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Electric power generation via plate type power generation unit from solar pond using thermoelectric cells

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HIGHLIGHTS

- The design of a plate type power generation unit coupling with solar pond using TECs is proposed.
- An open channel power generation unit operates at atmospheric pressure is realised.
- The power generation unit is able to generate favourable power even at low flow rate.

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ABSTRACT

Solar pond (SP) has been a reliable supply of heat source for heating process that requires temperature <100 °C. In this work, the capability of solar pond in generating electricity has been explored experimentally using a plate type power generation unit (PTPGU). The open channel PTPGU was designed and fabricated in order to accommodate the TECs. The heat stored in the lower convective zone (LCZ) is used as the heat source needed for generating electricity by utilising thermoelectric cells (TECs) and thus a combined SP-PTPGU system is proposed. The PTPGU was tested with different hot water temperatures and flow rates. Also, the possibility of performance enhancement utilising copper mesh as insertion is presented. From the testing conducted, the PTPGU is able to generate 35.9 W of electricity at the flow rate as low as 5.1 LPM (litre per minute) at the hot water temperature of 81 °C. Besides coupling with solar pond, the PTPGU designed can also be coupled with other type of hot water source, such as hot spring.

1. Introduction

As advocated by Rowe [1] and Bell [2], thermoelectric cell is a solid state heat engine will be able to perform a vital role in providing an alternative solution for sustainable power generation as long as its current limitation of low conversion efficiency and high cost per watt is overcome in the future. To date, the commonly available thermoelectric generators (TEGs) which are made of bulk material Bi_2Te_3, come with a *ZT* value of around 1 [3]. The summaries of the recent advancement on the development of thermoelectric applications for power generation are available from the review conducted by Zheng et al. [4] and He et al. [5]. In order to produce electrical energy from thermoelectric cells, heat is supplied at the hot junction and is removed at the cold junction in order to create a temperature difference across the junction. Typically, either water or air is used as the heat transfer medium of the heat sink. In the study presented by Yu and Zhao [6], the TEG system under a parallel plate heat exchanger arrangement was studied in one dimensional analysis. From the analysis, a linear variation of temperature profile across the length of the heat exchanger for both parallel flow and counter flow type of setting, which is different from conventional logarithmic variation of temperature profile in parallel plate heat exchangers. The numerical model presented has been compared with the experimental result in a later publication [7]. Using electric power maximizing configuration with ΔT of 120 °C, 56 pieces commercially available Bi_2Te_3 TEGs will able to produce 147 W of electric power with a conversion efficiency of 4.4%. Meanwhile, for water cooled heat exchanger with TEGs, David et al. [8] delineated an optimisation method for maximizing the power output via heat exchanger optimisation for thermoelectric heat pump for geothermal applications. In the design, the hot side and cold side flow channel was able to work interchangeably, depending on the operating mode of the heat pump. They showed, there is an optimal thermal point that leads to the maximum coefficient of performance of the heat pump for a given fluid temperature. Moreover, a computational study has been conducted by other researcher by taking into account the dependency of thermoelectric properties on temperature.

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Nomenclature

Abbreviations

LCZ	lower convective zone
LMTD	log mean temperature difference
LPM	litre per minute
NCZ	non-convective zone
PTPGU	plate type power generation unit
SP	solar pond
TEG	thermoelectric generator
UCZ	upper convective zone

Symbols

b	height (mm)
c_p	specific heat (J/kg °C)
D_h	hydraulic diameter (m)
ΔP	pressure drop (Pa)
ΔT	temperature difference (°C)
f	friction factor
h	convection heat transfer coefficient (W/m^2 °C)
I	current (A)
k	thermal conductivity (W/mK)
l	length (m)
n_p	number of plates
$\dot{P}$	pumping power (W)
$\dot{Q}$	rate of heat transfer (W)
R	thermal resistance (W/°C)
r	electrical resistance (Ω)
S	salinity (g/kg)
T	temperature (°C)
V	voltage (V)
$\dot{V}$	flow rate (m^3/s)
w	gap size (mm)
$\dot{W}$	electric power (W)
α	mixing coefficient
β	mixing coefficient
ε	absolute surface roughness (mm)
η	efficiency
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa S)
ω	error

Subscripts

c	cold
e	electric
g	glue
i	row number
in	inlet
j	column number
oc	open circuit
out	outlet
p	plate
s	steel
sc	short circuit
sg	steel and glue
T	total
w	water

Rodriguez et al. [9] described a one dimensional computational model that will aid the designer to simulate the performance of the TEG, by considering the variation of room temperature, electric load resistance as well as heat flux.

On the other hand, for air cooled TEG systems, Crane and Jackson [10] performed an investigation on optimising the TEG heat exchanger using a cross flow configuration. After taking into account the pumping requirements, their analysis showed that heat exchangers with Bi_2Te_3 TEGs will be able to achieve net power per unit volume of 45 kW/m^3 for a heat exchanger sized at producing 1 kW$_e$. On the other hand, Suter et al. [11] performed geometrical optimisation for a 1 kW$_e$ thermoelectric stack using a geothermal heat source. With similar type of configuration, Gou et al. [12] suggested several improvements that can be done on enhancing the system performance, such as taking into consideration the parallel/series connection of the TEGs as well as taking appropriate measures to increase the heat transfer at the heat sink by extending its surface area. To further elaborate the point of improving the heat transfer for the TEG-heat exchanger system, Nnanna et al. [13] proposed the use of nanofluids such as Al_2O_3-H_2O, which has the potential on reducing the contact resistance of the TEG and heat exchanger and thus enhancing the heat transfer.

Research has also been conducted on converting the heat available from automobile exhaust [14–16]. Furthermore, in order to enhance the heat transfer of the heat exchanger for harvesting the exhaust heat into electricity, different methods could be applied such as the use of a dimpled surface to replace the need of using fin proposed by Wang et al. [17], applying metal foam inserts into the heat exchanger [18] and minimising the contact thermal resistance in the heat exchanger [19]. Hsu et al. [20] developed a system consisting of 24 pieces of Bi_2Te_3 TEGs. From their study, they emphasized that a proper thermal distribution will improve both the thermal and electric performance. Despite the fact that a low heat input will eventually lead to low conversion efficiency, they opined, it will not be a major concern since the heat source is freely available. If a free heat source is available, such as from a hot spring, the research work conducted by Sasaki et al. [21] has shown that a TEG system incorporated with the hot spring is able to generate 1.927 MW h in 8966 h of operation. Recent study on the thermoelectric heat recovery system by using water as working fluid at hot side temperature <80 °C in both transient and steady state condition had been carried out by Massaguer et al. [22] along with a verified thermoelectric energy harvesting model through experiment. For coolant based working fluid, Bjørk et al. [23] realised a thermoelectric power generation system based on 100 pieces commercially available thermoelectric generators at the flow rate as low as 5.0 LPM. With a fluid temperature difference of 175 °C, their system generated 200 W of electric power.

As a large scale solar energy collector and energy storage system, the solar pond (SP) collects the solar radiation transmitted into the SP and stores the heat in the lower convective zone (LCZ) with saturated salt (usually NaCl) solution. The non-convective zone (NCZ) minimises the heat loss by suppressing the convection heat loss to the top of the SP. Working as both thermal collector and thermal storage, solar ponds absorb the energy radiated from the sun and as a result, the radiation energy that penetrates to the lower convective zone is stored, owing to the density variation of the solar pond. The heat stored in the SP is in the regime of low grade heat and ranges up to the boiling point of saturated salt solution at atmospheric condition. As an illustration of the characteristics of the SP, Fig. 1 represents a typical temperature and density profile of a 50 m^2, 2.05 m depth research solar pond available in RMIT, Melbourne, whereas Fig. 2 shows the temperature profile of an operating commercial solar pond at Granada, Spain. Research from the past decades has shown successful application of solar ponds in providing the heat needed for heating applications or generating electricity by using organic Rankine cycle [24].