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Novel thermosiphon-powered reverse osmosis: Techno-economic model for renewable energy and fresh water recovery

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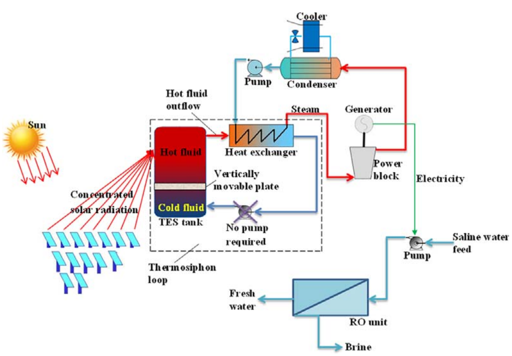
GRAPHICAL ABSTRACT



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ABSTRACT

Recently, thermosiphon has been considered as an economically competitive approach for the withdrawal of thermal energy from molten salt. This feature of thermosiphon is particularly attractive for concentrated solar power (CSP) technology because molten salt can be used both as the direct receiver and thermal energy storage material, and pumping requirements can be minimized. However, the thermosiphon loop must be properly designed; otherwise the heated molten salt can flow in the reverse direction or solidify before heat exchange is fully carried out. In this paper, the dependence of important molten salt flow characteristics such as temperature, velocity and friction factor on the thermosiphon loop dimensions is theoretically investigated. The model is carried out for the withdrawal of 1 MW of thermal energy from the molten salt. The economic assessment of the conversion of this energy to electricity for reverse osmosis desalination is also carried out. It is observed that by using the minimum possible value of leg length and maximum possible values of diameter and pressure head, the lowest decline of temperature and highest velocity of flow can be achieved along the loop. Fresh water production is more valuable than electricity and steam production by 460% and 480%, respectively.

1. Introduction

The principle of the thermosiphon system is that cold fluid has a higher specific density than warm fluid at its sub-critical conditions; and so being heavier, will sink down by natural convection. When a fluid is heated, it gains kinetic energy and becomes excited. As a result, it becomes less dense, expands, and thus rises. In contrast, when it is cooled, energy is extracted from its molecules; it becomes denser and tends to sink. Thermosiphoning is a passive heat exchange approach that harnesses the natural density differences between cold and hot fluids, and controls them in a system that produces natural fluid movement [1]. Thermosiphoning is also applicable for solar water

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Nomenclature

C_f	Salt concentration of the feed
C_p	Salt concentration of the permeate
c	Specific heat capacity
CSP	Concentrated solar power
CSPonD	CSP on Demand
d	Leg pipe diameter
f	Friction factor
g	Acceleration due to gravity
h_o	Head of leg 1 below tank lid
J_p	Flux of RO permeate
K_s	Salt permeability coefficient
K_w	Water permeability coefficient
L	Length of leg
MW	Megawatt
P	Pressure
P_a	Annual economic value of desalinated water
P_{losses}	Pressure losses
PV	Photovoltaic
Q_{el}	Electric power produced
Q_m	Rate of thermal energy withdrawal
Q_s	Specific energy consumption of RO process
RO	Reverse osmosis
s	Direction of flow of molten salt
T	Molten salt temperature
TES	Thermal energy storage
T_o	Reference temperature (inlet temperature in a leg)
u	Molten salt velocity
WT	Water tariff
y	Annual plant availability

Greek letters

μ	Molten salt viscosity
β_f	Volume coefficient of expansion
Δ	Change
η_{el}	Power block efficiency
η_{sg}	Heat exchanger efficiency
π	Osmotic pressure
ρ	Density
Θ	Angle between molten salt flow direction and vertical axis of tank

Subscripts

A	annual
El	electric
F	feed
f–p	feed to permeate
p	permeate
sg	steam generation
w	water

heating where water is heated by a solar thermal collector and the heated water can be transported via natural flow or circulation [2] (Fig. 1(a)).

Thermosiphoning depends on the environmental properties, materials and area available for thermal energy collection and storage, and the extent of heat exchange after thermal energy has been siphoned [3]. The design of the heat exchanger contributes significantly to the overall efficiency of a thermosiphon system. The helical-coil heat exchanger is commonly used for the transfer of the siphoned thermal energy. However, in a recent investigation, a parallel circular-tube rings-type heat exchanger has been shown to be more effective than the helical-coil heat exchanger [4]. The inclination of the solar collector and the configurations of the riser and header tubes in the collector are also important operating factors. Small header and riser pipe diameters in the collector have been shown to provide optimum results in terms of the thermosiphon system's thermal efficiency [5]. The principle of thermosiphoning might also be potentially applicable in concentrated solar power (CSP) technology (Fig. 1(b)). CSP technology uses mirrors to concentrate solar irradiance and generate thermal energy at high temperature, at a focal point or line. This thermal energy can then be used for steam generation in a heat exchanger and finally converted to electricity via a steam turbine. To a large extent, the electricity obtained from CSP plants is more environmentally friendly than that obtained from conventional plants powered by fossil fuels. The CSP systems that are operational in the world mainly use the parabolic trough collector system, central receiver or power tower system, and dish Stirling system [8].

The status quo of a modern CSP plant is the parabolic trough configuration of ANDASOL 1 CSP plant, where synthetic oil (Therminol VP-1) that operates between 292 and 393 °C is used as the heat transfer fluid. Meanwhile, research and commercial interest in the central receiver or power tower configuration has been intensified recently because the power tower provides more concentration ratio than the parabolic trough configuration and then higher concentration can be reached, increasing the power block efficiency. The state-of-the-art technology in the power tower system is a two-tank molten salt system

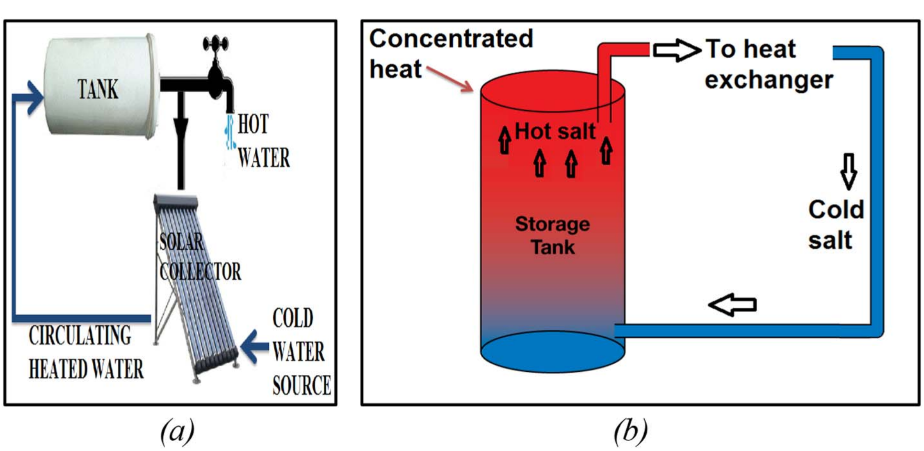

Fig. 1. Schematic of thermosiphoning (a) in a simple solar water heater, (b) for thermal energy recovery from molten salt in concentrated solar power.