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Multi-effect desalination plant combined with thermal compressor driven by steam generated by solar energy

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HIGHLIGHTS

- Simulation model for MED- TVC desalination plant driven by solar energy is built.
- The solar field along N- S provides 68% of the energy required to produce 40 L/m^2.
- MED- TVC plants produce 35-45 L/m^2/day when solar radiation above 4.8 kWh/m^2/day.

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ABSTRACT

This paper investigates the annual performance of multi-effect desalination plant combined with a thermo-compressor MED–TC driven by a solar steam generation plant. The desalination model is coupled with solar steam generation plant model to supply the necessary thermal energy to drive the desalination plant. The developed model determines the fresh water production rate and the specific energy consumption. The desalination plant is located in Aqaba, Jordan which is located in a coastal region that receives high levels of solar radiation. Simulations of the system (desalination plant + steam generation plant) are carried out under different operating and geometrical conditions to investigate the plant performance. The desalination plant is sized to produce 50,000 m^3/day of fresh water continuously to meet the expected commercial and tourism growth. Results show that with collector area equal to 1,080,000 m^2 and storage size of 75 l per square meter of solar collector, the solar energy is capable of covering up to 68% of the total thermal energy required using storage capacity by the desalination plant with annual solar field efficiency of about 55%. The solar field oriented along a north–south axis presents the best performance and the solar fraction does not increase significantly as the pressure of the saturated steam generated varies.

1. Introduction

Desalination is a process of removing dissolved minerals from salty water to produce fresh water. The most important desalination processes driven by thermal energy are multistage flash (MSF) and multi-effect distillation (MED). The electrical driven desalination processes are reverse osmosis (RO) and electrodialysis (ED). The global worldwide installed desalination capacity using RO is around 56% while 37% is using the thermal desalination.

Seawater (salt water) of the oceans represents 97% of the total water in the earth but only about 36 million km^3 of the earth's water is fresh (3%). Fresh water is found mostly in the form of ice (77%), mainly in the poles, in the ground water (22%), and only 1% is in lakes and river. Agriculture uses 70% of the total of fresh water used for human activities, 20% is used by the industry and only 10% is used for household needs. Desalination systems are a dependable strategy to provide fresh water in coastal areas. Demand for freshwater has risen due to the combination of several factors: growth of population, developing of economic, accelerated urbanization, and improvements in the living standard. Northern Africa and Western Asia countries (MENA) have the most serious water scarcity problem.

Research on desalination has regained large interest in the past few decades. This is due to the fact that the conventional desalination technology relays on conventional forms of energy. The energy is becoming a serious issue due to the fact that the world witnesses significant increase in fresh water demand and the fact that the fossil fuel resources in the world are finite. Therefore, it is essential to find alternative energy sources to completely or partially replace our dependence on fossil fuel. One of the promising methods is using solar energy. Desalination technologies driven by solar energy systems are a good choice in costal locations when high levels of solar radiation are available. Many regions that suffer shortage of water have high solar radiation such as the west coast of United States and Mexico, north of Chile and Peru, north and south of

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Africa, Arab countries, and some areas of India and Australia. Solar energy has strong potential to drive seawater desalination processes in these regions.

Jordan is considered among the poorest countries of water resources. Due to unpredictable rainfall and expanding population, agriculture and industrial development, water sector in Jordan is facing real challenge. The yearly average rainfall in the northern and western parts of Jordan (less than 10% of surface land) reaches around 500 mm in good years, while most parts of Jordan (90% of surface land) receive less than 150 mm. With current growth, the gap between water supply and demand will widen significantly. It is expected that by the year 2025, the available water per person will decrease to only 90 m^3. The Ministry of Water and Irrigation adopted water strategy in 1997 [1] with several different water policies in the area of: ground-water management [2], irrigation water [3], water utilities [4] and wastewater management [5]. The major water development plans established by the government are; a) the exploitation of fossil non-renewable groundwater in the Disi aquifer, b) the construction of the Al Wahda dam on the Yarmouk River in the north of the country, c) increase in the use of treated waste water, and d) desalination of seawater and brackish water.

Jordan's only access to the sea is at Aqaba, which is located in the southern part. Aqaba is very far from the main centers of population (300 km). The fact that these centers of population are at high elevations (around 1000 m above sea level) further worsen the situation. This would therefore require high pumping costs. Jordan does have reserves of brackish water and a small number of brackish water desalination plants have been built. Up to now, due to high cost, desalination of seawater and brackish water remains the only solution to solve the water shortage problems in the long run. Jordan depends almost entirely on the imported oil for meeting its energy demand. Jordan's national energy strategy is to increase the contribution of renewable energy. Jordan has adopted new regulations and law to attract investment in new wind and solar technologies. There are serious plans for a significant expansion of tourism and commercial activities in Aqaba which may require investment in seawater desalination in the near future [6]. Utilizing the local available renewable energy resources (solar energy) for desalination is likely to be a cost-effective solution particularly because the costs of renewable technologies continue to decline and the prices of fossil fuels continue to increase.

1.1. Desalination processes using solar energy

Desalination technologies using solar energy can be summarized as follows;

1) solar stills and humidification–dehumidification desalination using directly the solar energy,
2) generate electricity by using photovoltaic cells or other methods, to drive membrane processes,
3) thermal desalination (MED and MSF).

Ali et al. provided a comprehensive review of all the indirect solar desalination technologies along with plant specific technical details [7]. Recently, Sharon and Reddy presented a review about different desalination units integrated with renewable energy with special emphasis given to solar energy [8]. It helps researchers to choose appropriate desalination technology for further development. Solar stills use the greenhouse effect to evaporate seawater. This technology has low performance in comparison with other desalination technologies; only 45% of energy received is used to desalinate seawater. The energy consumption rate is about 1300 kWh/m^3 of fresh water. The water production of these solar stills is about 4–6 kg/m^2-day [9]. However, the initial cost of the still may be lower than alternative technologies which make them a good choice for remote area. Utilizing solar energy to derive HDH technology, the water production is found to be between 4 and 12 kg/m^2-day of solar collector.

Multi-effect desalination plant (MED) is formed by a sequence of evaporators. MSF is a desalination technology that evaporates seawater due to successive reductions in pressure of heated seawater. The most suitable technologies to desalinate on a large scale are RO and MED. MED is the most efficient distillation process and RO has the lower energy consumption. Also, MED can work with low grade energy source (70–80 °C). HDH is the most efficient solar desalination technology and it could be the best option when the applications are located in an isolated place where there is not a continuous supply of electrical energy [10]. However, HDH has worse performance than RO and MED. Finally, in both cases, small and large scales, the most suitable technologies using solar energy is MED and RO.

Solar MED technology has received significant attention by many researchers and its market share is growing [11]. E1-Nashar compared the economics of using solar energy to operate small seawater MED systems in remote areas against the conventional method of using fossil fuels [12]. He found out that the cost of producing water from the solar system is less than that from a conventional system which uses diesel oil when price is higher than 10 $/GJ. Gholinejad et al. concluded that using the tracking systems are very effective on the performance of a solar MED plant [13]. They concluded that for countries in high latitudes which receive less solar radiation, polar axis and E–W tracking systems are preferred; whereas, for countries in low latitudes N–S tracking systems are preferred due to their intense solar radiation.

Utilizing double effect Li–Br absorption heat pump powered by solar collector field and coupled to MED is more attractive and can lead to nearly 50% reduction of the thermal energy consumption and solar field requirement compared to conventional MED systems [14–16]. In this technology, the MED unit uses the heat rejected by the condenser and absorber of the heat pump. The generated water vapor in the MED unit is condensed using the evaporator of the absorption heat pump, thus the circulation of external cooling water is eliminated. Alarcón-Padilla et al. were the first people who experimentally validated the design proposal for a MED solar plant connected to a double-effect absorption heat pump [16]. It was found that the overall performance ratio, experimentally measured at the Plataforma Solar de Almería test facilities, was 20, which results in a 50% of reduction of the required solar field area compared to a solar MED system.

MED–TVC is characterized by high performance ratio, easier operation, low maintenance requirements and simple geometry [17]. One of the latest developments in MED–TVC technology is low compression ratio which reduces the amount of motive steam which allows to increase the unit capacity of the plant [17]. Gain output ratio of the MED–TVC unit depends mainly on the evaporator temperature of the last effect, temperature difference across the effects, and it is very much less affected by the temperature of the feed stream [18]. The evaporator and the steam ejector are the major roots of exergy destruction in the TVC systems [19,20]. Jianget al. studied the feasibility of low temperature MED unit integrated with flash chamber and solar collector [21]. It was found that the flash chamber pressure and feed water temperature have more effect on the amount of producing water compared to MED stage pressure. Decreasing the flash evaporation pressure leads to a higher desalination rate. Furthermore, it was found that replacing the condenser of a solar operated power plant for low temperature MED unit is more efficient than feed the MED unit by the exhaust steam of a solar operated power plant compressed by thermal vapor compressing unit [22]. Different configurations like multi-effect distillation-backward feed (MED-BF), multi-effect distillation-parallel feed (MED-PF), multi-effect distillation-forward feed with heater (MED-FFH) and multi-effect distillation-forward feed (MED-FF) are available and among these MED-FFH and MED-PF are found to be more efficient [23].

Steam generation from parabolic trough has received significant attention. Thomas [24], Kalogirous et al. [25] and Zarza et al. [26] carried out analyses on the parabolic trough collector systems for steam generation. Their studies showed that only the 48.6% of the solar radiation