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Transient analysis of a photovoltaic thermal heat input process with thermal storage

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HIGHLIGHTS

- A review of existing solar energy desalination systems was completed.
- A review of PVT systems that use heat pumps was completed.
- A numerical model of a MED system and a novel heat input system was created.
- A simulation of the system was completed using Phoenix Arizona weather conditions.
- 780% more distillate output per year per unit area can be produced than a solar still.

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ABSTRACT

A novel heat input process that is optimized for use with multi-effect desalination technology has been analyzed. The system proposes the use of heat pumps combined with photovoltaic thermal solar collectors, such that a renewable energy-based desalination process can be developed to distill ocean water. The proposed system implements an additional heat pump loop, compared to existing heat input systems, such that an optimal use of electrical and thermal power from the solar collector can be achieved. The system is anticipated to be used in remote locations where clean drinking water is often scarce, and a lack of existing infrastructure and highly trained labor do not allow for conventional desalination methods. A case study is then given that shows how the operating parameters of the system can be optimized such that the distillate output per unit of solar collector area is maximized. Finally, the model predicts that the proposed system produces distillate at a rate of 30.7 kg/m^2/day given a case study location of Phoenix Arizona.

1. Introduction

1.1. Research motivation

As the population of the world increases, so does stress on natural fresh water sources. Potable water throughout the world is not evenly distributed, which results in many areas facing water shortages. One solution to this issue is to use desalination technology for saline water such that the population can consume it safely.

The most common desalination process today is the reverse osmosis membrane process, which involves pumping the ocean water to a high pressure and passing it through a membrane [1–4]. As for distillation, there are several processes in use today and all of these processes require thermal energy to drive the phase change of the ocean water. This thermal energy usually comes from the burning of fossil fuels, or from waste heat from other industrial processes, which also usually originates from fossil fuel combustion [1]. Both of these methods are usually implemented using large-scale plants that require significant infrastructure and are often too expensive for sparsely populated regions [5].

Using fossil fuels to drive desalination, while currently more cost effective than using a renewable energy source, can have drawbacks related to the environment and in some cases related to the logistics of the desalination plant. Fossil fuels, when burned, produce greenhouse gasses that contribute to global climate change, which can increase drought in many areas. Also, over time fossil fuel supplies worldwide are becoming more expensive as the world reserves are being depleted. Finally, fossil fuels may not always be readily and reliably available in remote areas. Therefore, using fossil fuels as a long term solution for desalination is not always viable.

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Nomenclature

Distillation process

f	distillation fraction that is selected for the plant (dimensionless)
i	tank index number (dimensionless)
h_{brine_i}	enthalpy of saturated liquid in tank i (kJ/kg)
$h_{distillate_i}$	enthalpy of saturated vapor in tank i (kJ/kg)
h_{feed_i}	enthalpy of the feed water going into tank i (kJ/kg)
h_{ocean}	enthalpy of the water that is taken in from the ocean (kJ/kg)
$\dot{m}_{brine_i}$	mass flow rate of the brine for stream i (kg/s)
$\dot{m}_{cooling}$	mass flow rate of the rejected cooling water (kg/s)
$\dot{m}_{distillate_i}$	mass flow rate of the distillate for stream i (kg/s)
$\dot{m}_{distillate_{total}}$	total mass flow rate of distillate that the system will produce (kg/s)
$\dot{m}_{feed}$	mass flow rate of the feed water (kg/s)
$\dot{m}_{ocean}$	mass flow rate of the brine taken in from the ocean (kg/s)
$\dot{m}_{return}$	mass flow rate of brine being returned to the ocean (kg/s)
$\dot{Q}_{in}$	energy flow rate from the external heat source (kW)

Heat input process

A	solar collector area (m^2)
$c_{p_{tank}}$	specific heat capacity of the thermal storage tank (J/kg K)
c_{p_w}	specific heat capacity of the working fluid in loop WA (J/kg K)
E_{desal_i}	electrical energy used by the desalination process over time step i (J)
E_i	electrical energy production over time-step i (J)
h_{a1}	enthalpy of the working fluid in loop RA after the evaporator(J/kg)
h_{a2}	enthalpy of the working fluid in loop RA after the compressor (J/kg)
h_{a3}	enthalpy of the working fluid in loop RA after the condenser (J/kg)
h_{a4}	enthalpy of the working fluid in loop RA after the throttling valve (J/kg)
h_{b_1}	enthalpy of the working fluid in loop RB after the evaporator contained in the thermal storage tank (J/kg)
$h_{b1_{x_i}}$	enthalpy of the working fluid in loop RB after the evaporator joining loops RA and RB during time step i (J/kg)
h_{b_2}	enthalpy of the working fluid in loop RB after the compressor (J/kg)
h_{b_3}	enthalpy of the working fluid in loop RB after the condenser (J/kg)
h_{b_4}	enthalpy of the working fluid in loop RB after the throttling valve (J/kg)
i	time step index number
m_{a_i}	mass flow of refrigerant through loop RA over time step i (kg)
m_{b_i}	mass flow of refrigerant through loop RB over time step i (kg)
m_{desal_i}	mass of distillate generated over time step i (kg)
$\dot{m}_{solar}$	flow rate of fluid per unit area of solar collector (kg/s/m^2)
m_{tank}	mass of thermal storage tank (kg)
$\dot{m}_w$	mass flow rate of fluid in loop WA (kg/s)
$\dot{q}_{solar_i}$	incident solar flux for time-step i (W/m^2)
Q_{desal_i}	thermal energy transferred to the desalination tank 1 over time step i (J)
Q_{ext_i}	thermal energy used from the external heat source over time step i (J)
Q_{HX1_i}	thermal energy transferred through HX1 over time step i (J)
Q_{HX2_i}	amount of heat energy transferred through HX2 over time-step i (J)
$\dot{Q}_{HX2_{design}}$	the design heat extraction rate through the evaporator contained in the thermal storage tank (W)
Q_i	thermal energy production over time-step i (J)
$Q_{incident_i}$	incident solar radiation energy over time-step i (J)
Q_{tank_i}	net thermal storage tank heat flow over time-step i (J)
R_E	the amount of electrical energy required to produce one kilogram of distillate from the desalination process (J/kg)
R_T	the mass of distillate produced per unit of thermal energy from the desalination process (kg/J)
Δt_{step}	simulation time-step size (s)
ΔT_{HX1}	temperature difference between the saturation temperatures of the condenser in loop RA and the evaporators in loop RB (°C)
ΔT_{HX2}	temperature difference between the saturation temperature of the evaporators in loop RB and the thermal storage tank minimum temperature (°C)
ΔT_{HX3}	temperature difference between the saturation temperatures of the condenser in loop RB and the desalination first tank (°C)
T_{a_i}	air dry bulb temperature during time-step i (°C)
$T_{cond,a}$	saturation temperature of the evaporator in loop WA (°C)
$T_{cond_{HX1}}$	saturation temperature of the condenser in HX1 (°C)
$T_{cond_{HX3}}$	saturation temperature of the condenser in HX3 (°C)
T_{desal}	saturation temperature of the first tank in the desalination cycle (°C)
$T_{evap_{HX2}}$	saturation temperature of the evaporator in HX2 (°C)
T_{m_i}	mean temperature of the solar collector during time-step i (°C)
$T_{solar_{in_i}}$	temperature of the fluid entering the solar panel during time step i (°C)
$T_{solar_{out_i}}$	temperature of the fluid leaving the solar panel during time-step i (°C)
T_{tank_i}	temperature of the thermal storage tank over time-step i (°C)
$T_{tank_{min}}$	minimum temperature set point of the storage tank (°C)
T_{r_i}	reduced temperature of the solar collector over time-step i (°C m^2/W)
W_{a_i}	electrical consumption of the compressor in loop RA over time step i (J)
W_{b_i}	electrical consumption of the compressor in loop RB over time step i (J)
η_{comp}	isentropic efficiency of the compressors in the heat pump loops (%)
η_{elec_i}	electrical efficiency of the solar collector during time-step i (%)
η_{th_i}	thermal efficiency of the solar collector during time-step i (%)

Alternatively, using renewable energy to power the desalination process can be much more viable in the long-term. Typically, areas that have water shortages are situated in parts of the world that have abundant and untapped renewable energy sources [5].