeate quality and the amount of drinking output water were significantly better if nanofiltration was added to the system.

Ion exchange (IX) may be defined as the process at which ions exchanged between two electrolytes or between a complex and an electrolyte solution. Ion exchange (IX) resins are coated with substituting hydrogen ions and hydroxide ions for two main phases of the ion exchange process respectively. Consequently, IX resins are used in water treatment application. In the cation phase the hydrogen ions will be exchanged with sodium ions from sodium chloride salt in the water being processed. During the anion phase the chloride ions is exchanged with hydroxide ions [4]. Zeolites are natural ion exchange (IX) material with porous structures and capable of exchanging cations [5]. Zeolites have a negative charge, which originates from the replacement of Silicon with Aluminum and balanced with cations such as potassium, sodium, magnesium and calcium [6]. Zeolites material has high ion exchange (IX) ability for cations and for its molecular sieve properties, it was used in water purification and removal of heavy metals processes [6]. Moreover, due to its negative charge, natural zeolites have a small attraction for anions and low adsorption for organics in aqueous salt solution [7]. There are different zeolite types with different cations preferences. The most used and available types are Clinoptilolite and chabazite zeolites, which have a partiality for larger cations. Clinoptilolite selects cation in the following order: Cs >Rb> K > NH4> Ba > Sr > Na > Ca > Fe > Al > Mg > Li [8].

Natural zeolites were used to decrease sodium ions from produced water by replacing them with calcium, thus reducing sodium concentration. The work in [9] reported that natural zeolites could become a cost efficient technology for the treatment of high sodium concentration of coal seam gas (CSG) co-produced water. Moreover, natural zeolites were considered as low cost material with abundant availability and have high sorptibility for inorganic and organic ions. In addition, Natural zeolite is easy of activation and regeneration and nontoxic material [10, 11]. In [12], the sorption ability of zeolite by the reduction of salinity and efficiency of that reduction were studied. The highest value of reduced salinity and efficiency were 3200 ppm and 9.14%, respectively with 7.5 g of sorbent material. They found also that the desalination process effectiveness can be enhanced by increasing the zeolite weight as in [13] which proved that untreated natural zeolite had a capacity of 16.16 mEq/100g to adsorb sodium ions. In [14], they examined the elimination of sodium ions from waters with utilization of calcium rich natural zeolites. They found that the maximum adsorption capacities for BR-Zeolite and ST-Zeolite were 12.3 and 9.6 mg/g, respectively, which equal approximately 38% and 39% of their measured cation exchange capacity values.

In [15], the effect of Rhyolitic tuff and clinoptilolite on sodium adsorption ratio (SAR) and the total dissolved solids (TDS) reduction in a reverse osmosis (RO) system concentrate were studied. They found that the two types of zeolites decrease the SAR and TDS of waste water by neglecting the residence time, however clinoptilolite decreases the water salinity. The ion exchange (IX) process comprising the steps of exposing water containing sodium chloride to an ion exchange material in divalent form, where monovalent sodium ions are exchanged for divalent or polyvalent ions, thereby producing a solution with an osmotic pressure lower than the osmotic pressure of water containing sodium chloride, and using the solution as feed water of a semi-permeable membrane for separating ions from the solution and producing desalinated Water [16, 17]. In [18], the effect of using zeolite on desalination of saline sludges was studied. They kept the water in the IX (zeolite) column for 20 min and then drained. They found that the efficiency of sodium salt removal was 72.25% and increased to 92.96% when using two ion exchange columns.

It could be noted from the previous review or up to the author's knowledge, zeolite IX material studied in contact with water tank or column but never studied in IX bed before reverse osmosis (RO) system. In the present work, a novel hybrid IX and RO system is designed and studied. This is done by adding a new IX bed before RO system. Therefore, IX processes will be examined in a continuous water flow system. Natural zeolite is chosen as a cheap (100\$/ton) adsorbent for IX process. The main aim of the IX process is to enhance the RO performance by reducing feed water electrical conductivity and hence decreasing the cost of the produced potable water.

#### II. EXPERIMENTAL WORK

## A. Materials

There are many types of natural zeolites. We used Clinoptilolite because it is the most abundant and low cost type. Table 1 shows the chemical composition of major elements for used natural zeolites (Clinoptilolite), which was reported from the central metallurgical research institute (CMDRI) for A&O Company. Synthetic feed water was made by addition of appropriate amount of Sodium Chloride salt to filterated water from RO system.

 TABLE I

 CHEMICAL COMPOSITIONS FOR MAJOR ELEMENTS OF USED NATURAL

| ZEOLITE          |                                |                                |       |       |                   |                  |                  |
|------------------|--------------------------------|--------------------------------|-------|-------|-------------------|------------------|------------------|
| SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | CaO   | MgO   | Na <sub>2</sub> O | K <sub>2</sub> O | TiO <sub>2</sub> |
| 62.22            | 11.096                         | 4.033                          | 3.583 | 0.599 | 0.78              | 3.266            | 0.339            |

#### B. Experimental apparatus

The experiment is divided into two stages. The first stage is the IX process by natural zeolite bed, and second stage is RO process, as shown in Fig. 1. The First stage consists of a tank for the feed water, feed water pump with speed controller, IX bed (zeolites bed) and IX outlet tank. IX bed has a cylindrical shape with 7 cm diameter and 25 cm height. As IX process needs about 20 min contact time or more (Ghaly & Verma, 2008) therefore the used feed water pump runs with a very small flow rate of 30 ml /min. The IX process performance was evaluated by means of the solution pH and electrical conductivity measurements.

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In the reverse osmosis (RO) process, this process uses the produced water from the IX process to the membrane. This stage consists of a diaphragm pump (Water world CDP-9000, maximum flow rate of 1.6 Lpm, maximum pressure of 80 psig, and motor 24VDC/1.2A), adjustable DC power supply, pressure regulator in the produced line, and finally a spiral wound RO membrane FilmTecTM TW30-1812-100. The system was also completed with pressure indicator (0–140 psig).

Electrical conductivity is measured by electrical conductivity probe (KDS-1038) from ScienceCube. pH is measured by inoLab pH 720 from WTW GmbH.



Figure 1. The proposed hybrid system set up

### III. THEORETICAL ANALYSIS

### A. Zeolite IX bed process

A theoretical simulation of the IX process was done using MATLAB program code. Advection diffusion equation is used to describe mass transport in column bed filled with porous media where advection causes translation of the solute with the flow velocity and dispersion causes solute spreading. For one dimensional flow in the vertical direction, the advection diffusion equation (ADE) formed in [19] is used:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial Z^2} - V \frac{\partial C}{\partial Z}$$
(1)

where C is the solute concentration (ppm), t is time (s), Z is the vertical coordinate (m), D is the diffusion coefficient (m2/s) and V is the advection velocity of the flow (m/s).

Forward difference scheme is used for the first order derivative of function and central difference scheme is used for the second one. The final form of numerical solution by finite difference method (FDM) in implicit condition is given as follows:

Forward difference scheme:

$$\frac{\partial C}{\partial Z} = \frac{C_{i+1} - C_i}{\Delta Z} \tag{2}$$

Central difference scheme:

$$\frac{\partial^2 C}{\partial Z^2} = \frac{C_{i-1} - 2C_i + C_{i+1}}{\Delta Z^2}$$
(3)

From equations (1), (2), and (3), the final form of ADE in [20] is as follow:

$$-D\frac{\Delta t}{\Delta Z^2}C_{i-1}^{t+1} + C_i^{t+1}\left(1 - V\frac{\Delta t}{\Delta Z} + 2D\frac{\Delta t}{\Delta Z^2}\right) + C_{i+1}^{t+1}\left(V\frac{\Delta t}{\Delta Z} - D\frac{\Delta t}{\Delta Z^2}\right) = C_i^t$$
(4)

where the diffusion coefficient D (m2/s) was estimated in [21].

#### C. Reverse osmosis performance calculations

There are many calculations methods that are used to judge the performance of an RO system and also for design considerations. In the present work, membrane recovery %, and salt rejection %, are used to judge the performance of an RO system after adding the new IX bed to determine its effect on RO system.

Membrane percent recovery, Re%, was defined as the percentage of permeate (being recovered) to feed water flow rate and is calculated as follows:

$$\operatorname{Re}^{m} = \frac{Q_{p}}{Q_{f}} X100 \tag{5}$$

where  $Q_P$  and  $Q_f$  are the flow rate of permeate and feed water in (m<sup>3</sup>/h), respectively.

$$J = \frac{V}{At} \tag{6}$$

where J is the membrane flux  $(L/m^2 h)$ , V is the permeate volume (L), A is the membrane area  $(m^2)$  and t is the time (h).

The salt rejection, (SR %), is the measure of the effectiveness the RO membranes in removing contaminants. The salt rejection, (SR %) is calculated by the salt concentration difference in the feed and permeate solution:

$$SR\% = (1 - \frac{C_p}{C_f}) \times 100 \tag{7}$$

where  $C_p$  and  $C_f$  are the concentration of salt in permeate and feed solutions (mg/L), respectively.

## IV. RESULTS AND DISCUSSION

The results include the performance of IX process when it works in continuous water flow bed and will be presented experimentally and theoretically. In addition, the performance of hybrid RO system when IX bed is added before RO will be presented.

## A. Performance of continuous water flow IX processes Experimental results

Figs. 1 to 4 illustrate the variation of the electrical conductivity of IX produced water (at zeolite bed outlet) with time for different amount zeolite mass in the bed and inlet water with TDS of 1060, 1660 and 2020 ppm, respectively. The water solution electrical conductivity is measured at zeolite bed inlet (inlet condition at t=0) and then at the bed outlet. The water flow spends about 30 min to arrived to the zeolite bed outlet, therefore the first measuring point of the produced water (at the bed outlet) is measured after about 30 min or more, as shown in Figs. 2 to 4. It could be noted that the produced water solution electrical conductivity firstly sharply decreases by about 0.90 % to 19.2 % and then increases with time. This is because natural zeolite uptake the sodium ions and this lead to electrical conductivity decreasing. Also, it is noted that, for the studied range of water pump flow rate, zeolite mass and TDS, the lowest achievement of the produced water solution electrical conductivity is occurred at 250 gm zeolite mass, which equivalent to 8.33 grams of natural zeolite per ml/min of water flow rate ( $\emptyset$ ).



Figure 2. Variation of the produced water solution electrical conductivity with time for different amount zeolite mass in the zeolite bed when solution TDS=1060 ppm



Figure 3. Variation of the produced water solution electrical conductivity with time for different amount zeolite mass in the zeolite bed when solution TDS=1660 ppm



Figure 4. Variation of the produced water solution electrical conductivity with time for different amount zeolite mass in the zeolite bed when solution TDS=2020 ppm

That is because this is the best weight for our bed size to make good contact between zeolite and water solution and enhances the diffusion process for Sodium ions in zeolite particles.

The effect of zeolite particle size ranging from 0.5-6 mm on produced water electrical conductivity is investigated experimentally. In these experiments, the experimental conditions were selected to be; the solution concentration of 2020 mg/L, electrical conductivity of 4058  $\mu$ S/cm, pH of 7.5 and zeolite mass of 250 g. Fig. 5 illustrates the variation of the IX produced water electrical conductivity with time for different zeolite particle size and indicates that as particle size decreases, the produced water electrical conductivity decreases. This is due to that as zeolite particle size decreases, the surface area/volume ratio of the natural zeolite increases. And for small particle the diffusion path is short and it will be easy for zeolite to adsorb solute ions.



Figure 5. Variation of the produced water electrical conductivity with time for different zeolite particle sizes

#### B. Theoretical results

In this section the experimental results will compared with the theoretical results to verify the theoretical model. Moreover, some more working parameters with wide range will be studied. Figs. 6 to 8 show the relation between IX produced water concentration and time for different inlet TDS values, when ratio of zeolite mass to water flow rate ( $\Phi$ ) is 8.33 g/ml.min<sup>-1</sup> (equivalent to 250 gm zeolite mass and 30 ml/min water flow), for experimental and theoretical results. It can be seen from these figures that the produced water concentration sharply decreases by 7.21 % to 16.3 % at first and then increases with time for experimental results. This is because the natural zeolite uptake the sodium ions and this lead to TDS reduction. Also, from Fig. 8, we can see that there is nearly concentration reduction of 16.3 % for experimental and theoretical results at the same time (40 min).



Figure 6. Produced water concentration versus time at 1060 mg/L inlet water NaCl concentration



Figure 7. Produced Water concentration versus time at 1660 mg/L inlet water NaCl concentration



Figure 8. Water NaCl concentration versus time at 2020 mg/L inlet water concentration

Fig. 9 illustrates the relation between IX produced water electrical conductivity and time for different water flow rates. The inlet water NaCl concentration is 2020 mg/L and zeolite weight is 250 g. It could be noted that as water flow rate decreases, IX produced water electrical conductivity decreases. This is because as water flow rate decreases, the contact time between water and zeolite will be increased and hence the adsorption equilibrium can be reached. The best reduction in the electrical conductivity is by 45.1% which is occurred at 10 ml/min water flow rate with about 120 min

experiment time. The electrical conductivity reduction for 30 ml/min is about 16.9% which is very close that obtained experimentally, which was about 16.7% as in Fig. 4.



Fig. 10 shows the effect of zeolite bed diameter with fixed bed height (10cm) on IX process performance theoretically. It shows that the increase of zeolite bed diameter enhanced the performance of IX zeolite bed. The electrical conductivity of the produced water is decreased from  $3500.5\mu$ S/cm to  $1001.7\mu$ S/cm, when the bed diameter is increased from 5 cm to 15 cm. This is because increasing the bed diameter will increase the contact time between zeolite and water solution. It should be noted that bed aspect ratio (length/diameter) should be between 2 to 7 in [22], this to avoid the difficulty of distributing the feed over the area of the bed. Also, it can be noted that the most improvement in IX process is happened by changing the bed diameter from 5cm to 8cm, which can be taken as the best diameter for present bed.



C. Performance enhancement of hybrid reverse osmosis *desalination* system

In this section, the effect of adding a new zeolite bed on the performance of reverse osmosis (RO) desalination system will be studied experimentally. This is done by studying the membrane water recovery and salt rejection percentage.

Fig. 11 shows the relation between RO membrane recovery, Re%, and feed water concentration without IX bed and with IX bed for different weights of zeolite bed (200, 250, and 300 g). It could be seen that as feed water

concentration increases, membrane recovery ( $Re^{0}$ ) decreases. Moreover, adding IX bed to RO system improves the performance of RO system. This is because IX bed decreases water electrical conductivity, which decreases the osmotic pressure of feed water and hence increases membrane permeate, which increase membrane recovery. The Membrane recovery is increased by 9% to 27.1%, when zeolite IX bed with 250 g weight was added for different concentrations. Finally, the higher membrane recovery has been occurred for 250 g zeolite mass.



Figure 11. Effect of adding IX bed on RO membrane recovery for different amount zeolite mass in the zeolite bed

Fig. 12 shows the effect of the inlet water concentration on permeate increasing ratio due to using IX bed for different masses of natural zeolite in the IX bed. Permeate is enhanced by ratio from 8.5% to 29% for water treated by IX bed with 250g zeolite mass. Therefore, in the present studied range, the optimum ratio between natural zeolite mass per ml/min of water flow rate is 8.33.



Figure 12. Effect of feed water concentration on permeate increasing ratio for different natural zeolite IX weights.

Fig. 13 compares between salt rejection percentage for RO system without IX bed and with natural zeolite IX bed for different water solution concentrations. It is clear that the salt rejection decreases when the inlet water concentration increases. This is due to the increasing of osmotic pressure of the feed water. Also, it could be seen that adding natural zeolite IX bed has nearly no effect on the system salt rejection. Therefore, using IX bed before RO process will increase the membrane water permeate without affecting its salt rejection. Finally, Fig. 14 compares between membrane flux for RO system without IX bed and with natural zeolite

IX bed for different feed water electrical conductivity. It could be seen from this figure that the membrane flux is enhanced by using IX bed. At inlet water electrical conductivity of 6712  $\mu$ S/cm, hybrid RO system membrane flux is higher than that for conventional RO system by 30%.



Figure 13. Comparison between salt rejection percentage for RO system without IX bed and with natural zeolite IX bed at different water solution concentration



system at different inlet feed water electrical conductivity.

### V. CONCLUSION

A novel hybrid IX (ion exchange) reverse osmosis (RO) system is designed and investigated experimentally and theoretically. The performance of IX process in continuous water flow is examined. The effect of adding natural zeolite bed as IX bed before RO system is studied. From the experimental and theoretical results, it could be concluded the following proof of concepts:

- 1. IX process using natural zeolite works effectively in a continuous water flow system.
- 2. The smaller zeolite size particles, the higher IX performance is obtained.
- 3. In the present studied range, the optimum ratio between natural zeolite mass and water flow rate is 8.33 at which highest IX process performance is obtained.
- 4. IX process is simulated theoretically and has a fair agreement with experimental results
- 5. In the present studied range the best water flow rate and bed diameter for zeolite IX process is predicted.

- 6. The proposed hybrid system has higher performance and lower osmotic pressure than that for the conventional RO system.
- The proposed system water recovery, permeate water and membrane flux is higher than that for conventional RO system by 9% to 27.1%, 8.5% to 29 % and 30% respectively for 250 g zeolite bed at different inlet water concentrations.

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