Desalination 414 (2017) 51–62

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Modeling geothermal energy efficiency from abandoned oil and gas wells to desalinate produced water

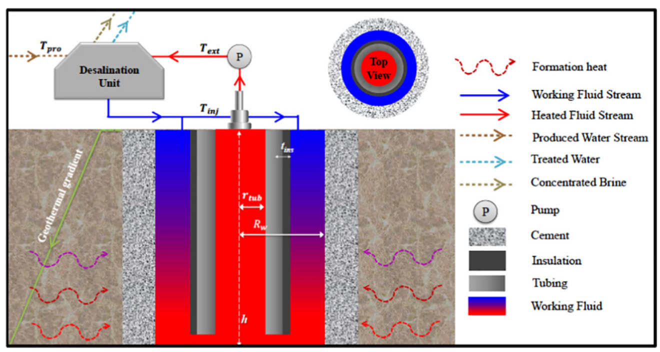
Amin Kiaghadi [a], Rose S. Sobel [a], Hanadi S. Rifai [b,*]

[a] *Civil and Environmental Engineering, University of Houston, Houston, TX 77204-4003, USA*
[b] *Civil and Environmental Engineering, University of Houston, 4726 Calhoun, Houston, TX 77204-4003, USA*

HIGHLIGHTS

- Uses low temperature geothermal resources to desalinate produced water
- Retrofits abandoned oil and gas wells into geothermal wells
- Combines heat transfer model with water treatment thermodynamics
- Identifies key influencing variables to be well depth, geothermal gradient, and total dissolved solids
- Delineates significant parts of drilled formations in Texas that are feasible candidates for technology

GRAPHICAL ABSTRACT



Geothermal energy – desalination system via a retrofitted soon-to-be-shut down oil and gas well can provide sufficient energy to desalinate significant quantities of produced water and generate a sustainable freshwater supply.

ARTICLE INFO

Article history:
Received 5 November 2016
Received in revised form 5 March 2017
Accepted 16 March 2017
Available online xxxx

Keywords:
Heat transfer
Water treatment
Total dissolved solids
Shale
Permian Basin
Eagle Ford Shale

ABSTRACT

This study investigated the use of low temperature geothermal resources to convert salty produced water into a freshwater resource. The research retrofits soon-to-be-shut-down oil and gas wells as geothermal wells, simultaneously overcoming drilling costs and scale formation by using a freshwater closed loop system for thermal energy delivery. Heat transfer modeling was combined with water treatment thermodynamics to develop a predictive tool that can be used to estimate daily deliverable treated water. Results indicated that the developed model was most sensitive to well depth, geothermal gradient, and total dissolved solids in the produced water. Results also indicated that a 4000 m deep well with a geothermal gradient of 0.05 °C/m can successfully treat produced water with as high as 170,000 mg/L total dissolved solids and still deliver almost 600,000 L of clean water per day. An illustrative demonstration indicated that in the Eagle Ford Shale in Texas, >60% of the drilled basin area can deliver at least half a million liters of treated water daily under ideal conditions. This is particularly meaningful as Texas experiences extended periods of drought and the treated produced water would represent a new and resilient source of water.

1. Introduction

Population growth and a changing climate will increase global water demand and costs while decreasing water availability [1,2]. This

* Corresponding author.
E-mail address: rifai@uh.edu (H.S. Rifai).

http://dx.doi.org/10.1016/j.desal.2017.03.024
0011-9164/

motivates an almost universal call to action to ensure the sustainability of water. Surface and groundwater resources are increasingly stressed [3], necessitating the introduction of new freshwater sources. Desalination of seawater [4] and water produced from oil and gas formations [5] represent promising new streams of freshwater.

Produced water is co-generated during oil and gas extraction activities over the lifetime of a production well. Produced water varies greatly in quality and quantity [6] but generally contains large concentrations of total dissolved solids (TDS), necessitating desalination, as well as dissolved and dispersed oil components, other dissolved formation minerals, production chemicals, and dissolved gases [7]. Produced water is typically perceived as a waste stream, and generally disposed of via deep well injection. However, the almost 21 billion barrels (2.5 trillion liters) of produced water extracted annually can be beneficially reused as a useful by-product or a salable commodity [8,9].

The handling of produced water, including the choice of desalination method, and the quality of the treated water depend on: i) the composition and quantity of produced water; ii) the location of oil and gas wells; and iii) the availability of resources [10,11]. Previous studies have established that produced water can be successfully treated using existing desalination technologies, and converted from a waste to a freshwater source. Cakmakci et al. [12] and Melo et al. [13] used Nano-Filtration and Reverse Osmosis (RO) to treat produced water in Turkey and Brazil, respectively, and reported satisfactory results. Guirgis et al. [14] investigated the use of tubular ceramic membranes in removing oil and grease from produced water and reported 95% efficiency. Importantly, the most energy intensive component of produced water to treat is the TDS content, which can range from 30,000 to 300,000 mg/L [6,15,16]. Thermal and membrane separation desalination processes are presently the two most successful commercial water desalination approaches. For produced water with high TDS levels (>70,000 mg/L), thermal separation is preferable because of the low efficiency and the fouling challenges associated with membrane desalination [17].

While the development of advanced desalination technologies has accelerated, the key remaining barrier is the cost of powering desalination units, which can make up as much as 60% of the total treatment cost [17–19]. This large energy demand can be attributed to elevated TDS levels along with the desire for large recovery ratios [20,21]. For thermal based separation methods, the quality of the heat source (higher temperature) is a key factor in desalination efficiency [22]. Accordingly, the challenge in treating produced water is to reduce the energy cost component sufficiently to be competitive with conventional disposal costs and to do so in a manner that is environmentally beneficial and with minimal infrastructure requirements. Thus, integration of renewable energy systems such as solar, wind, wave, waste heat, and geothermal with desalination is a natural and strategic course of action. It can potentially overcome cost and regulatory barriers associated with the disposal of produced water and provide a resilient and drought resistant source of clean water to meet water demands for multiple uses from hydraulic fracturing to agriculture [23,24].

Recently, newer technologies that utilize low-temperature heat have been developed: Membrane Distillation (MD) which combines thermal and membrane distillation processes [25], and Adsorption Desalination (AD) which can provide potable water and cooling energy at the same time [26,27]. Such technologies provide the opportunity to use low temperature heat sources supplied by renewable sources to treat produced water with high TDS levels. Currently, using solar energy to power such desalination units is the most common technology. Meindertsma et al. [28] reported solar energy as the most reliable and available renewable energy source for desalination in Israel. Ghaffour et al. [29] developed a solar-powered AD facility to treat seawater. However, geothermal energy output is more stable compared to other renewable energy sources such as solar and wind energy [29,30] and, as noted by Sablani et al. [30], does not require thermal storage. Geothermal resources above 150 °C are typically used for electric power generation [31,32], however, resources with lower temperatures can be used to power desalination units (such as AD and/or MD), representing a new application of this resource. Geothermal energy can be used to directly heat produced water in thermal based desalination units, or to generate electricity for operating Reverse Osmosis (RO) units [32,33]. Missimer et al. [34] and Ghaffour et al. [29] combined solar energy with geothermal energy and developed a hybrid approach to desalinate seawater. Missimer et al. [35] demonstrated two successful strategies to desalinate seawater using geothermal energy. They used the latent heat from their geothermal electricity generation site to power a coupled Multiple Effect Distillation (MED)-AD system, and diverted some of the generated electricity to power an RO system.

Geothermal heat plants most often operate by injecting water in one well, and extracting heated water in a separate production well. A longer contact time of heating water with the formation will give higher extracted water temperatures at the production well [36]. Though a renewable energy source, the conventional method of drilling geothermal wells and extracting energy still presents challenges that include drilling costs and scale formation. A one-hole geothermal system reduces capital costs, while using existing wells, drilled during oil and gas exploration, is even more economical [37]. In brief, the mechanism for one-hole geothermal heat extraction involves working fluid injection into the annular zone between the well tubing and casing and extraction of heated fluid through the tubing [37–39]. Insulation of the tubing prevents heat loss while the heated fluid is pumped to the surface.

The use of abandoned oil and gas wells for harnessing geothermal energy has garnered attention and support over the past decade. Kujawa et al. [37] assessed the possibility of extracting geothermal energy from an existing oil well and developed a computational model to calculate the geothermal heat flux. They reported a heat flux of 140 KW and working fluid surface temperature of 86.6 °C for a four km well with a flow rate of 2 m^3/h. The authors also investigated the effect of different insulating materials on the extracted fluid temperature. Bu et al. [38] developed a heat transfer model and conducted a parametric study to optimize one-hole geothermal well operational variables. They concluded that the working fluid flow rate and geothermal gradient (the rate of temperature increase with depth) are the key variables affecting the temperature of extracted fluid and net generated power. Davis and Michaelides [40] and Han and Yu [41] found similar results and reported well depths and geothermal gradients as the most important variables. Templeton et al. [42] developed a more complex heat transfer model using the finite element model FlexPDE. The results for generated power (kW) were 60%–80% lower than the ones reported in Kujawa et al. [37], and Bu et al. [38]. A similar study undertaken by Wight and Bennett [39] showed potential electricity generation of 109–630 kW using abandoned oil and gas wells. Cheng et al. [43] developed a one dimensional model (in the vertical or z direction) based on radial heat flow using Ramey's definition (a simple analytical equation for wellbore temperatures based on heat balance), and fluid energy equations. They compared different working fluids and reported R134a and R245fa as the best fluids for geothermal power generation using abandoned oil wells.

It is noted that almost all of the studies supporting the use of abandoned wells for harnessing geothermal energy have focused on electricity generation [40,43,44]. However, energy loss due to low efficiencies in power generation and transmission, accompanied by the fact that most abandoned oil and gas wells are located in remote areas without proper electrical transmission infrastructure, makes this idea less favorable. The application of geothermal energy for desalination, however, is clearly a promising alternative to electricity generation [33]. The repurposing of expiring oil and gas wells (referred to as *decommissioned* wells) for geothermal powered desalination also benefits from other existing infrastructure such as pipelines, pumps, and pretreatment facilities.

This paper investigates the feasibility of using geothermal energy from decommissioned wells to power desalination of produced water and generate clean water. The research proposes a novel integration