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A novel design for a solar powered multistage flash desalination

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ABSTRACT

This work presents a new design for a solar powered multistage flash (MSF) desalination plant, which reduces solar collector area compare to other designs and is capable of operating continuously. The proposed design uses an array of concentrating solar collectors and a pair of thermal storage tanks, each with enough capacity to supply the MSF with brine for one day. Unlike many other solar desalination approaches, the brine is directly circulated through the array, eliminating the need for a heat exchanger and medium fluid. Each day, one of the tanks receives pre-heated brine from the MSF, which is further heated to a top brine temperature (TBT) by circulation through the solar array (charging mode). At the end of each day, the fully charged tank switches to discharging mode, and feeds the MSF with brine while the other tank enters charging mode. The system is designed for the tanks to alternate roles at approximately sunset each day. Seasonal changes in available solar energy are handled by modifying the mass flows, such that the same TBT is always achieved. This novel dual-tank approach serves to isolate the MSF from daily variations in solar energy, and it allows the brine to gradually reach TBT each day, minimizing losses. A dynamic model of the heat and mass transfers is used to simulate this design, resulting in an average daily production of 53 kg of distillate per square meter of solar collector area. The resulting system uses a solar collection area of 42,552 square meters to provide the average daily production about 2230 cubic meters of fresh water with total water price $2.72 per cubic meters.

1. Introduction

Globally, the demand for freshwater is rapidly escalating, presenting crucial challenges in the coming decades (Pugsley et al., 2016). Industrial and domestic water consumption is increasing at twice the rate of the population growth, and two-thirds of the world's fresh water is currently utilized by agriculture (Stuber, 2016; Al-Nory and El-Beltagy, 2014). By the year 2025, it is projected that about 60% of the world population will experience water shortages (Qadir et al., 2007). To meet this demand for freshwater, desalination plants are increasingly utilized. In 2014, about 19,000 desalination plants with a total capacity of almost 60 million cubic meters per day had been installed worldwide (Gorjian and Ghobadian, 2015). A majority of global water desalination capacity (65%) is in the Gulf region of the Middle East, which uses its oil resources to fuel primarily multi-stage flash (MSF) desalination (Shatat et al., 2013; Liu et al., 2014).

MSF allows for large capacity and reliability, but it is much more energy-intensive than other desalination technologies (Junjie et al., 2007). Conventional MSF systems burn fossil fuels to heat brine to a top brine temperature (TBT) between 90 °C and 120 °C (Saidur et al., 2011). This hot brine is then passed into a series of vacuum chambers where it evaporates, simultaneously creating distillate and pre-heating incoming brine, usually seawater. Solar-powered MSF desalination is currently being studied, with various small to medium scale plants at several locations around the world (Gambier and Badreddin, 2005; Abdel-Rehim and Lasheen, 2005). Schemes for solar MSF vary widely in terms of the amount of distillate produced, level of thermal storage, and solar collection technology. Some methods use heat exchangers and medium fluids to transfer heat to the brine (Manjarrez and Galvan, 1979; Ibarra-Herrera, 1979; Moustafa et al., 1985; Farwati, 1997; García-Rodríguez et al., 1999; Ayala et al., 2011), while others directly circulate the brine through solar arrays (Rajvanshi, 1980; Signh and Sharma, 1989; Reddy et al., 2012; Garcia-Rodriguez and Gómez-Camacho, 1999). Some systems produce distilled water during daylight hours only, while others employ control systems and thermal storage to achieve continuous production of distilled water. Rates of distillate production, on a

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Nomenclature

Variable	Description [units]
A_{ro}	receiver area [m^2]
D_T	tank diameter [m]
$D_i(k)$	Distillate produced at each stage [kg/h]
F_R	heat removal factor
H_T	tank height [m]
$I_p(t,k)$	available solar power [W/m^2]
$M_{BD}(k)$	blow down mass [kg/h]
$M_{DIST}(k)$	distillate feedwater production rate [kg/day]
$M_{FW}(k)$	feedwater flow rate from MSF [kg/day]
M_{SA}	solar circulation flow rate per collector [kg/h]
$M_{chg}(t,k)$	mass of charming tank [kg]
$M_{dis}(t,k)$	Mass of discharging tank [kg]
M_{min}	constant minimum mass each day [kg]
M_{pk}	peak mass [kg/h]
N_c	number of collector
N_s	number of MSF stages
$Q_u(t,k)$	Useful heat gain [J/h]
$T_A(t,k)$	ambient temperature (°C)
T_{BD}	blow down temperature (°C)
$T_{FW}(k)$	feedwater temperature from MSF (controlled to be constant) (°C)
T_{INS}	thickness of tank insulation [m]
T_K	thermal conductivity [KJ/kg K]
T_{TBT}	top brine temperature [°C]
$T_{chg}(t,k)$	charging tank temperature [°C]
$T_{dis}(t,k)$	discharging tank temperature [°C]
T_i	stage temperature [°C]
T_{th}	tank wall thickness [m]
TWP	total water price [\$/m^3]
V_{st}	volume of the storage tank [m^3/s]
X_{BD}	blow down salinity [ppm]
X_{SW}	sea water salinity [ppm]
η_0	optical efficiency
η_m	motor efficiency
η_p	pump efficiency
$\lambda_{avg,i}$	latent heat for the MSF [J/kg]
$\Delta T(t,k)$	total brine temperature increases [°C]
DC	direct capital cost [(\$)]
SPC	specific power consumption [kWh/m^3]
EP	electric price [\$/kWh]
F'	efficiency factor
HSP	heating steam cost [\$/kJ]
IDC	indirect capital cost [(\$)]
MC	operating maintenance cost [(\$)]
OC	operating cost [(\$)]
CC	total capital cost [(\$)]
Tsw	seawater temperature [°C]
$UA_{chg}(t,k)$	loss coefficient for charming tank [J/(h) °C]
$UA_{dis}(t,k)$	loss coefficient for Discharging Tank [J/(h) °C]
a	amortization
$chemP$	chemical price [\$/m^3]
f	plant availability
i	annual interest rate
k	day
n	plant lifetime
t	time [h]
ΔT_B	brine flow decreases [°C]
ΔT_{FW}	feedwater temperature increases [°C]
ΔP	pressure drop [kPa]
β	cost per square meter of collector area [(\$)/m^2]
α	cost per cubic meter of storage tank [(\$)/m^3]
η	collector efficiency

per-collector area basis, vary from 10 to 60 L/m^2/day, depending on efficiency of heat transfer and available solar energy (Qiblawey and Banat, 2008).

The unique element of the proposed design is a dual-tank system for directly storing hot brine, instead of a medium fluid. This system is designed to allow continuous MSF operation. One tank is charged with pre-heated seawater that is heated to TBT by circulation through the solar array, while the other tank, which was charged the previous day, discharges through the MSF. Decoupling the charging and discharging functions allows the charging tank temperature to gradually increase to TBT, which reduces thermal losses. Furthermore, as will be shown in the results, the temperature and flow-rate from the discharging tank into the MSF are calculated nearly constant for each day of operation, and these quantities undergo small, predictable changes from day to day. This semi-static approach minimizes the need for control systems. The performance of this approach is modelled with commonly used equations for describing MSF operation, solar heating and thermal storage.

2. System description

The proposed solar desalination system consists of three components: the MSF unit, a pair of storage tanks and an array of solar collectors. Fig. 1 illustrates an overall schematic of the system. Tank #1 is shown in charging mode, where it receives pre-heated brine from the MSF and circulates this brine through the solar collector array in order to gradually raise the brine temperature to TBT. Tank #2 is shown in discharging mode, where its stored brine at TBT feeds the MSF. As the brine from Tank #2 flows from left to right through the stages of the MSF, it evaporates to produce distillate and transfers heat to the incoming seawater. The following sub-sections provide further details about the design of the MSF, thermal storage tanks and solar array, and the interaction of these systems.

2.1. Multi-stage flash desalination

MSF is a type of thermal desalination, which generally refers to the process of evaporating heated brine, usually seawater, and collecting the condensed vapors. The most common energy source for heating brine is excess steam from electrical power plants. MSF desalination operates by passing the hot brine through a series of vacuum stages, in which the brine undergoes sudden evaporation called “flashing”. The flashed vapors condense on the surface of preheating tubes, simultaneously producing distillate and transferring heat to incoming feedwater flowing inside the tubes.

Fig. 2 contains labelled details to illustrate this process. There are five separate flows of brine that pass through the MSF stages. The hot brine that feeds the MSF enters the first stage (label A), and the portion of this flow that does not evaporate within the stages exits the last stage as highly concentrated “blow-down” waste (label B). Source seawater enters the last stage (label C), passes through pre-heating tubes within each stage, and exits the MSF at the first stage as preheated brine (label D). The collected distillate is passed from stage to stage, exiting the last stage as the