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Comparatively study between single-phase and two-phase modes of energy extraction in a salinity-gradient solar pond power plant

Behrooz M. Ziapour*, Mehdi Shokrnia, Mohammad Naseri

Department of Mechanical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

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The common process in all applications of a salinity-gradient solar pond (SGSP) is the energy extraction process using single-phase mode heat transfer with some limitations such as pumping the large amount of mass flow rate, and need for big size of heat exchanger. In every respect, two-phase mode heat transfer can be selected as an advantage due to its passive case of operation and comparatively high heat transfer capacity with rational system size. In this paper, an enhanced design of a large scale SGSP power plant using some two-phase closed thermosyphons has been simulated and compared with the single-phase mode heat transfer. The simulation results showed that the overall thermal efficiency of the solar pond power plant was the highest using both thermosyphons and heat exchangers.

1. Introduction

Many investigations have been performed on the solar ponds. The first report was written on a natural solar lake (Medve Lake in Transylvania, Hungary) by Kalecsinsky in 1902 [1]. Medve Lake had temperatures growing up to 70 °C at a deepness of 1.32 m at the end of the summer. The smallest temperature of this Lake was 26 °C during early spring. The salinity-gradient solar pond (SGSP) is an economically solar energy system which gathers the sun beams and stores them as thermal energy for a long period of time. This allows a number of useful applications such as heating [2–5], cooling [6,7], power generation [8–13] and desalination [14–18].

To introduce, Fig. 1 shows schematically a SGSP system. As shown in Fig. 1, it has not any glazing cover or mirror surface to be kept clean. It consists of three zones as [19–22]: (1) – The upper convection zone (UCZ) with the lowest and constant grade of salinity (about 5–10%) and constant temperature (close to ambient temperature). Its thickness changes from 0.15 to 0.3 m. The natural convection heat transfer is exhibited by the UCZ; (2) – The Non-convection zone (NCZ) or gradient zone. In this zone, both the salinity and temperature increase with depth. Therefore, each layer of this zone is heavier and warmer than the ones above it. This stratification enables the gradient zone to prevent upright convection and act as an insulating layer of pond. The NCZ thickness usually varies from 1.0 to 1.5 m; and (3) - The lower convective zone (LCZ) with the highest and constant grade of salinity (about 15–30%) and constant temperature. In this zone, heat is stored and extracted. Thickness of this zone (about 1.0–2.0 m) depends on the temperature and amount of the stored energy.

Tabor [23,24] declared that an artificial small solar pond using magnesium chloride gave maximum temperature of over 90 °C; and after, the modified 1200 m^2 pond gave temperature of 103 °C. Also, in an experimental solar pond a temperature of 109 °C was recorded [25]. It has been shown that the pond temperatures were powerfully dependent on the effective extinction coefficient for solar radiation and the thermal losses from the pond bottom [26]. Karakicik et al. [27], theoretically and experimentally, determined the total heat losses from the inner surface of the pond and its bottom and side walls. For example, 84.94% from the inner surface, 3.93% from the bottom and 11.13% from the side walls.

It is proven that the larger SGSP is more economically feasible. The sun is the biggest source of energy that is plentifully available all over the earth. Salinity-gradient solar ponds (SGSP) are essentially matchless systems to present economically the large scale of the available energy. Report of Tabor [23], in past years, has

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* Corresponding author.
E-mail address: bmziapour@gmail.com (B.M. Ziapour).

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Nomenclature

A	pond outer surface area (solar pond size), m^2
A_{LCZ}	mean area of the LCZ surface, m^2
A_{NCZ}	mean area of the NCZ surface, m^2
A_{UCZ}	area of the UCZ top surface, m^2
c_{Pf}	liquid phase of the thermosyphon working fluid specific heat $J(\mathrm{kg})^{-1}\ \mathrm{K}^{-1}$
D_c	condenser diameter, m
D_e	evaporator diameter, m
g	gravity acceleration, ms^{-2}
$\bar{h}_c$	heat transfer coefficient at the condenser, $Wm^2\ K^{-1}$
$\bar{h}_e$	heat transfer coefficient at the evaporator, $Wm^2\ K^{-1}$
h_{fg}	specific enthalpy difference between saturated gas and liquid inside the thermosyphon, $kJ(kg)^{-1}$
I_B	radiation at the pond bottom surface, Wm^{-2}
I_{BR}	radiation flux reflected from bottom of pond, Wm^{-2}
I_r	radiation flux in water at the outer surface of pond, Wm^{-2}
I_{LCZ}	available radiation at the depth x, Wm^{-2}
I_{SR}	radiation flux reflected back into pond from pond outer surface, Wm^{-2}
I_x	available radiation at the depth x (only incident part), Wm^{-2}
K_{b1}	conductivity of pond liquid relation with the brine LCZ, $Wm^{-1}\ K^{-1}$
K_{b2}	conductivity of pond liquid relation with the brine UCZ, $Wm^{-1}\ K^{-1}$
k_f	liquid phase of the thermosyphon working fluid thermal conductivity, $Wm\ K^{-1}$
L_c	length of the condenser section, m
L_e	length of the evaporator section, m
n_{TH}	numbers of two-phase closed thermosyphons
P_{atm}	pressure of atmosphere, Pa
P_{sat}	saturated pressure inside thermosyphon, Pa
q	heat transfer rate per unit area, Wm^{-2}
Q_c	condenser section of each thermosyphon heat flux, W
Q_e	evaporator section of each thermosyphon heat flux, W
$\dot{Q}_{lb}$	heat loss rate from the pond bottom surface, W
$\dot{Q}_{lr}$	absorbed heat rate by the LCZ due to solar radiation, W
$\dot{Q}_{lt}$	conduction heat loss through the LCZ top layers, W
$\dot{Q}_{lu}$	useful heat extraction rate from the LCZ, W
$\dot{Q}_{lw}$	heat loss rate from the pond wall surfaces, W
R	pond bottom surface reflectivity
T_{amb}	ambient temperature, K
T_c	condenser section working fluid temperature, K
T_{c1}	heat exchanger inlet cold side temperature, K
$\overline{T}_{eva}$	mean temperature of the evaporator section of the ORC cycle, K
T_{h1}	heat exchanger inlet hot side temperature, K
T_{h2}	heat exchanger outlet hot side temperature, K
T_{in}	inlet temperature of the evaporator section of the ORC cycle, K
T_{LCZ}	LCZ temperature, K
$T_{NCZ,b}$	bottom surface of NCZ temperature, K
$T_{NCZ,t}$	top surface of NCZ temperature, K
T_{out}	outlet temperature of the evaporator section of the ORC cycle, K
T_v	evaporator section working fluid temperature, K
$\dot{W}_{net}$	overall net work of the all ORC system, MW
$\dot{W}_{pump}$	ORC system pump work, MW
$\dot{W}_{turbin}$	ORC system turbine work, MW
x	depth of the pond till the LCZ surface, m

Greek letters

α	bottom surface shortwave absorptivity of the pond
δ_{LCZ}	LCZ thickness, m
δ_{NCZ}	NCZ thickness, m
δ_{UCZ}	UCZ thickness, m
ε	effectiveness of the heat exchangers used in ORC systems
η_P	pond heat collection efficiency, %
η_0	overall thermal efficiency of the solar pond power plant, %
μ_f	liquid phase of the thermosyphon working fluid kinematics viscosity, $kg\ m^{-1}\ s^{-1}$
ρ_f	liquid phase of the thermosyphon working fluid density, $kg\ m^{-3}$
ρ_v	vapor phase of the thermosyphon working fluid density, $kg\ m^{-3}$

been provided the background to non-convecting solar ponds as verified viable large area collectors capable of supplying both inexpensive thermal energy and electricity. For example, at Beith Ha'Arava, a 210,000 m^2 solar pond connected to an ORC system was operated between 1982 and 1988 to produce 5 MWe [28]. In 2004, Lu et al. [29] reported from the El Paso solar pond operation. This solar pond with area of 3000 m^2, located on the wealth of Bruce Foods, Inc. was launched in 1983, by the University of Texas. Economic analysis of the El Paso solar pond showed that SGSP technology was highly dependent on local conditions, application and size. The larger SGSP is more economically feasible. In 1987, at Bhuj in the property of milk processing dairy plant, a SGSP system with area of 6000 m^2 was established to supply process heat [30]. The construction cost of the Bhuj SGSP was US$90,000 (1997 prices), comprising heat exchanger, piping, etc., corresponding to a unit cost of US$15 m^{-2}. Recently, Vergara and Garrido [31] proposed a design of a SGSP, with area of 23,240 m^2 and a gradient zone thickness of 1.8 m, for water preheating used in the copper cathodes washing at a mining operation at Sierra Gorda. They declared that the analyzed performance of the SGSP shows that reductions of 77% of diesel and 38% of the energy cost could be anticipated.

The common process in all applications (heating, cooling, electricity and desalination) of a SGSP system is the energy extraction process. There are three methods to transfer the stored thermal energy from the LCZ of a SGSP system as follows: (1) – Hot salty water is pumped through a diffuser (that is known as single-phase heat transfer and active mode of operation). Finally, the cold salty is returned back to the pond by another diffuser, after exchanging its main thermal energy in a proportional heat exchanger (see Fig. 2(a)). In diffusers, the velocity of fluid is adjusted to prevent the erosion of the gradient layer. This method was prevalently used for large scale applications. For example, at Beith Ha'Arava [28], El Paso [29] and Bhuj [30] solar ponds. (2) – Cold working fluid inside the coiled pipes of an internal heat exchanger, installed in the LCZ near to the gradient layer, removes the hot salty water thermal energy,