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A neutron Scattering Method for Monitoring Water Salinity during Desalination Processes

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Abstract: Desalination of saline water became an obligation., and the measuring of salinity as electric charge as sodium chloride is interfered. A method based on neutron scattering was proposed for monitoring salinity of water during desalination processes. It is based on the use of a fast neutron source (Pu-Be) and thermal neutron detectors. Due to the reaction of fast neutrons with saline water during the desalination processes, neutrons are thermalized by water. Neutron thermalization depends on salt concentrations in water. High density of thermal neutrons inside the irradiated sample, indicate low concentration of dissolved salts and vice versa. Such a working principal was used for monitoring the removal efficiency of dissolved salts in saline water during desalination processes using microorganisms. Biomaterials (fungal organisms) used in desalination of seawater were extracted using well established procedures. The most efficient extracted product of the fungal organism was used to perform real desalination of seawater. The fungal organism was added to a container containing seawater. It was irradiated by fast neutrons, and backscattered thermal neutrons from a certain position in the container were registered continuously as the desalination process proceeds. Results obtained showed that the neutron scattering methods was effective in monitoring the desalination process. The fungal organism used was very effective in precipitating dissolved salts withing several minutes.

Keywords: Desalination, Neutron, Scattering, fungal organism.

1 Introduction

Salinity is defined as the amount of dissolved inorganic salts in seawater. Water salinity is an important indicator of water quality. It was reported that the average salinity of seawater is around 35 ppt (35 g/kg) [1,2]. Usually, salinity is not measured directly. However it is computed from the measurement of saline water properties such as electrical conductivity of chloride and/or ions, ultrasonic speed and refractive index [1-3]. Other methods for determining salinity are the atomic absorption spectroscopy (AAS) (absorption, emission, or fluorescence) including flame atomic absorption spectroscopy, inductively coupled plasma-mass spectrometry (ICP-MS), inductively coupled plasma-atomic emission spectroscopy (ICP-AES) [4], ion chromatography [5] and neutron activation analysis-based methods [6]. Mainly these methods are used for determining concentrations of ions and/ or elements such as Na, Cl, K, Mn. …..etc. The basic principles, advantages and limitations of these method were reported in [1,4].

High energy-neutrons lose energy and become thermalized due to inelastic and elastic scattering with the nuclei of surrounding medium [7,8]. The inelastic and elastic scattering reactions moderate the neutron's energy till reaching thermal energy range. During the inelastic scattering reaction, compound nuclei are formed for very short time. Such nuclides de-excite emitting neutrons of less energy and prompt gamma rays. In the elastic scattering reactions, fast neutrons are thermalized as results of potential scattering and resonance scattering. For low atomic number elements and/or compounds such as water, the potential scattering is the most important scattering mechanism for thermalization of fast neutrons. However, the resonance scattering of fast neutrons is of less importance in thermalization of fast neutrons because it does not change the enteron energies. Population of thermal neutron are reduced in the presence of nuclides having large absorption cross section. Thermal neutrons can be captured by the absorbing nuclei such as Na, Cl, …etc. from the surrounding medium forming excited nuclides which emit characteristic gamma rays.

Neutron scattering and/or moderation - based techniques

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are based on registering scattered thermal neutrons resulting from moderation (thermalization) of fast neutrons by the hydrogen atoms contained in the sample investigated. Neutrons scattering were used in in the paper–recycling and oil industries, void fraction measurements, detection of landmines, soil contamination, moisture transport in porous media and bulk hydrogen analysis [9-15]. Cf-252, Am– Be, and Pu–Be isotopic neutron sources as well as 14 MeV neutron generators were used in the different applications of NS

To the best knowledge of authors, neutron scattering based techniques were not used for determining salinity of water. Therefore, the present works aims at introducing a NS method for determining water salinity during water desalination processes. Such a method should be simple, quick, reliable and accurate. Additionally, it can be easily upgraded at the commercial scale.

[11,12]

2 Methodology of neutron scattering

High energy neutrons obtained from isotopic neutron source (such as Pu-Be) are moderated and become thermal neutrons in the presence of a low atomic medium such as water due to elastic scattering. In the presence of elements characterized with high absorption cross section such as Na and Cl, thermal neutrons are captured and hence its population decrease (i.e. thermal neutrons count rate decrease). Such working principal can be used for determining salinity of seawater and/or ground waters. As the concentrations of NaCl salt increase in water, the count rate of thermal neutron decreases. Thus, low count rate of thermal neutrons indicates water of a high salinity and vice versa. The thermal neutron capture can be expressed by the macroscopic absorption cross-section, Σ_a . . It can be determined for any compound by the following equation [16,17]:

$$\Sigma_a = \rho \sum_{1-1}^{2} q_i \; \Sigma_{ia}^{m} = \; \rho \, \Sigma^{m} \tag{1}$$

where, Σ_a(cm^{-1}) is the linear macroscopic absorption cross section of thermal neutron for a mixture of n components, ρ is the bulk mass density of the mixture, q_i is the mass fraction of the i-th component and Σ_{ia}^{m} is the mass macroscopic thermal neutron cross-section for absorption (cm^2 .g^{-1}) of the i-th component. . Σ_{ia}^{m} is calculated by following equation:

$$\Sigma_{ia}^{m} = \rho \sum_{i}^{d} \frac{N_{Av}}{A_i} f_i \sigma_i, \tag{2}$$

where NAv is Avogadro's number and fi , Ai , and σi are the mass fraction, atomic weight and thermal neutrons microscopic absorption cross-section at the standard neutron velocity, v0 (2200 m/s) of the i-th element, respectively. Seawater is consisting of pure water, inorganic salt (NaCl, KCl, MgSO4, CaCl2, MgCl2 and NaHCO3) and suspended solids. The inorganic salts of seawater on the average mainly consists of 55.3% of chlorine, 30.8 % of sodium, 7.7 % of sulfur, 3.7% of magnesium, 1.2% of calcium, 1.1% of potassium [18]. Other trace elements in the ppm range were reported in seawater including B, Br, SR and Li [19]. The value of Σ_a was calculated for these concentrations in water and found to be 0.0327 cm^2.g^{-1}. The same value can be obtained assuming water contain 3.22% of NaCl. Thus, standard solutions of distilled water containing fractions of NaCl up to 3.22 % can be prepared to simulate seawater of 3.5 % salinity.

Counting thermal neutrons perturbed by standard solution containing known fractions of NaCl by a proper thermal neutron detector such as He-3 detector is an indicator for the removal of dissolved salts during desalination processes. The removal efficiency ε , of dissolved salts in saline water due to desalination processes can be determined using the following formula:

$$\varepsilon = \frac{C - C(t)}{C} x100 \tag{3}$$

where C is the initial concentration of salts before starting the desalination process, and $C(t)$ is the concentration as a function of the desalination time, t. To determine the removal efficiency, NS experiments should be carried out for standard solutions consisting of distilled water containing known factions of NaCl- Calibration experiments. From such experiments, empirical relationship is established between thermal neutron count rate and, Σ_a and /or NaCl content. The concentration of salts (C, C(t)) for real water samples subjected to desalination are determined from the calibration results.

3 Experimental details

3.1 Producing of desalinating Biomaterials

The used biomaterials in estimating the efficiency of the neutron scattering method for calculating the online desalination rate of seawater was produced by the following procedures:

1) Different fungal isolates were isolated from the saline of Max Company for saline (Egyptian Company for production of salts , Alexandria),
2) Each fungal isolate was grown on saline modified Dax's media in specific temperature for different specific incubation periods. The pH values were adjusted through the optimum incubation period at specific pH within the range of 6.5 -8 of the media.
3) The fractionation of the high dominant and efficient in the precipitation of salt from the laboratory prepared seawater solution and seawater, fungal isolates occurred under critical conditions. Each fraction was examined for the ability of precipitation of Sodium, Magnesium,

and Calcium salts .

4) The most efficient extracted product of the fungal organism (GA1) was studied in the precipitation of Sodium, Calcium, and Magnesium ions. The rate of precipitation was estimated by different methods (ICP, flame photometer, and radiotracer methods).

3.2 Experimental set-up

Two experimental arrangements were used in this work. The first set up is shown schematically in Fig.1. It consists of a cylinder made of polyethylene of 80 cm diameter and 100 cm length. A tube of 10 cm diameter is fixed along the central axis of the cylinder. The cylinder filled with water and is surrounded by blocks of borated paraffin. A Pu-Be neutron source (1 Curie) is fixed inside the tube contained in the water cylinder. One end of the tube is opened -exist face of neutrons, while the other end is blocked by a rode made from borated paraffine. The exit face of neutrons is covered by Cd sheets of thickness 0.5 mm except an opening of ~10 cm diameter. Role of water and borated paraffine surrounding the Pu-Be source is to minimize leakage of neutrons. Neutron beam can be obtained from the water cylinder. Cylindrical vessels of thin walls and having a volume of 1.3 liter was prepared to accommodate standard water samples. ^{3}He neutron detectors (LND-252172) were fixed on the sample vessels at two positions as shown in Fig.1. The detector fixed in the first position records back-scattered thermal, however, the detector fixed inside the sample records thermal neutrons inside the sample. High voltages to the He-3 detectors were provided by power supply (Canberra model 31060) through preamplifiers (Ortec-142PC). Output signals from the preamplifiers were amplified (Canberra Amp/TSCA 2015A) and then fed to multi-channel analyzer (Multi-Port II. MCA) which is installed on a PC. These MCA are controlled by a genie software. It was used for acquiring and analyzing spectra recorded by the detectors.

This set-up can be used for online monitoring of the rate of desalination processes. In such a case the He-3 detector installed recording backscattered neutrons is adjusted to record neutrons from a specific position of the container containing the saline water and/or seawater. Increasing of the count rate of the detector at certain position in the water container means success of removal of dissolved salts.

The second set-up is shown in Fig.2. It consists of a cylinder container made of polyethylene of 40 cm diameter and 60 cm length. It is filled with distilled water and fixed vertically. Along the central axis of the water container, a polyethylene tube was fixed. A Pu-Be neutron source (1 Curie) is inserted in the middle of the tube during the measurements. The distilled water surrounding the neutron source moderates emitted fast neutrons from the Pu-Be source. Blocks of borated paraffine were used to shield the water container to minimize leakage of fast neutrons and thermal neutrons. Small cylindrical containers of different volumes were prepared- samples containers. Such containers are fixed at the left of the neutron source inside the cylindrical container containing the distilled water. A ^{3}He neutron detector (LND-252172) was fixed inside the sample container. Another identical detector was fixed in the distilled water container at the right of the neutron source. The electronic used in the first set-up were used in the second one.

The second set-up is used for static measurements. Namely, during the desalination process, samples of water can be taken and counted.

Standard water samples consisting distilled water and fractions of NaCl, H_3BO_3 and mixture of NaCl and H_3BO_3 were prepared. Σ_a was calculated for these mixtures – Table 1.

Table 1. Percentage concentrations (%) of NaCl and NaCl+ H_3BO_3 in water and calculated Σ_a x10^{-2} ($cm^2.g^{-1}$)

NaCl	Σ_a	H_3BO_3	Σ_a	NaCl +H_3BO_3	Σ_a
0.00	2.22	0.77	8.0	2+0.75	8.6
0.75	2.47	1.5	13.4	9.6+1.5	16.6
1.5	2.72	2.3	19.4	15.12+2.24	24.0
2.3	2.98	3.0	24.6	20.0+3.0	31.3
3.0	3.21	3.7	29.8		
3.7	3.44				
5.1	3.9				
6.5	4.36				
9.8	5.44				
15.5	7.31				

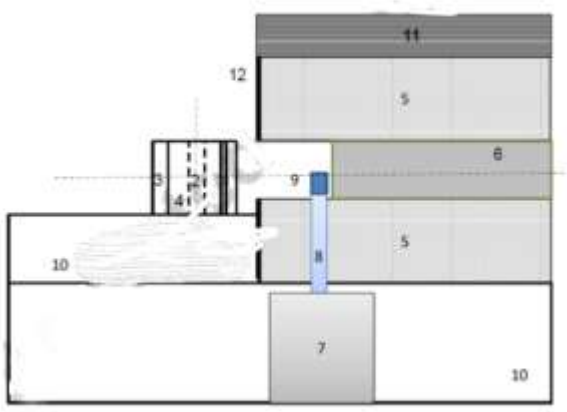

Fig. 1: Schematic diagram of the experimental set-up (side view - vertical projection). Not to scale. 1,2 and 3: the neutron detector positions at 180^0 , inside the sample and 0^0 , respectively; 4 : sample; 5: water moderator; 6 : paraffin wax plug; 7 : a Pu-Be neutron house; 8: tube through which the source is raised during measurements; 9: neutron source, 10: wooden table; 11:borated paraffin ; 12: Cd sheets. The dashed dotted lines are symmetry axes.

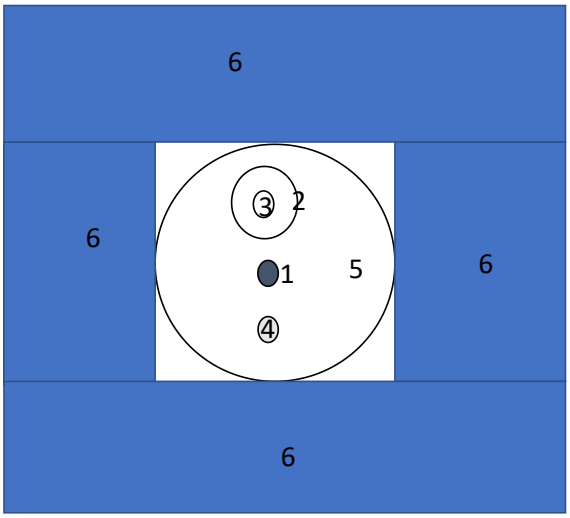

Fig. 2: Schematic diagram of the second experimental set-up (side view - vertical projection). Not to scale. 1: a Pu-Be neutron house, 2: saline water sample, 3 and 4: the neutron detectors positions inside the saline and water samples, respectively; 5: water sample (moderator); 6: borated paraffin wax shielding,

Cylindrical containers having different volumes 1.3 -2 liters were prepared to accommodate the samples investigated

4 Results and Discussion

The count rate for the inside versus the back detectors based on the measurement of NS using the first set-up is shown in Fig. 3. As one can see, the inside detector is 3.6 better than the back one. This was estimated from the slope of the fit lines using straight equations. The standard samples listed in table 1 were used in this experiment. Such results can be used as follow: the backscatterd neutrons can be used, however after transforming the results of the inside detector to the back one. The inset represents results for standards containing NaCl up to 3.7 %. Fig. 4 shows the results for standard samples containing NaCl only. As can be seen, the response of the detectors linearly decreases as Σ_a increases. The inside detector is better than the back one. The results shown in Fig. 4 – for the inside detector- were fitted with straight line equation with R^2=0.99. The fitting equation is given by

$$CR = -2471 * \Sigma_a + 385, \quad (4)$$

In terms of the empirical equation 4 and eqs 1 and 2, one can easily arrive at

$$CR = -810 x f_{NaCl} + 330, \quad (5)$$

where CR is the thermal neutron count for the inside detector, and f_{NaCl} is the NaCl fraction ($f_{NaCl}x100$ = percentage weight of NaCl relative to water). For example if the value of f_{NaCl}=0.035, it means the NaCl concentration is 35 ppt (3.5 %). Equation 5 can be obtained directly from the results via plotting CR versus NaCl concentration and then fitting the results using straight line equation. Such a process yielded an empirical equation given by

$$CR = -802 x f_{NaCl} + 329 \quad (6)$$

The two equations 5 and 6 are in a very good agreement – deviations of CR determined from both equation for all calculated values of f_{NaCl} are less than 0.2 %. Salinity is expressed in terms of equivalent concentration of NaCl. Since the value of Σ_a for NaCl is 1.032 times the equivalent concentration of the different elements in water, this factor should be taken into account. This leads to the modification of equation 5 to become

$$CR = -825 x f_s + 327 \quad (7)$$

In such a case, the fraction of NaCl, f_{NaCl} is modified to fraction of dissolved salts in water, f_s .

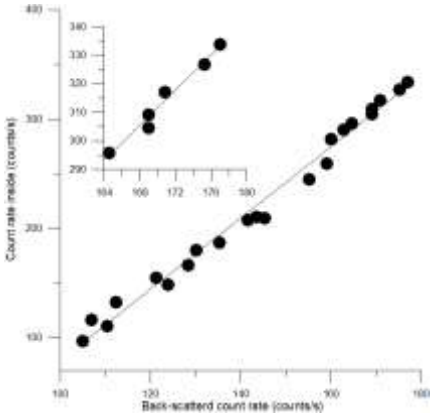

Fig.3: Scattered neutrons count rate for the inside versus the back detector.

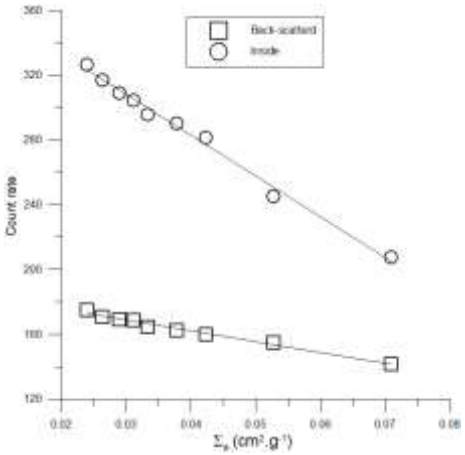

Fig. 4: Scattered neutrons count rate for the inside and back detectors versus Σ_a

The removal efficiency ε, of the first experiment set-up for saline water containing 3.7 % NaCl in terms of thermal

neutrons count rates was determined and found to be 12.8 %. It means that the reduction of 1.28 % in the count rate corresponds to 10 % removal efficiency of NaCl from the saline water. Thus, the second set-up was designed to improve the results. The corresponding removal efficiency ε based on the second set-up was found 20 % for samples of 1.2 L, however increasing the volume of the sample to 2 L improved the efficiency to 25 %.

The fungal organism (GA1) was used for real desalination processes using the experimental set-up shown in Fig. 1. A rectangular container contain 20 liters of seawater was used. The backscatterd thermal neutron count rate at 5 cm from top of surface of water was registered before adding GA1. After adding certain amounts of the fungal organism, GA1 to the seawater container by two minutes, the count rate was registered continuously as the desalination process proceeds. It was noted that the count rate of the backscatterd neutrons increased abruptly once the GA1 was added. With increasing time of desalination, it was noticed that the count rate changed slowly – Fig. 5. This means that the desalination process is relatively fast. After finishing the experiment, it was observed by the naked eye the existence of precipitate at the bottom of the water container. Removal efficiency describing desalination process was calculated and found to be ~ 95 %. Such high removal efficiency means the success of the used fungal organism, GA1 in precipitating dissolved salts in water. The results were credited by performing desalination processes using the second set-up.

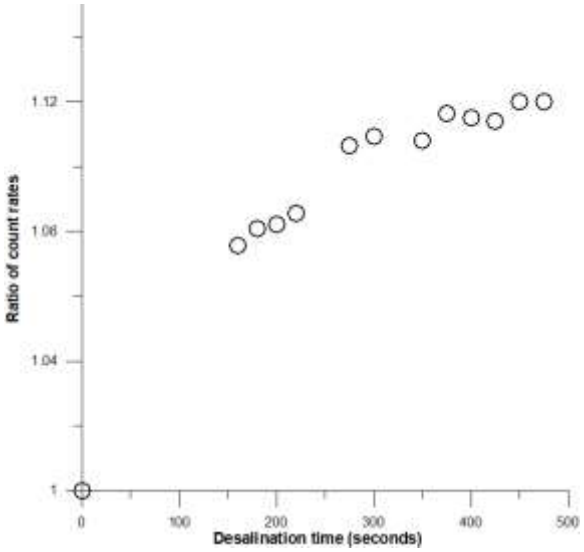

Fig.5: Ratio of count rates of scattered neutrons using the GA1 to count rate of scattered neutrons without GA1 versus desalination time.

Equation 7 can be used for determining salinity (fraction of dissolved salts) of water during the desalination process. With the knowledge of recorded count rates of scattered neutrons salinity can determined.

5 Conclusions

A neutron scattering method was proposed for online monitoring salinity of water during desalination processes using microorganisms. The method is based on irradiating saline and/or seawater with fast neutrons and recording thermally scattered neutrons. Efficiency of fungal organisms for desalination processes of seawater can be determined. The desalination process for a sample of seawater using the fungal organism (GA1) was carried out and monitored online successfully by the developed method. Salinity (fraction of dissolved salts) can be determined at any time and position during desalination processes. The neutron scattering method can be used in field work. It can be installed and calibrated easily and used for determining removal efficiencies during desalination processes.

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