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Energy efficient multi-effect distillation powered by a solar linear Fresnel collector

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ABSTRACT

Solar-driven desalination is a potential solution to the problem of freshwater scarcity in many parts of the world. However, this technology requires considerable efforts to overcome a number of technical challenges such as high-energy consumption, intermittency of solar radiation, and high-water consumption. This paper proposes an optimized multi-effect distillation (MED) process driven by steam at 70 °C and 0.3 bar, which is provided by a linear Fresnel collector. The aim of the proposed integrated system is to reduce the equivalent mechanical energy of the MED process, and utilize the most cost-effective storage system. Moreover, we incorporated an air-cooled condenser instead of a water-cooled condenser, to reduce the water cooling facilities. A computer model was developed using the Engineering Equation Solver tool, to solve the mass and energy balance equations of the integrated system (under different operating conditions). Under the operating conditions of Qatar, the simulation results showed that 1 m^2 of solar linear Fresnel collector produces 8.6 m^3 of freshwater per year. The equivalent mechanical energy of the optimized MED desalination plant is 8 kWh/m^3, which is 59% lower than that of existing commercial MED facilities with thermal vapor compression (19 kWh/m^3). This significant reduction in equivalent energy consumption would reduce the required solar field size by 25%. This study also showed that using a water storage system (instead of thermal energy storage) results in a lower total system capital cost. Furthermore, by integrating an air-cooled condenser, the overall plant water consumption reduced by 2 m^3 of sea water per m^3 of feed water. The performance of the air-cooled condenser can vary by as much as 300% due to fluctuations in dry-bulb temperature and relative humidity.

1. Introduction

Water scarcity in many regions around the world means that reliance on desalination technologies is imminent. In the Gulf Cooperation Council (GCC) countries, 80% of drinking water comes from desalination plants [1,2]. In fact, 38% of global desalination capacity is in the GCC region [3]. Thermal desalination, including multi-stage flash (MSF), multi-effect distillation (MED), and MED with thermal vapor compression (MED-TVC) technologies dominate the desalination industry in the GCC countries. Furthermore, the reverse osmosis (RO) membrane technology market is also growing, owing to its high energy efficiency [4]. The harsh gulf seawater conditions (high temperature, high salinity, high impurity, and sometimes red tide) make the use of thermal desalination technology a reliable solution [5]. Thermal desalination processes (such as MSF and MED) are also preferred in the GCC region due to their robustness [6]. Among the thermal desalination technologies, MED operates at a lower specific power consumption (SPC) than the MSF process. This is a result of using falling film evaporation around the tubes (three times the distillate) instead of pumping a bulk flow of seawater feed (ten times the product) [7]. A techno-economic analysis showed that plain MED desalination technology delivers a lower unit water cost compared with existing MSF and MED-TVC technologies [8]. This is because plain MED uses a low steam pressure of 0.3 bar at 70 °C, which is lower than MSF and MED-TVC (3 bar at 180 °C).

The demand for freshwater is rising because of population increase, and this will further magnify the problem of freshwater scarcity [9]. This will increase pressure on current desalination plants and require more plants to be built, which will in turn escalate energy and fuel demands. These factors will also lead to a greater impact on the environment. Solar-driven desalination is a potential solution to this problem.

The coupling of solar power technologies with desalination is an interesting area of research, but requires further development and improvement [10]. Among the currently developed solar desalination technologies, the solar-driven MED process is possibly the most suitable

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Nomenclature

η_{fan}	fan electric efficiency
$\eta_{optical}$	optical efficiency
ΔP	condenser pressure change
A	aperture area (m^2)
$A_{specific}$	specific area (m^2/kg/s)
CSP	concentrated solar power
DHI	diffuse horizontal irradiance (W/m^2)
DNI	direct normal irradiance (W/m^2)
EES	engineering Equation Solver
GHI	global horizontal irradiance (W/m^2)
GOR	gain output ratio
HTF	heat transfer fluid
LFC	linear Fresnel collector
$L_{receiver}$	receiver length (m)
MED	multi-effect distillation
MR	mixing ratio
MSF	multi-stage flash
PTC	parabolic trough collector
Q_{field}	solar field power (kW)
Q_{loss}	thermal losses (kW)
RO	reverse osmosis
SAM	system Adviser Model
SPC	specific power consumption (kWh/m^3)
T_1	HTF inflow temperature (C)
T_2	HTF outflow temperature (C)
TES	thermal energy storage
$T_{receiver}$	receiver temperature (C)
TVC	thermal vapor compressor
V_{air}	air volumetric flow rate
W_{fan}	fan power

for large-scale implementation. This is because of its superior thermodynamic and heat transfer performance (compared to the MSF process), and lower levelized cost of water [11,12]. The MED process generally has a lower energy consumption rate than the MSF process.

Generally, research into solar-driven MED and solar desalination is still in its early phases, with many critical problems remaining unsolved [13].

The Plataforma Solar de Almeria plant (Spain) is one of the earliest solar-driven thermal desalination pilot plants. This plant used compound parabolic collectors, a 14-effect vertical stack MED configuration, with an absorption heat pump. Results showed that the heat consumption of the plant could be optimized by using a heat pump [14]. The Abu Dhabi solar desalination plant is also among the earliest of the pilot plants [15]. The plant used flat plate collectors, a 14-effect MED system, and a thermal storage system that facilitated 24 h operation. The distillate production was 120 m^3/day, and the water cost was 7–10 $ per m^3.

Sharaf et al. [16] carried out a thermo-economic analysis for two configurations of a solar-driven MED plant (both with and without a TVC), and considered the cogeneration of desalted water and electric power in both cases. The study found that solely producing desalted water is better than cogeneration in terms of water cost and solar field area. Hamed et al. [17] conducted an experimental study to characterize the thermal and optical performance of a new linear Fresnel collector (LFC) that can supply heat to a MED-TVC plant. The study used oil as the heat transfer fluid (HTF), with an inlet temperature of 100 °C and an outlet temperature of 300 °C. The LFC had a peak optical efficiency of 67%, which is slightly higher than other similar commercial systems. The coupling of the solar collector to the MED-TVC plant was simulated under a scenario where the LFC provided 20% of the thermal requirements of the MED-TVC unit. Based on this, it was found that to produce a thermal energy of 13.6 MW_{th} to power the MED-TVC unit, a solar field area of 55,737 m^2 was required. The authors suggested setting the outlet temperature of the HTF to a low value, to increase the thermal efficiency of the solar field. Askari and Ameri [13] conducted a simulation study in which the performance of an LFC solar field coupled to an MED plant was modeled, using MATLAB and the System Advisor Model (SAM) software. This hybridized system incorporated a natural gas boiler and a thermal energy storage (TES) tank. The authors performed a detailed techno-economic analysis of the plant under different scenarios, in which the system scale was modified. Results showed that the minimum water cost was obtained at the lowest solar share (27.54%). In addition, if the TES system cost is more than $100/kWh, then using a water storage system is more economical. Furthermore, the authors highlighted the fact that solar thermal energy is still very expensive as a replacement for conventional desalination energy.

Iaquaniello et al. [18] carried out a technical and economic analysis on an MED-RO plant that produces electricity and desalted water, and is powered by solar heat from a parabolic trough collector (PTC). The simulations in their study were based on a robust computer model. Their hybrid configuration resulted in a water cost of less than $1.23/$m^3$. It was found that increasing the plant life from 20 to 30 years reduces the water cost by 8%. Mabrouk et al. [19] presented the design and simulation of an MED system powered by a PTC. The system proposed the use of brine recirculation and an air-cooled condenser. The study found that using an air-cooled condenser reduces the capital cost of groundwater.

A further study experimentally investigated a high-performance MSF desalination unit, integrated with a nano filtration membrane, and driven by a concentrated parabolic collector [20]. The nano filtration pilot was built to enable the MSF desalination unit to operate at high top brine temperature. The capacity of the desalination pilot plant is 1.0 m^3/day of water. This newly developed NF-MSF configuration is tested at a top brine temperature of 100 °C, and the gain output ratio (GOR) is calculated as 15, which is almost twice that of a conventional MSF under the same operating conditions. This newly developed high-performance NF-MSF process (with its lower input thermal energy) makes integration with relatively expensive solar power collectors a viable option.

A critical review by the authors discussed the literature on a solar-driven MED in detail, and highlighted key research gaps that should be addressed [21].

A number of conclusions were derived from the literature. Most studies in the literature considered using the PTC [16,22–26]. The PTC is a commercially mature technology, and has been widely used in power generation for many years. However, it is more expensive (in terms of specific capital cost) than similar concentrating solar power (CSP) collectors, such as the LFC. The specific capital cost for a PTC is 378–430 $/$m^2$, compared to 246–307 $/$m^2$ for an LFC [27]. The LFC could be a better choice for MED as it has a lower concentration factor, which is suitable for an MED process that requires steam at 70 °C and 0.3 bar. The LFC is also more compact and has a smaller mass per m^2, resulting in better land utilization. Some studies on solar-driven MEDs used an LFC in their system [13,17]. The use of LFCs in MED systems needs to be explored in more detail, to fully understand the potential of this solar collector.

A critical review [28] explored thermal and non-thermal storage systems (used with desalination systems), and showed the features of both. The review asserted that the addition of thermal storage to a desalination system can lead to both lower water costs, and better management of the intermittent solar resource. A number of solar-driven desalination studies used a TES in the system design [13,15,17,22,23,25,29,30]. Some studies did not use the TES