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Application of ohmic heating technique to approach near-ZLD during the evaporation process of seawater

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ABSTRACT

The aim of this study is to investigate the application of the ohmic heating during the evaporation process of the seawater for the purpose of reaching near zero liquid discharge (ZLD). Ohmic evaporator was designed and used to evaporate seawater at electrical field strengths 24, 56 and 87 V/cm using alternating electric current at frequency of 60 Hz. The apparent electrical conductivity, recovery rate and energy consumption were determined during the evaporation process. Some physico-chemical properties of the concentrated brine (sludge) were measured such as electrical conductivity, pH, density and color. Results indicate that the apparent electrical conductivity was reduced by increasing the electrical field strength. The ranges of the recovery rate and specific energy were 81–93.5% and 4550–5071 kJ/kg respectively. It was demonstrated that the ohmic evaporator performed better at electrical field strength 56 V/cm. One major output of this research is the assessment of the generation of heat in the seawater by alternating current during evaporation process for near-ZLD; although, more studies are needed for continuous pilot production system, modelling for commercial production as well as economical evaluation of the system.

1. Introduction

Many countries depend on seawater desalination to provide a secure source for drinking water. To meet the fresh water requirements of many countries in the Middle East, desalination technology of seawater is a growing option [1]. Furthermore, desalination plants are being used increasingly in inland areas for supplying water for domestic purposes. Production of distilled water and adequate disposal of reject brine are an integral part of an overall desalination process. The concentrated effluent that is referred to as brine, blow down or reject is the main waste stream resulting from the desalination process. The reject brine from the seawater desalination is generally discharged to sea; while in the inland desalination plants, the brackish water is the feed source and the reject brine is disposed using evaporation ponds or discharged to the surface [2]. According to Saline Water Conversion Corporation (SWCC) in Saudi Arabia, the TDS upper limit for the reject was set at 67,000 ppm for the reject from the SWRO plants and at a maximum of 80,000 ppm for the final blow down from the MSF unit [3]. It has been mentioned that the discharge of effluent from the desalination plants to surface raises environmental concerns and may affect the environment and lead to soil deterioration [4]. Brine discharged is more concentrated than the brackish water and contains inorganic salts, chemicals, and other substances [5]. Consequently this may cause soil and groundwater contaminations with chemical constituents from various sources (i.e. reject brine, pretreatment waste and cleaning waste of desalination plants). Thus, adequate treatment of the waste streams becomes significant.

An alternative approach to the discharge of effluent is to further process it to extract all the salts. This has the advantages of being environmentally friendly and producing commercial products (i.e., salts and fresh water). It has been reported that due to the water insufficiency for the increasing population in many places in the world and the need to preserve the environment, the zero liquid discharge (ZLD) approach has been under consideration and focus although it has been regarded for many years as an uneconomic solution [6]. The ZLD approach is considered an important strategy in many areas such as managing water resources towards maximizing water savings, reducing desalination and water treatment costs and protecting water resources and the environment [6]. It is a promising approach to recover more water and perhaps useful by-products. The concept of the zero liquid discharge (ZLD) approach refers to further concentrate the brine towards near or, if possible to complete dryness in cost effective methods. The removed water can be recycled to the process for increasing its recovery ratio. The remaining, reduced volume waste is a dry or semidry solid that should be disposed off in special sites [6] or further processed for production of salts.

Many methods have been suggested for zero or near zero liquid discharge. Evaporation ponds are especially suitable to dispose of reject brine from inland desalination plants in arid and semi-arid areas due to the abundance of solar energy. A desktop prefeasibility

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study [7] confirmed the technical feasibility of treating reject brines in simple processing routes using SAL-PROC technology. SAL-PROC is an integrated process for sequential extraction of dissolved elements from inorganic saline waters in the form of valuable chemical products in crystalline, slurry and liquid forms. The process involves multiple evaporation and/or cooling stages, supplemented by mineral and chemical processing. An analysis indicated that various types of salts including gypsum, sodium chloride, magnesium hydroxide, calcium chloride, calcium carbonate, and sodium sulphate can be produced from the reject brine of Petroleum Development Oman (PDO) desalination plants. These products have an approximate market value of US $895,000 annually [7]. A zero-discharge direct-contact freezing/solar evaporator desalination complex was proposed [8] as an efficient system to reduce the environmental impact of concentrated brine from seawater desalination plants. In a recent review of the desalting process techniques of the recovery of salts from retentates reported that many techniques has been developed and used such as electrodialysis, ion-exchange, eutectic freezing, and chemical processing [9]. Fluidized ion exchange was used to remove positive multivalent cations, and then followed by ultrafiltration, nanofiltration and granular activated carbon filtration to increase the recovery of the membrane installation to its limits for Zero liquid discharge process [10]. The construction and preliminary evaluation of a small advanced solar dryer (ASD) was studied to promote brine concentration and/or ultimate salt recovery from the MED brine effluent, thus contributing to the production of salt, adding one more valuable output to the whole system, improving the economics and the environmental performance of a multiple-effect distillation (MED) desalination plant [11]. A pilot study was conducted [6] on high recovery using hybrid process by combining brackish water reverse osmosis and electrodialysis in a reversal mode (BWRO-EDR) to approach near zero liquid discharge. This process was shown to be effective in recovering 97–98% of brackish water as product water. The super-concentrate from the electrodialysis in a reversal mode (EDR) unit was further concentrated in a wind powered unit that brought final brine TDS to >30%, and showed promise as a method to recover mineral by-products such as magnesium salt.

Regarding energy requirements, high energy consumption is usually associated with ZLD techniques. It has been reported that a desalination plant uses 2–4 kW h/m^{3}and a ZLD system uses 20–40 kW h/m^3 [12]. Research Foundation (formerly AwwaRF) study that focuses on the unique challenges of desalinating brackish water for Zero Liquid Discharge reported that the energy required to produce 1 kgal product water from brackish water was reported to be 4–13 kW h for RO and greater than 70 kW h for the brine concentrator [13], this equates to approximately 20–22 kW h/m^3.

Since there was no published work found in the evaporation of seawater by ohmic heating, it may be worthwhile to investigate the application of this method during the evaporation process of high concentration brine above 80,000 ppm. In this context, it is proposed to study the potential application of ohmic technique to recover more water from the effluent of desalination plants for the purpose of approaching near-ZLD. Ohmic heating, also called Joule heating, electrical resistance heating or electroconductive heating: basically, this technique refers to the generation of heat in electrolyte solution by passing alternating electrical current. When alternating electrical current (I) is passed through a conductive material of resistance (R), fast and uniform ohmic heating occurs with the resultant energy generation causing temperature rise. The rate of ohmic heating is directly proportional to the square of the electrical field strength and the electrical conductivity [14]. It has been reported that the electrical conductivity of seawater was 58, 67.8, 67.5 and 72 mS/cm corresponding to TDS of 44, 58.26, 57.78 and 62.82 mg/l respectively [15]. In another RO experimental study, the conversion from bulk concentrate conductivity to TDS for seawater was given by ($C_b = 732.56\,\sigma_b - 3831.6$) where C_b is the bulk feed concentration in parts per million and σ_b is the electrical conductivity in milli Siemens per centimetre (mS/cm) [16]. During ohmic heating, the range of seawater conductivity was reported to be 55–399.6 mS/cm and strongly dependent on TDS and temperature [17]. The temperature and TDS concentrations dependent electrical conductivity relation can be described by (Eq. (1)), where the units of the electrical conductivity (σ), temperature (T) and concentration (C) are S/cm, °C and ppt (part per thousand) respectively.

$$\sigma = 0.032 + 2.95 \times 10^{-5} T.C + 8.58 \times 10^{-6} C^2 \quad (1)$$

This equation can be applied under non boiling conditions of the seawater during ohmic heating. During the boiling process, the electrical conductivity is expected to drop due to the formation of vapor. The properties of the ohmic heating process — which include the rapid and uniform heating, technical simplicity and low capital and maintenance cost — suggest that it could be a highly competitive evaporation method for the discharged brine from membrane or thermal desalination plants. By this method, more distilled water can be produced by excessive concentration of the brine to a level of over saturation as a preparation for further treatments for salt production. To design a successful ohmic evaporator for desalination system, it is important to investigate the changes in the electrical conductivity and the performance of ohmic heater during the evaporation process of the seawater. Therefore, the objective of this study is to evaluate the application of ohmic heating during the evaporation process of seawater for the purpose of approaching near zero liquid discharge.

2. Material and methods

Raw seawater was obtained from the Gulf, East of Saudi Arabia, north of the desalination station in Jubail, (26° 54′ 50.78″ N, 49° 45′ 42.83″ E). The initial concentration of the total dissolved solids, pH, density and electrical conductivity of the raw seawater were 38.9 ppt, 8.01, 1.042 g cm^{-3}, and 61 mS cm^{-1} respectively. The seawater was evaporated using a batch ohmic evaporator. The heating element was made from PTFE Teflon base with two cylindrical titanium electrodes (Purchased from Ti-anode Fabricators PVT.LTD, Chennai-India). Parallel electrodes were inserted through the Teflon base where the electrode gap was 3.66 cm (Fig. 1). The complete setup schematic diagram of the experiment is shown in Fig. 2. The volume of the initial seawater liquid in the ohmic evaporator was 700 ml. The electrodes of the ohmic evaporator were connected to a relay switch protected by 20 Å fuse. The sample was heated and boiled using alternating current of 60 Hz at applied voltages of 110, 220 and 330 V, corresponding to measured electrical field strengths (∇V) of 24 ± 2.93, 56 ± 1.53 and 87 ± 1.85 V/cm, respectively.

Temperatures of the brine, vapor, internal and external surfaces of the tube wall were continuously measured with a T-Type copper constant, Teflon coated thermocouple (Omega Instrument). Voltage and current were measured using calibrated voltage and current transducers, respectively (model VTR-004X5 and CTRS-050x5, respectively, Ohio Semtronics, INC). Temperature, voltage and current data were logged using data logger (Model: OM-3000, Omega Engineering, Inc, New Zealand) at 30 s intervals. During the evaporation process, the apparent electrical conductivity of the seawater was calculated from the voltage and current data using the following equation [18,19]:

$$\sigma_{app} = k_c \frac{I}{V} \quad (2)$$

where;

σ_{app}	apparent electrical conductivity, [S/cm].
k_c	ohmic heater constant, [cm^{-1}].
I	alternating current passing through the sample, [Amp].
V	voltage across the sample, [V].