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Passive small scale electric power generation using thermoelectric cells in solar pond

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A B S T R A C T

Solar ponds have been widely utilised in providing low grade heat needed for industrial processes and for heating applications <100 °C. In this paper, a small scale passive electric power generation unit was devised for generating electricity from the heat available in the solar pond. The power generation unit proposed operates without the use of a pump and involves no moving parts. The design of the power generation unit was finalised after performing a comprehensive theoretical study on the possible geometrical arrangements. The power generation unit was fabricated and tested experimentally. The power generation unit consists of 120 commercially available thermoelectric cells accommodated in the outer and inner layers of this dual layer power generation unit. The power generation unit had produced a maximum power of 40.8 W under the condition of $T_h = 99$ °C. Under the normal operation of solar pond, the lower convective zone will have a temperature that lies within in the range of 40 °C –80 °C. Thus, maximum output in the range of 19.5 W–27.4 W is more realistic for the system proposed with the heat to electric conversion efficiency ranges between 0.37%–0.68%.

1. Introduction

Solar power generation can be divided into two main categories which are in the form of solar photovoltaic and solar thermal system. The status quo of the research on solar thermal power plant are presented by Reddy et al. [1]. Solar ponds are classified into the category of a solar thermal system, functioning as both a collector and a storage facility of solar energy for future use. Solar ponds have been researched extensively over the past decades. The heat stored at the lower convective zone (LCZ) can be used as a heat source for process heating or be utilised to drive a turbine for electric power generation by the means of an organic refrigerant. The thermal application of solar pond has been analysed comprehensively in terms of thermodynamics and economics feasibility and it is available from the work carried out by Ranjan [2] and Gupta [3]. Meanwhile, it is also worthwhile to mention the work outlined by Khalil et al. [4] for the methodology in the optimisation of electric power generation using solar pond. In the past, medium or large scale electric power generation from solar pond utilises a modified Rankine cycle by using organic fluid that will be able to evaporate at lower temperature and lower pressure in contrast with steam cycle. The Beith Ha'Arava solar pond power plant that operated until 1988 had the capacity of generating 5 MW of electrical output [5]. For a typical solar pond, it has a thermal efficiency of 15–25% and a solar to electric overall efficiency of 0.8–2% [6]. For small scale power generation particularly utilising a solid state material based on thermoelectric effect, Date et al. [7] collated the progress of the application of thermoelectric cells (TECs) in generating electricity from various heat sources such as solar evacuated tubes, solar ponds, biomass source, waste heat and internal combustion engines. In order to create the temperature difference across the TECs using the heat available at the LCZ of solar pond, Singh et al. [8] and Tundee et al. [9] conducted a conceptual experimental study using heat pipe acting as the heat transfer medium to transfer the heat from LCZ to the upper convective zone (UCZ) where cold water is available. The TECs located at the UCZ will be able to generate electricity with the presence for both heat source and heat sink. 3.2 W of electricity had been produced in their study. The objective of their study was to develop a concept of electric generation using a solar pond with a fully passive design. On the other hand, the work presented by Baljit et al. [10] demonstrated another method of generating electricity from the heat available from solar pond with the use of pump to circulate the hot and cold water from solar

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Nomenclature

a_p	apothem (m)
A	area (m^2)
c	specific heat (J/kg.°C)
d	diameter/thickness (m)
d_h	hydraulic diameter (m)
Δ	difference
ε	absolute surface roughness (mm)
f	Darcy friction factor
g	gravitational acceleration (m/s^2)
Gr	Grashof number
h	convection heat transfer coefficient (W/m^2°C)
k	thermal conductivity (W/m°C)
l	length/height (m)
l_t	side length of the TEC (m)
$\dot{m}$	mass flow rate (kg/s)
η_t	conversion efficiency
N	number of
Nu	Nusselt number
P	perimeter (m)
Pr	Prandtl number
$\dot{Q}$	rate of heat transfer (W)
ρ	density (kg/m^3)
r	radius (m)
$\bar{r}$	maximum power efficiency ratio
R	thermal resistance (°C/W)
Ra	Rayleigh number
R_{io}	area ratio
R_e	electrical resistance (Ω)
Re	Reynolds number
R_L	load resistance (Ω)
T	temperature (°C)
TEC	thermoelectric cell
V	velocity (m/s)
$\dot{V}$	flow rate (L/s)
ω	error/uncertainty
$\dot{W}$	electric power (W)

Subscripts

C	cold
$conv$	forced convection heat transfer
h	hot
i	inner
j	row number
L	of length L
LCZ	lower convective zone
min	minimum
max	maximum
nat	natural convection heat transfer
o	outer
s	steel
$TEC+g$	TEC and glue
UCZ	upper convective zone
p	polygon
w	water

pond in a counter flow arrangement. Similarly, by using 16 TECs, their system will be able to generate a maximum power of 9.56 W when a temperature difference of 100 °C is available. Beside studying how a solar pond can be used to generate electricity, research also had been conducted into how the heat available in solar ponds can be used to replace the need of electric power to drive a pump. From the theoretical study conducted, Date and Aliakbar [11] proposed a new power cycle to drive a thermal powered pump utilising a piston action similar to that of an internal combustion engine.

Applying a similar concept to the work conducted by Singh et al. [8], this work examine the potential of passive electric generation using a solar pond (SP)-TECs system. The difference with the aforementioned studies [8–10] is, instead of transferring the heat to the top of solar pond, the cold water available at the UCZ that is acting as the heat sink is flowing down to the LCZ. This method enables the heat exchange with hot water at LCZ where the TECs are located by using the pressure head available at UCZ with a siphon.

2. Design concept and theoretical model

2.1. The design

The proposed SP-TECs system for this study is illustrated in Fig. 1 and a typical salinity gradient SP will possess a general salinity and temperature profile as depicted in Fig. 1. Starting with the UCZ layer where the salinity almost identical to the fresh water at the top and moving further down, its salinity is gradually increases across the NCZ until it reaches the LCZ, where the water is saturated with salt which is usually NaCl for industrial application. The solar radiation that reaches LCZ is stored in LCZ thus raising the temperature in LCZ. Due to the density stratification that suppressing the buoyant force of hot fluid in LCZ, the convection current happens only at LCZ and UCZ, whereas in NCZ, conduction is the main mode of heat transfer. As a result, the temperature in the LCZ could increase up to the boiling point of saturated NaCl solution. Furthermore, a typical SP is usually constructed at a LCZ thickness of 0.5 m–1.0 m, and total depth of about 2 m–3 m.

As shown in Fig. 1, the power generation unit (PGU) is submerged in the SP. The TECs are mounted on the outer surface of the polygonal cylinder and directly expose to the hot saline water in the LCZ of SP. The flow of cold water from the UCZ in the PGU is achieved with siphoning effect. By considering the transverse cross section of a polygonal cylinder, for any regular polygon with N_p number of sides, consists of N_t TECs per side with the TEC side length of l_t, the total cross sectional area of that polygonal cylinder is given by

$$A_p = \frac{1}{4} N_p N_t^2 l_t^2 \cot\frac{180}{N_p} \tag{1}$$

where N_p = number of polygon sides, l_t = side length of the TEC, N_t = number of TEC along one side of polygon and accordingly, its perimeter is given by

$$P_p = N_p N_t l_t \tag{2}$$

Since the TECs attached at the outer surface of a polygonal cylinder, maximising the perimeter/area in 2-D plane is actually maximising the surface/volume in 3-D for polygonal cylinder. Thus, similar to the concept of surface-volume ratio, perimeter-area ratio is adopted for regular polygon which serves as an indicator for the purpose of maximising the perimeter for a polygon for a given