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Sustainable renewable energy seawater desalination using combined-cycle solar and geothermal heat sources

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ABSTRACT

Key goals in the improvement of desalination technology are to reduce overall energy consumption, make the process "greener," and reduce the cost of the delivered water. Adsorption desalination (AD) is a promising new technology that has great potential to reduce the need for conventional power, to use solely renewable energy sources, and to reduce the overall cost of water treatment. This technology can desalt seawater or water of even higher salinity using waste heat, solar heat, or geothermal heat. An AD system can operate effectively at temperatures ranging from 55 to 80˚C with perhaps an optimal temperature of 80˚C. The generally low temperature requirement for the feedwater allows the system to operate quite efficiently using an alternative energy source, such as solar power. Solar power, particularly in warm dry regions, can generate a consistent water temperature of about 90˚C. Although this temperature is more than adequate to run the system, solar energy collection only can occur during daylight hours, thereby necessitating the use of heat storage during nighttime or very cloudy days. With increasing capacity, the need for extensive thermal storage may be problematic and could add substantial cost to the development of an AD system. However, in many parts of the world, there are subsurface geothermal energy sources that have not been extensively used. Combining a low to moderate geothermal energy recovery system to an AD system would provide a solution to the thermal storage issue. However, geothermal energy development from particularly Hot Dry Rock is limited by the magnitude of the heat flow required for the process and the thermal conductivity of the rock material forming the heat reservoir. Combining solar and geothermal energy using an alternating 12-h cycle would reduce the probability of depleting the heat source within the geothermal reservoir and provide the most effective use of renewable energy.

Keywords: Adsorption desalination; Renewable energy; Solar energy; Geothermal energy

1. Introduction

1.1. Background

Use of solely a single renewable source of heat to allow thermal desalination of seawater has presented some difficult issues when attempts are made to "scale up" such systems to capacities required to meet water demands of large users. Solar systems providing heated water can do so only during daylight hours, and diminished heat production also occurs on cloudy or rainy days or seasonally. Therefore, heat storage is required to allow continuous operation of

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thermal desalination facilities using solar-produced heat. Thermal storage has been accomplished in shallow groundwater systems in the past (known as aquifer thermal energy storage [ATES]), but has significant limitations when applied to large-scale water-supply production systems. Hot, raw water provided by geothermal sources can operate continuously in locations where there is a very high heat source of either dry steam or wet water discharge (e.g. Iceland or other volcanic regions). However, in the shallow subsurface, dry heat exchange systems, such as those using a closed-loop pipe system containing water or a light oil for heat exchange, the thermal conductivity of the rock or sediments is commonly insufficient to maintain the necessary heat exchange rates required for continuous production of the heat required to operate a large-scale desalination facility.

An alternative method for providing low temperature heat to a thermal desalination system using renewable sources would be to cycle between solar and geothermal sources on a daily basis or a preset time-frame based on the measured properties of the geothermal heat source. Solar heating can provide raw water with a temperature of between 55 and 90˚C and a low-grade geothermal system can provide water or water heated in exchangers from a dry subsurface heat source with a temperature range of 60–120˚C. Raw water or steam temperatures in these ranges can be used in combination with adsorption desalination (AD) to produce high volumes of freshwater from seawater and chilled water simultaneously. The number and depth of potential geothermal heat sources would be much greater using this general low temperature range, thereby reducing the cost for the geothermal source development. The combination of cycled solar and geothermal heat sources with AD and possibly with multiple-effect distillation would also allow scale-up to virtually any capacity water treatment system desired (Fig. 1).

1.2. Adsorption desalination

AD is a promising and relatively low-cost emerging technology that can be used to desalt a wide range of water qualities using a quite low feed temperature [1–3]. The technology can quite successfully operate with a feed temperature range of 55–100˚C with an optimal temperature at 80˚C. This low temperature requirement allows AD to operate using waste heat or solar energy, thereby, producing freshwater from sea/brackish water at a very low energy requirement. Small demonstration pilot facilities are currently operating at the National University of Singapore (4 m^3/day and 5 Rtons cooling capacity) and at the King

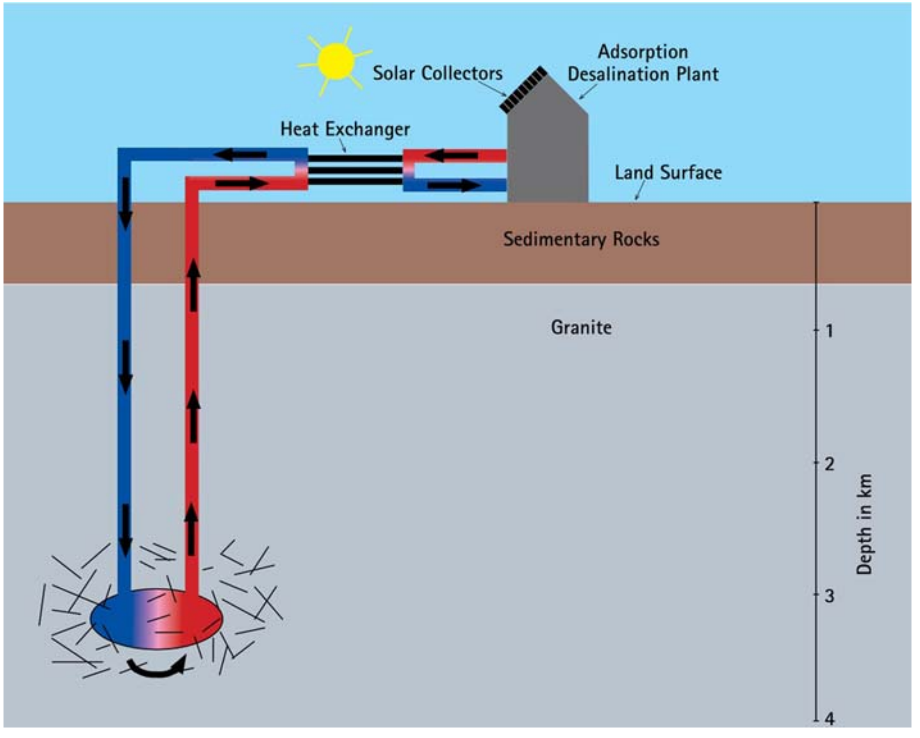

Fig. 1. Coupled solar and geothermal energy powered AD.

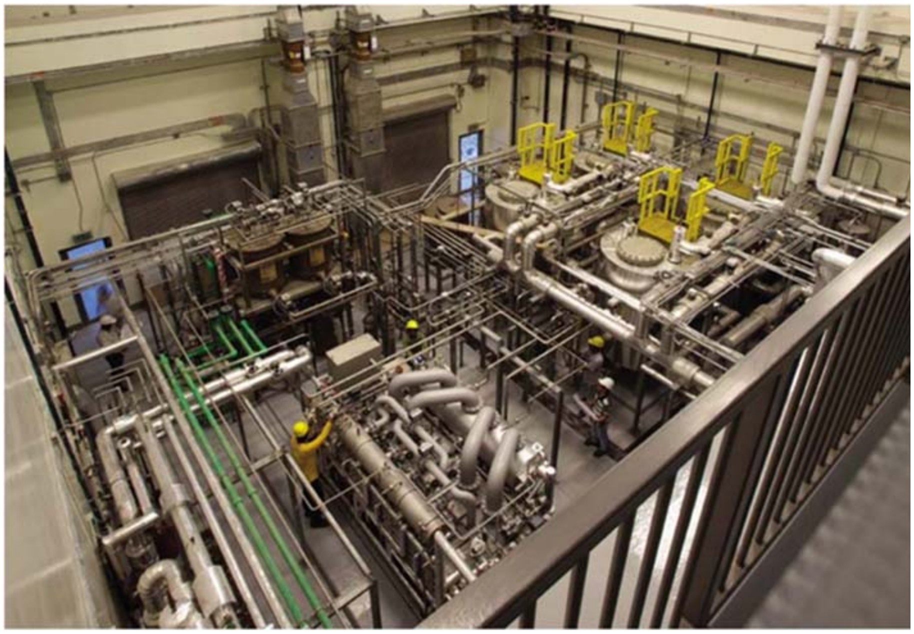

Fig. 2. View of the AD desalination cum cooling pilot plant at KAUST.

Abdullah University of Science and Technology (8 m^3/day and 10 Rtons cooling capacity) (Fig. 2).

AD is an emerging, low-cost, and environment-friendly method for producing potable water and cooling. It uses a silica gel pair that can be regenerated by low temperature heat [22]. The processes of the AD cycle are batch operated with one or more pairs of reactors. In one instance, the adsorbent in one of the reactor beds is in communication with a saline/brackish water filled evaporator for vapor uptake (and thus produces cooling) and concomitantly, the adsorbent in the other bed is regenerated by a low temperature heat source, rejecting the previously captured vapor from the pore surfaces of adsorbent. The vapor condenses on the tube surfaces of a condenser to give high-quality water. The latent heat is rejected at the condenser which is purged into the ambient. Fig. 3 shows a schematic of an AD plant, consisting of an evaporator, condenser, and four beds containing silica gel absorbent. Both the condenser and the designated adsorption beds are cooled by the cooling tower. The heat source, typically ranging from 50 to 80℃, is supplied directly to the designated desorber beds, which regenerate the silica gel by dislodging the water vapor from the pores of the absorbent. The water vapor then migrates to cooler tube surfaces in the condenser, where it condenses to form the distillate. It is noted that the adsorption cycle is batch operated, wherein each half cycle can be varied from 4 to 10 min for water production rates and the change-over of the halfcycle is preceded by a switching time interval of 20–40 s. Details of the AD cycle are described in Ng et al. [3].

1.3. The problem of heat storage

Future development of AD technology using renewable energy to power it will require the system to operate at a larger scale. If solely solar energy would be used as an energy source, during periods of darkness or reduced solar input (rainy days, fog, etc.), a mechanism for heat storage would be required or a large amount of treated water storage could also be used to maintain the desired supply capacity. Although heat storage can be economically accomplished by placing water in underground facilities, for very large capacity systems (>100,000 m^3/day), the required heat storage to operate for periods ranging from 12 h to 3 days would be extensive and have a large cost.

In some cases, the issue of heat storage is not relevant, especially in systems using a combination of solar energy and waste heat from some type of industrial operation (power generation facility, any facility with a boiler). The waste heat may be sufficient to help maintain a heat storage facility or to meet the energy needs of nighttime operations when water demand is lower. For large stand-alone facilities, the use of geothermal energy during nighttime or low solar

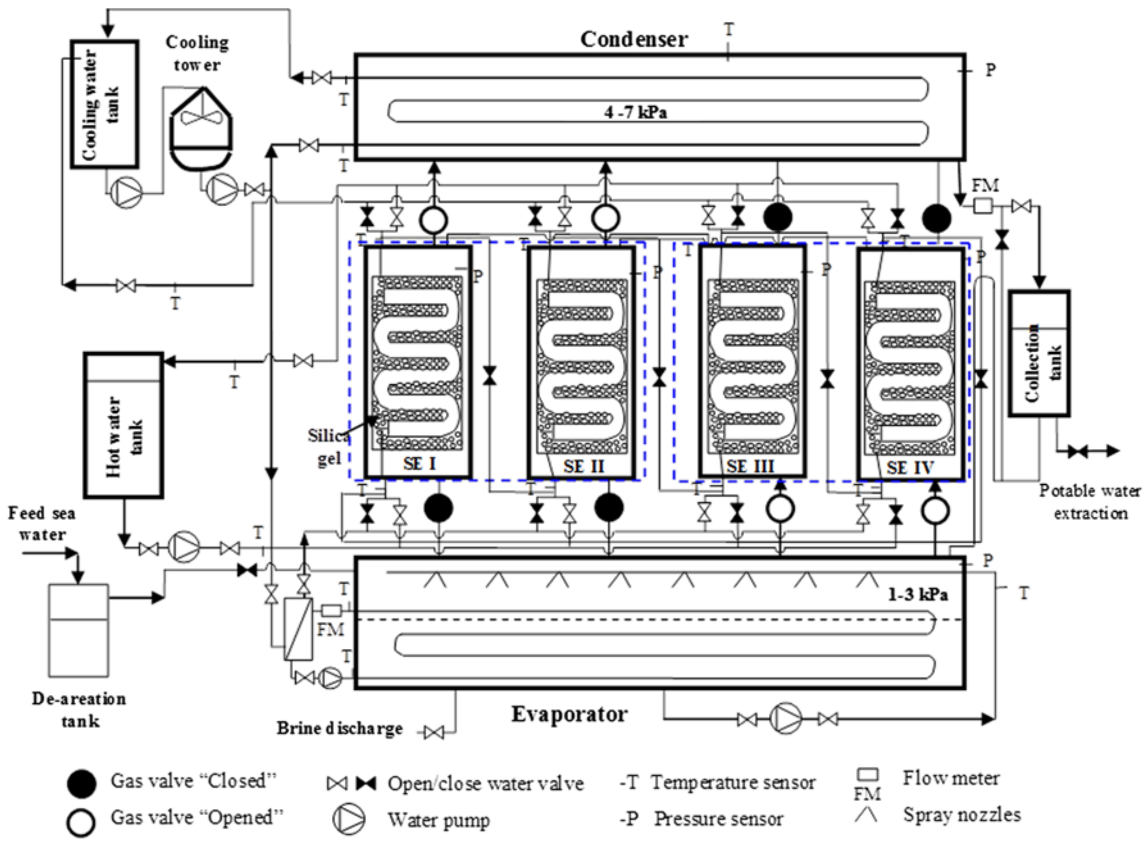

Fig. 3. Schematic diagram of an AD/cooling system showing the integrated components.

energy production periods would increase the reliability of the system and could reduce the overall cost.

1.4. Desalination using geothermal energy

The concept of using geothermal energy in desalination is not new [4–6,23]. Ophir [23] showed that the desalination of a geothermal brine at temperatures ranging from 110 to 130°C could be accomplished using a modified multiple-effect distillation process. The cost to produce water using this process was estimated to be at about USD \$0.50/m^3. Bourouni et al. [4,5] describe the use of a falling-film evaporator and condenser using geothermallyheated saline water to produce small quantities of freshwater. The feedwater temperature used in the analysis was 60–90°C. They concluded that if geothermally-heated water is used as the feedwater source, then the cost of the desalinated water would be less than USD \$1.2/m^3.

Geothermal energy use has some limitations depending upon the nature of the source within the Earth and on how the energy is harvested for use. There are two methods used to harvest geothermal energy wet and dry [7]. Geothermal energy can be extracted from hot fresh, groundwater, or seawater using wells or springs. The systems can be free-flowing, such as the thermal springs of Iceland. A single-pass exchange of the heat from produced water is made and the water then is discharged at surface. Heat exchange can also occur within a closed-loop system wherein water is pumped from an aquifer at one location using a production well and returned to the aquifer at another location via an injection well. These systems are commonly used in heatexchange air-conditioning systems, commonly termed geothermal heat pumps [21]. In a dry exchange system (hot dry rock [HDR]), one or more deep boreholes are drilled into the Earth's crust to a depth where the temperature of the rock is sufficient to allow an effective heat exchange. In some cases, separate injection and recovery wells are drilled to inject cool water and recover hot water with the connection between the injection and recovery wells enhanced by hydraulic fracturing [8]. In other schemes, a piping system is then installed to establish a closed-loop heat exchange system by using circulating water or light oil [9]. The fluid is heated in the well and the heat is extracted using exchangers at land surface and then the fluid is

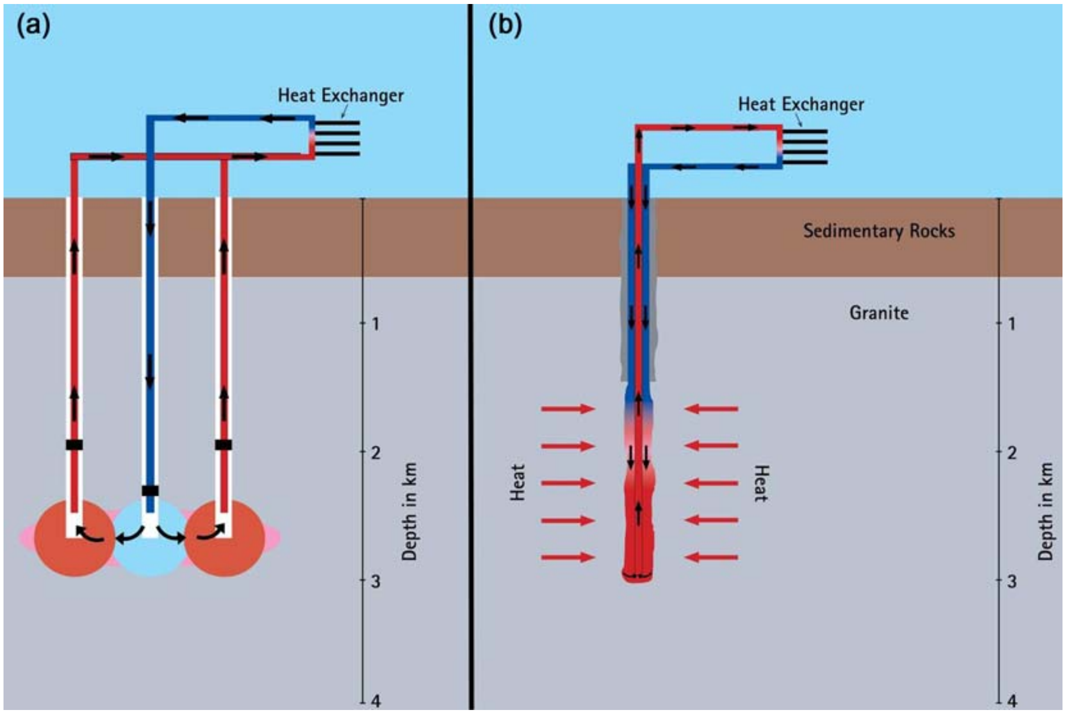

Fig. 4. Geothermal heat collection systems from HDR sources.

pumped back into the well to reheat (Fig. 4). The most efficient exchange is to produce water with a temperature of 100˚C or greater to allow flashing to steam in the exit well or at land surface.

There are limitations on the harvesting of heat from aquifer systems and the Earth based on the heat reservoir characteristics, particularly in dry hot rock exchange systems [10,11]. The thermal conductivity of the hot rock must be sufficient to maintain the required temperature surrounding the borehole to allow the water to remain at the required temperature. If the thermal conductivity of the rock is too low, the heat reservoir in the ground will cool, resulting in a reduction in the temperature of the circulating water, the inability to create flashing to steam, and ultimately failure of the system.

While the use of solely solar or geothermal energy to power an AD system may be insufficient for maintaining operation of a very large system, the combination of both energy sources could provide a sustainable operating system. The nighttime use of geothermal energy would eliminate the necessity of developing thermal storage and the daytime use of solar power would allow the geothermal source to rest and would lessen the probability of depleting the heat reservoir. The daytime resting period for the geothermal system would allow the reheating of the rock surrounding the well and could allow use of rock units that have a relatively low thermal conductivity. Therefore, a truly sustainable low-cost renewable energy system could be used to power AD. Coupling of geothermal and solar energy systems has been investigated in the past for assisting the use of seasonal solar energy collection for operation of heat pump systems in very cold regions [12].

2. Methods

2.1. Literature review of the geothermal gradient along the eastern Red Sea coast

A test of the feasibility of using geothermal energy for partial powering of AD is focused on the Red Sea coastline of Saudi Arabia. The Red Sea is an area characterized by relatively high heat flows [13–15] and it has the long-term need to expand desalination to meet water-supply demands. It is an active rift system where oceanic crust is being generated and pushing bounding continental crust away from the central rift. Although the heat flow and geothermal gradients lessen from the rift to the margins, the geothermal gradients on land near population centers appear to be sufficient to produce the desired heat flux in wells drilled to reasonable depths.

2.2. Harvesting geothermal energy

Since many regions of the world that have a generally higher than average geothermal gradient are located along active continental margins, spreading centers, or hot spots, the heat flow may not produce hot water, but only heating of the rock matrix within a dry or partially saturated state. Therefore, the heat exchange mechanism is assumed to be a dry thermal exchange system (Hot Fractured Rock) using a closed-loop system (Fig. 4). It is known that the energy available in geothermal reservoirs is vast; a cubic kilometer of rock being cooled by 1˚C will yield an energy content equivalent to 70,000 metric tons of coal [16].

A preliminary model was developed using a 2-dimensional empirical heat flow model developed for a fractured rock system using equations contained in Zhao et al. [17], Belayneh et al. [18], Shaik et al. [19] with the assumption that the required temperature of the recirculated water must be constant at a temperature of at least 80˚C at land surface (coolest temperature). The input to the model in terms of the geothermal gradient was taken from the literature search, and the thermal conductivity was assumed to be that of massive granite (initially not fractured) at a depth of between 1,500 and 2,700 m.

2.3. Combined-cycle solar and geothermal energy usage

It was assumed that the latent heat required to operate the AD process would be obtained using combined solar and geothermal energy. The schedule of operation would be to use solar power during daylight hours and geothermal at night. Because there are few days having severely cloudy weather or rainfall, it was assumed that the system would be operated by using alternately 12-h cycles.

3. Research results

3.1. Geothermal gradient and heat flow along the Red Sea coastline of Saudi Arabia

On the basics of the literature, the geothermal gradient along the nearshore areas of the Red Sea of Saudi Arabia ranges from 27 to 46˚C/km [13–15]. Schutz ([15]) also suggested that another well located in the central coastal region has a higher than average geothermal gradient. However, this very high heat flow area is not considered in the analysis. Also, it is well known that extremely high subsurface temperatures occur in the Medina area and are associated with volcanism with the last lava flow occurring about 1,256 AD [20].

The geology with depth along the Red Sea shoreline is mostly Pre-Cambrian age crystalline rock, commonly of a granitic nature. Based on this geology, it is assumed that the geothermal reservoir would be essentially a HDR type using the terminology of Fridleifsson and Freeston [7]. An assessment of the expected temperature with depth under the region can be made by combining field data collected on relativity shallow groundwater temperatures with the known geothermal gradient temperature obtained primarily from oil test wells. Although there are many “hot spots” located along the Red Sea coast, it was assumed that a lower, perhaps, an average geothermal gradient occurs along much of the coastline. Groundwater temperature data collected from wells ranging from 15 to 30 m in depth yielded an average temperature of 33˚C. The estimated range in geothermal gradient is 27–46˚C per kilometer of depth. Based on these data, the estimated bottom-hole average temperature variation with depth beneath the Red Sea coastal area is shown in Fig. 5.

3.2. Energy balance

For investigation of the use of geothermal energy in a combined cycle with AD, a 10,000 m^3/day capacity AD plant was assumed. This capacity plant would use about 100 MW/day of energy equivalent per day. Because of the generally low efficiency of heat exchange at surface for circulating 80˚C water (20˚C heat exchange would cause the flow volume to be very large), it would be much more efficient to allow geothermal heating of the circulated water to a temperature in the ground of over 100˚C and then allow it to flash to steam in the return flow pipe or at land surface, thereby causing some suction to help aid the circulation process and to increase power harvesting efficiency (Fig. 6).

3.3. HDR geothermal energy extraction

There are a variety of different methods that can be used to harvest geothermal energy from HDR sources. The design and scale of a method depends on the local geothermal gradient and the thermal characteristics of the heat reservoir. Key factors are the initial ambient temperature of the rock at the injection and recovery depth and thermal conductivity of the rock which controls the ability of the reservoir rock to transmit heat at a sufficient rate to maintain the in-ground heating of the cooler circulating fluid.

The Saudi Arabian Red Sea shoreline, where the geothermal systems would be developed, is underlain

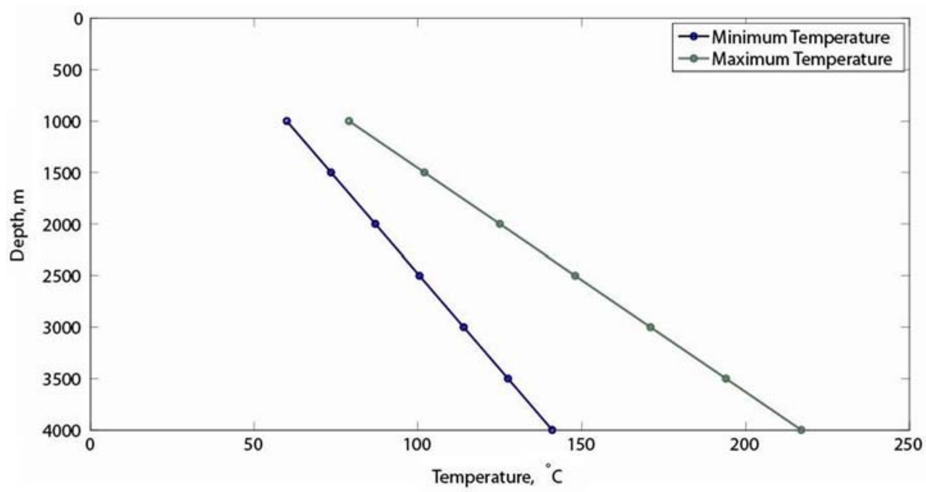

Fig. 5. Geothermal gradient estimates beneath the eastern Red Sea coastal region.

at depth by Pre-Cambrian rocks commonly granitic in nature. Gneiss and schistose lithologies also occur in this area. It is assumed that geothermal wells would be drilled to depths in excess of 1,500 m into the granitic material. It is likely that this rock will be hot, dry, and relativity dense with a very low effective porosity. Based on experimental work done on dense granites (2.61–2.68) with effective porosities below 1%, measured thermal conductivities average about 2.75 W/mK [24]. Gneiss and schist lithologies would tend to yield slightly higher thermal conductivities.

The energy balance of the AD plant requires very high volumes of water to be pumped through the geothermal system if a continuous flow of water with an 80˚C temperature would be used for heat exchange at land surface. Therefore, a more efficient system is required using a higher temperature with steam flashing in the subsurface or at land surface.

A two-dimensional model was developed to obtain an assessment of the initial temperature required to operate a two-well system to produce the necessary geothermal energy source to produce the necessary stream to run the desalination facility. It was assumed that the wells would be located about 100 m apart and that there would be a zone of 10 m in thickness wherein the rock would be hydraulically fractured (note that the fractured interval could be much greater in thickness, but the model was built conservatively). A pattern of vertical and horizontal fractures was assumed to be homogeneous with fracture spacings of about 5 cm and fracture apertures of 3 mm to produce an engineered effective porosity of about 0.03. The required equilibrium temperature is estimated to be 106˚C, which occurs between 1,500 and 2,700 m below surface in the central Red Sea coastal area (Fig. 5).

A two-dimensional heat and fluid flow model was constructed based on the governing equation for slightly compressible fluids and transient flow and energy balance equations for rock and fluid [17–19]. The governing equations are discretized with the finite volume method and solved in conjunction with Dirichlet and Neumann boundary conditions. These equations are discretized by using a nonuniform grid system with denser grid cells in the region adjacent to the artificial fractured rock (granite) and employing the control volume approach and the backward difference scheme in time and the central implicit difference scheme in the spatial direction. The equations are solved using a standard tri-diagonal matrix algorithm with a successive line under-relaxation scheme. The key question to be answered by the modeling effort concerned the ability of the heat reservoir and geothermal gradient to maintain sufficient heat flow to allow the return water temperature to be consistently above 100˚C to cause flashing to stream within the shallow part of the recovery well. It was assumed that the injected water had a temperature of 50˚C and the flow rate was 0.6 m^3/min. Based on the model inputs, breakthrough of the injected water at a temperature below 100˚C would occur at times greater than 95 h (Fig. 6). Since the system would be operated on a 12-h cycle, the temperature should be maintained at above 100˚C. The breakthrough curve estimated from the model is shown in Fig. 7. This simplistic approach to the geothermal modeling shows that a HDR system could be developed, but the spacing between the injection and recovery wells and the depth of operation will be dependent on local site conditions and would require sophisticated three-dimensional modeling of the heat flow to develop a final design.

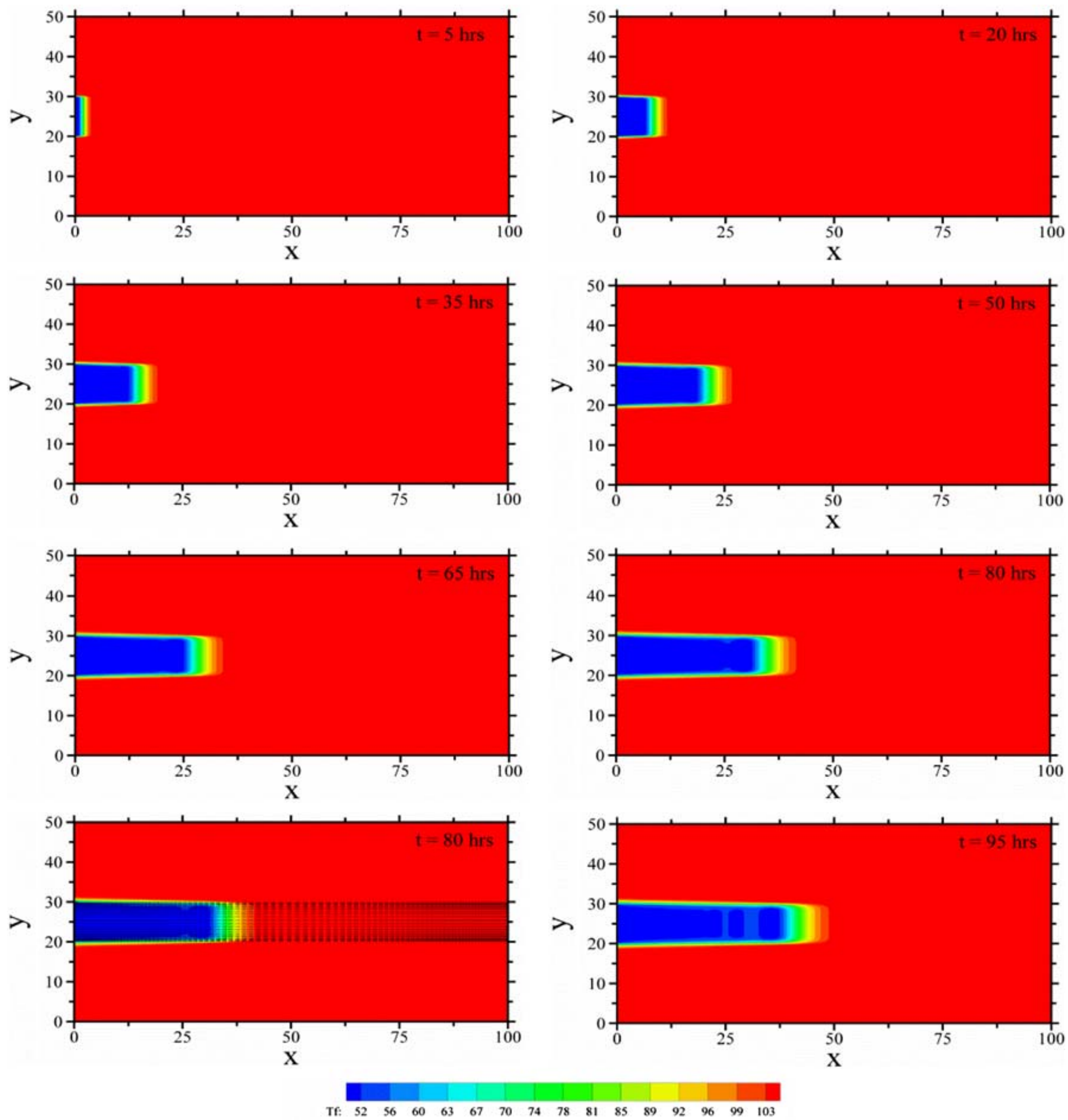

Fig. 6. Model showing the migration of cool water from the injection well on the left side of the field to the recovery well on the right side of the field. The scale is in ℃. Note that the cool water does not break through to the recovery well for over 95 h. The second graphic showing flow at $t = 80$ h includes the flow vectors.

3.4. Combined-cycle solar/geothermal powered AD

Properlydesigned and maintained solar collectors systems used to power AD located along the Red Sea coastline can generate daytime heat flows as high as 90˚ C and maintain an 80℃ heat stream. The production time of solar heat usage to power AD corresponds to the maximum water production requirements until the early evening timeframe. The use of geothermal heating would begin in the early nighttime hours as the solar heat source wanes and the heated water production lessens. Geothermal heating can then become the primary heat source for the nighttime for a period of approximately 12 h. This period generally corresponds to low water production requirements.

4. Discussion

On the basics of the AD technology energy requirements (low heat requirement compared to other commercial thermal desalination system require-

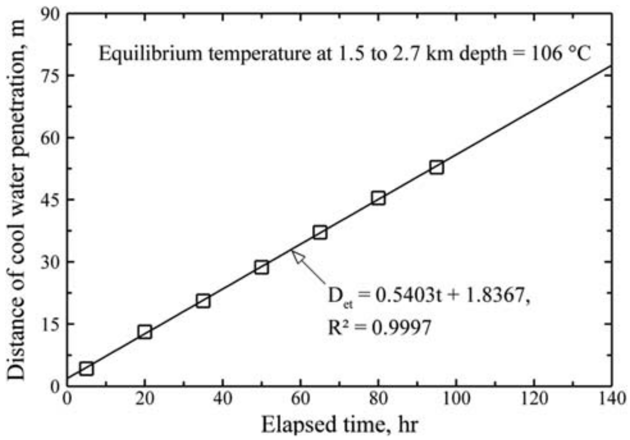

Fig. 7. Distance of penetration of cool water (m) vs. time (hours) from the injection well toward the recovery well.

ments), the combined use of solar and geothermal energy sources would allow the up-scaling of AD plants to competitive capacities with more conventional thermal and membrane desalination systems. Geothermal energy could be used as the sole source of heat, in combination with solar energy as described, or in combination with thermal storage of solar-heated water to prevent heat loss during storage time. The depth, capacity, and yield of geothermal wells required for AD system operation is dependent on the desired water treatment plant capacity, the type of system desired (sole heat source, combined with solar, or heat storage maintenance), and the thermal characteristics of the heat reservoir used.

The focus of this research effort has been on areas of relatively high heat flow, but moderate within the geological framework. There are some hot-spot regions located in western Saudi Arabia having very high heat flows that could sustain very large AD facilities and perhaps electrical generation of considerable capacity. The Medina area is an example of where very high temperature rocks occur that could be tapped for geothermal energy development. The southern end of the Red Sea also contains some high flow areas of significance.

Dry hot rock geothermal systems that would yield generally low temperature discharges of 70–80˚C are not likely to be able to sustain cycled heating of large-scale AD plants. The efficiency of conversion to usable energy at land surface would cause the circulating flow rate to be very high which is not practicably possible using a two-well fractured rock connected system. The use of a hotter collection system with flashing to steam in the exit well is much more efficient based on the use of steam to generate power. Therefore, the successful development of geothermal energy to partly power AD may be limited to higher heat flow areas or hot spots where wells could be drilled and fractured at reasonable costs.

5. Conclusions

AD is a relatively new and promising desalination technology that also can produce chilled water as a byproduct in the process. It can operate effectively using relatively low temperature water at a range of 55–80℃ with 80℃ being optimal. The cost to desalt seawater or even high salinity water is substantially lower compared to more convention desalination process, such as thermal or membrane, because AD can utilize, waste heat, solar, geothermal, or combinations of these heat sources. Combining solar power with geothermal energy development could produce a sustainable energy scheme to provide a very high degree of reliability for the development of large-scale AD systems. The daily cycling between solar and geothermal eliminates the need for heat storage. Use of totally renewable energy sources is very energy efficient and would significantly reduce the carbon footprint of desalination in the future.

Additional research will be required to assess the energy balance of these cycled systems used geothermal energy. The regions where the geothermal gradient is sufficient to maintain the system must be further investigated as well as the costs to construct and operate geothermal collection systems in a variety of geologic and subsurface geothermal settings.

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