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Water Out of Waste – Solar-Desalination-Humidification-Dehumidification Auxiliaries Processing Extractive Industrial Operations

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Abstract

Oil and gas drilling produce saline brine, posing a threat and great risk to the environment. Desalination is a pathway to freshwater production and brine removal, however, the energy required for processing and highly concentrated brines curtail the approach. Solar desalination humidification dehumidification (SDHDH) systems are a low energy and economical response that solves the problems. The current study aims to demonstrate saltwater solar-desalination, an innovative SDHDH design, used to process the waste materials. The method was successfully tested at full scale as follows: In a 400 m^2 application containing 600 m^3 saline-water, the total dissolved solids (TDS) were equal to 141 g l^{-1}, requiring an input of 196.2 kW electrical energy. As a result of SDHDH 266 m^3 of freshwater was obtained, with TDS equal to 210 mg l^{-1}. The water-recovery percentage achieved was 44%. The salt removal efficiency was near 100%. Surface-time efficiency varied, between 8 to 30 l $m^{-2}day^{-1}$. SDHDH use is an effective mechanism to elute freshwater from concentrated brines, maximizing productivity, and lowering hazardous impact to the environment providing benefits to ecosystem and human services alike.

Keywords: SDHDH; Solar-Desalination; Salt-Water; Water-Recovery; Water Productivity.

INTRODUCTION

Disqualified drilling fluids and drill cuttings are wastes generated from oil and gas well drilling operations (Ball et al. 2012). Waste characteristics are dependent on the mud they contain, its composition, and formation material. Two principle types of muds are involved in oil and gas drilling operations, being water-based fluids and oil-based fluids (Caenn et al. 2011; Khodja et al. 2007). The waste has a detrimental effect on the environment. In order to make an agreement with authorities and public concerns, oil well drilling companies must use management techniques to reduce the impacts of waste on surrounding environmental conditions (Caenn et al. 2011; Onwukwe & Nwakaudu 2012).

Generally, waste management steps are based on reduction, reuse, and recycling of all products produced by drilling rigs (Sharif et al. 2017). Consequently, several parameters, including equipment, drilling operations, handling rates, costs, authorities, risks and environmental impacts are considered within methods of drilling waste management (Ball et al. 2012; Cripps et al. 1998). Drilling cutting and mud wastes water are recovered by physical and chemical processes within limited processes, highly saline fluids are not economic to process and so are not demanded by processing rigs. Saline brines

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*Corresponding author: amir.parnian@gmail.com pose a harsh threat to the environment. Desalination provides a potential pathway for freshwater production and brine removal.

The lack of freshwater is of great concern in human communities and has driven water desalination research and process. Desalination removes salt from water, though conventional methods have high energy requirements (Karagiannis & Soldatos 2008). Solar desalination (SD) methods efficiently remove salt from the water with little or no surplus energy requirement; humidification dehumidification (HDH) systems provide an optimal solution which may couple the SD method with air humidification and air dehumidification (Giwa et al. 2016). In order to supplement these methods, the current study focuses on seawater ‘greenhouses’.

The seawater greenhouse is considered an HDH system, that is partially or entirely powered by solar energy (Davies & Paton 2005). Moreover, as illustrated in Fig. 1, it uses seawater to humidify and cool the greenhouse atmosphere, consequently, freshwater is produced and ‘extracted’ by plants, in warm arid seashores, with great benefits to productivity (Davies & Paton 2005; Davies & Paton 2006).

Various types of HDH have been conceived and advanced (Giwa et al. 2016); additionally, different forms of condensers have been used in seawater greenhouses (Dawoud et al. 2006). In the development of the seawater greenhouse system, structures use a water heater-air humidifier constructed on a shallow water reservoir filled with saline water (Fig. 2), which achieves a higher gradient of salt removal than prior seawater-greenhouse systems (Davies & Paton 2005).

In Fig. 2 saline water flows into a lined base pool covered by double sheets of clear plastic curtains to form a greenhouse; water is pumped and sprayed into the air by vortex nuzzles. In the humidifier of the system water and the atmosphere of the semi-greenhouse are partially warmed by the sun's radiation, producing moist atmospheric conditions. Fans evacuate the humid air to the dehumidifier section (ground dehumidifier) and freshwater is produced, which flows to the reservoir.

The approach of Fig. 2 develops the HDH and would provide a low cost and efficient system with benefits that specialize it in water evaporator-production systems. Innovations from previous systems are:

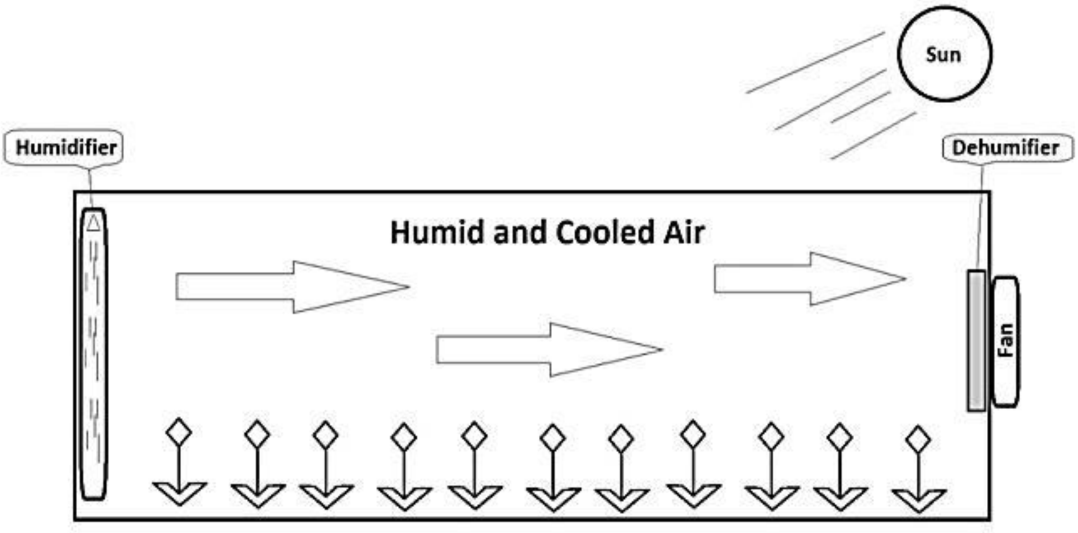

Fig. 1. Seawater Greenhouse

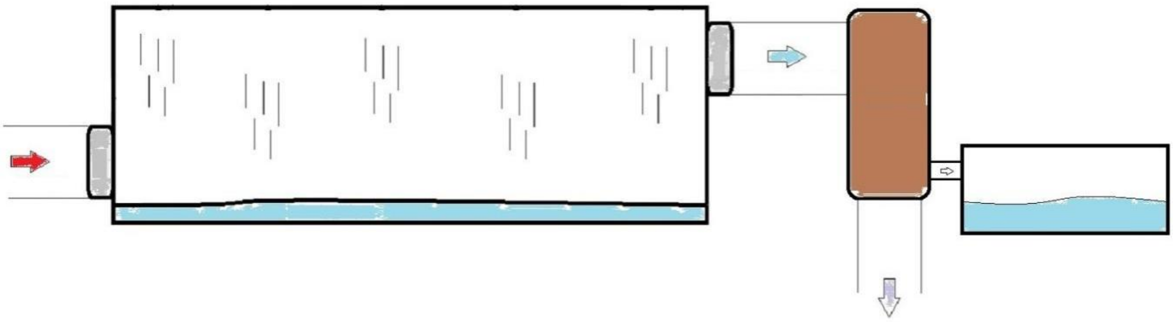

Fig. 2. Humidification Dehumidification within the seawater greenhouse

Merging the solar water heater and the humidifier

In the new desalination system, solar water heater and humidifiers merge to make a low-cost HDH. Saline-water flows into a room covered by a double-layer of clear plastic membranes, and the air is vacuumed out to a dehumidifier by fans. Solar radiation passes into the heater-humidifier room, heating the air and, saline-water.

Using vortex spray nozzles to spray water

Systems have been developed for air humidification in HDH methods, including water spraying (Lerner, 1993; Srithar & Rajaseenivasan 2018), evidently increasing air humidification performance, with an electrical pump and some vortex nozzles by spraying water into the heater-humidifier room. Water sprays increase air humidification more rapidly and efficiently. Use of vortex nozzles avoids plugging by salt and germs.

Using a ground dehumidifier

The soil has lower temperatures than the air during the day in warm seasons (Jury & Horton 2004). Inspired by a ground-source heat pump system, a prototype of ground dehumidifier has been designed (Han &Yu 2016); which may be used to dehumidify air and produce fresh water. Herein a length of a PVC tube may be placed underground for dehumidification purposes, with water collected in a plastic reservoir.

Possibility of salt production

Saline brine processing is known to be most difficult in desalination methods (Abdul-Wahab & Al-Weshahi 2009). However, the use of vortex nozzles to spray water and in the heater-humidifier room makes salt production possible, by spraying saline water up to the salt super-saturation point. The described trial system would potentially alleviate the demand for brine management and reduce environmental concerns.

The objective of the current study is to demonstrate an innovative SDHDH at full scale in the processing of waste produced by oil and gas drilling operations in Iran, further the study aims to show the efficiency of the approach and suggests its application in additional locations.

MATERIALS AND METHODS

Technical application for desalination

The technique of Fig. 2 was employed in the current study where it was novelly used for desalination of oil and gas drilling saline wastewater in Iran by Parnian Sazeh Chehelsotoon Co. The desalination plant produced freshwater for each square meter of its surface (Fig. 3).

The main specialized reinforced concrete (with no permeability achieved by adding bentonite to the waste solution) pond was 400m^2, with an average depth of 1.2 meters. Vortex nozzles within the chamber were designed and 3-D printed by Parnian Sazeh Chehelsotoon Co. The pond

Fig. 3. New HDH based on seawater greenhouse, Naft e Sefid, Shushtar, Khuzestan, Iran, 2019.

covers were made of UV resistant Polyethylene sheets of 2µm thickness with 7% anti-UV material, were in a 6mm envelope and formed a cube shape greenhouse. A fan (80 cm diameter; 800 W power and 11500 m^3h^{-1} ventilation capacity) extracted humid air to the condenser. Ground dehumidification was carried out in a condenser made of PVC tubing of 20 cm diameter 2 m underground over a distance of 50 m, the air was allowed to flow in and freshwater was produced and stored in the reservoir.

Set productive relative humidity to start the fan

Pre-tests indicated that water system production depended on the humidifier atmosphere relative humidity (RH), which was controlled by the operation period of the fan. Constant periods of fan operation require a stable temperature of the dehumidifier, which is fed back to check the system water production performance dependency to RH of the humidifier atmosphere. In the system performance tests, the optimum RH for turning the fan on was experimentally calculated as follows: in 5 days, 5 different RH percentages (80, 85, 90, 95, and 100) were set as starting points for the fan to extract the humid air of the humidifier for 20 minutes, controlled by a sensor-controller device (Electronic20, Iran), and equipped with an AM2305 sensor (Electronic20, Iran) which has 3% accuracy of moisture measurement. Desalinated water volume was quantified, and the most productive RH set for the system was implemented.

System performance evaluation

In drilling operations, water may be contaminated by petroleum. As floated oil prevents water evaporation and slows the process, a skimmer tool and line-up procedure were used for oil removal. These methods work based on the difference between water and oil density, some oil pollutants may reside on the water surface. Consequently, to reduce the oil thickness on the water further, oil absorbents were applied to clean the water. After the oil has been removed by this process, performance evaluation was carried out on 600 m^3 saline-water. The volume of saline-water was inputted into the desalination system, whilst pH, TDS, and turbidity of the inputted, and outputted water was examined in a local potable water lab unit (APHA 2005). System removal efficiency (R) was calculated by equation 1 (Parnian et al. 2015):

$$R\ (\%) = [(C_0 - C_t)/\ C_0] \times 100 \qquad (1)$$

Where C_0 and C_t represent the residual amount of the pollutant at time = 0 and at time = t, respectively.

The area efficiency performance (AEP) of solar desalination is how much water was produced per unit area and was calculated by equation 2:

$$AEP = ASA/\ FW \qquad (2)$$

Where ASA represents the solar accumulator surface area and FW is the amount of produced freshwater.

Surface-time efficiency (STE) uses FW and ASA to show how much water was produced by desalination each day per unit area, and was calculated as follows in equation 3:

$$STE = FW/ [(T_1 – T_0) * ASA)] \quad (3)$$

Where, T_1 and T_2 represent the time = 0 and at time = t, respectively.

Electrical energy efficiency (EEE) of freshwater production details the electrical energy consumption of the system for each produced freshwater unit. EEE was calculated by equation 4:

$$EEE = TEE/ FW \quad (4)$$

Where TEE represents the total electrical energy consumption by the desalination system, which was calculated by total working hours of electrical devices multiplied by their electrical consumption per hour.

Statistical analyses (standard deviation; one-way Analysis of Variance and Duncan's Multiple Range Test) were performed by Microsoft Excel 2010 and SPSS Version 16 software respectively.

RESULTS AND DISCUSSIONS

Productive RH evaluations to starting the fan

Water distillation efficiency in the geothermal condenser depends on the RH of the inputted air (Narayan et al. 2010). Water evaporation depends on the humidifier atmosphere RH (Giwa et al. 2016). The pre-test data used to select the most productive RH for starting the system's fan is shown in Table 1.

In Table 1 the best water production occurred in RH = 85 %, it should be noted that the humidity sensor-controller device had 3% RH accuracy, consequently, the difference in the selected set of RH was 5%. Excess humidity benefitted the closed greenhouse environment.

Desalination efficacy and performance of the system

The desalination system was developed to reduce soil water salt content (Huang et al. 2019). System performance behaves variably depending on the desalination method (Calise et al. 2019). The inlet and produced freshwater properties examined results are shown in Table 2.

Table 1: RH of humidifier effects on system water production

Semi-greenhouse RH (%)	80	85	90	95	100
Water production per day (m^3)	10.2^b	11.2^a	10.5^b	8.8^c	8.1^d

Different letters in the same row indicate a significant difference one-way ANOVA and Duncan's Multiple Range Test at $P < 0.05$, n = 3.

Table 2: Water properties and desalination efficacy

Examined parameters	Inlet	Outlet	Performance
pH	8.5 ± 0.3	7.1± 0.1	-
TDS (mg l^{-1})	141000 ± 100	210 ± 12	99.9 %
Turbidity (NTU)	1881 ± 22	2 ± 1	99.9 %
Amount of water (m^3)*	600	266	44 %

The different parameters measured are expressed as: average ± standard deviation, n = 5.
* Cumulative amount mentioned and performance calculated based on freshwater production.

In Table 2, outlet water pH is lower than inputted water, the reduction was caused by ion removal through desalination. Furthermore, TDS of produced freshwater was greater than expected of distilled water which resulted and was near 200 mg l^{-1}, this may have been caused by aerosols that exist in the humidified air or surrounding dust. Produced freshwater turbidity was examined until results were constant and equal to 2 nephelometric turbidity units (NTU).

The performance of water production in the desalination system was 44%, which was higher than most reverse osmosis (RO) or other thermal desalination processes. Further, the process of the current study was seen to be less dependent on the inputted water salinity than other technologies (Shatat and Riffat 2014; Youssef et al. 2014).

HDH desalination and other water purification methods have brine problems (He et al. 2019; Nayar 2019), which leads to environmental pollution (Panagopoulos et al. 2019) or ecosystem disruption (Kenigsberg et al. 2020). The SDHDH desalination of the current study had less brine (around 240 m^3) than expected, after 10 days it turned brine to salt when the pump-nozzles were off, with the fan on continual (24 hours per 7 days) operation. SDHDH of the current study enables a greater quality of water being recycled back to the environment than alternative methods.

Solar desalination production depends on solar energy, which also relies on solar accumulator expansion. In

Table **3** desalination performance of the system is detailed, calculated by area, time, and electrical energy consumption.

Surface-time efficiency for conventional solar desalination has been reported to be 2-4 $lm^{-2}day^{-1}$ (Kabeel 2009). AEP of solar desalination in the current study was 0.66 m^3/m^2 and STE which is higher than conventional systems. SDHDH had a high area performance, especially regarding the high salt concentration of inputted water and its rising TDS, due to evaporation processes. The system's electrical energy input was calculated by the sum of all energy used by the fan and the pump-nozzles parts- 196.2 kW. EEE of the SDHDH is 0.74 kW/m^3, which was lower than previous reports of desalination techniques (Al-Karaghouli & Kazmerski 2013; El-Ghonemy 2012; Miller et al. 2015; Shatat and Riffat 2014), and notably less than multi-stage flash desalination (MSF), multi-effect desalination (MED) and RO technologies. The increased performance was supplemented by the use of a grounded dehumidifier.

CONCLUSIONS

Desalination provides the only way to produce freshwater for development in some communities. Energy consumption and environmental impacts of desalination methods drive increases in efficient and environmentally friendly methods. The innovative approaches to SDHDH addressed these concerns. The full-scale test of the new SDHDH conformed to Standards of the Iranian Department of Environment, environmental criteria for treated wastewater, and return flow reuse (Issue No: 535, 2010). The current study showed promising results of low EEE = 0.74 kW/m3, good water production, low

Table 3. Desalination system performance

Index	Performance
Area efficiency performance	0.66 m^3/m^2 of water heater-humidifier
Surface-time efficiency	8 - 30 $lm^{-2}day^{-1}$
Electrical energy efficiency of fresh water production	0.74 kW/m^3

dependency on input water salinity and zero discharge possibility. Future work may include the use of automation techniques and control systems within the system – for example with the use of logical operations such as the Kalman filter, in order to optimize the RH percentage for fan operation and water quality produced. Future studies are recommended to validate the use of SDHD in alternative locations (Furze et al. 2017; Nikolaou et al. 2020; Noshadi et al. 2012; Parvizi and Sepaskhah 2016) and in order to benefit different social and ecosystem services with sustainable water reuse.

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