Combined Thermosyphon and Thermoelectric Modules for Power Generation from Salinity Gradient Solar Ponds

Sura Tundee[1*], Narong Srihajong[1], Randeep Singh[2] and Aliakbar Akbarzadeh[2],

[1]Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Isan Khon Kaen Campus,Thailand.40000 Tel. +66-43-336371 Fax. +66-43-237483
[2]Energy CARE Group, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora East Campus, Bundoora 3083, Australia,
suratundee@hotmail.com

Abstract

Salinity-gradient solar ponds can collect and store solar heat at temperatures up to 80°C. They can thus be a renewable source of heat for generation of electricity using thermoelectric modules capable of operating at temperature differences in the range 30 °C to 50 °C. The temperature difference between the lower convective zone and the upper convective zone is applied across the hot and cold surfaces of the thermoelectric modules. A system in which heat from the lower zone is transferred to the hot surface of the thermoelectric modules using gravity-assisted heat pipes as thermosyphons has been investigated experimentally. The modules are located so that their cold surfaces are in contact with the upper convective zone of the solar pond. The pipe surfaces are insulated in the region they pass through the gradient layer of the solar pond. Results for power output of the proposed combination of thermosyphon and thermoelectric cells operating over temperature differences existing in solar ponds are reported. The prospects for using solar pond – thermoelectric power generation for remote area power supply system are discussed. A potential advantage of such a system is its ability to continue to provide useful power output at night time or on cloudy days because of the thermal storage capability of the solar pond. The proposed combined thermosyphon and thermoelectric system was installed in a small experimental solar pond at RMIT campus in Bundoora and electric power was generated utilizing the temperature difference between the top and the bottom of the pond. Research results in the present work indicate that there is a significant potential for electric power generation from small solar ponds through a simple and passive device incorporating thermosyphons and thermoelectric cells.

KEY WORDS**:** thermosyphon, thermoelectric generator, solar pond, power generation

1. Introduction

Salinity gradient solar ponds are large bodies of water that act as solar collectors and heat storages. Solar pond is a simple and low cost solar energy system which collects solar radiation and stores it as thermal energy for a relative longer period of time. When solar radiation penetrates through the solar pond surface, the infrared radiation component is first absorbed in the surface mixed layer or upper convective zone. However, this heat is lost to the atmosphere through convection and radiation. The remaining radiation will subsequently be absorbed in the non convective zone and lower convective before the last of the radiation reaches the bottom of the pond. The temperature difference created between the top and the bottom of the solar ponds can be as high as 50°C to 60°C. The collected and stored heat can be extracted and used for industrial process heat, space heating, and even power generation [1]. The solar pond consists of three regions, the Upper Convective Zone (UCZ), the Non Convective Zone (NCZ) and the Lower Convective Zone (LCZ) as shown in Fig 1.

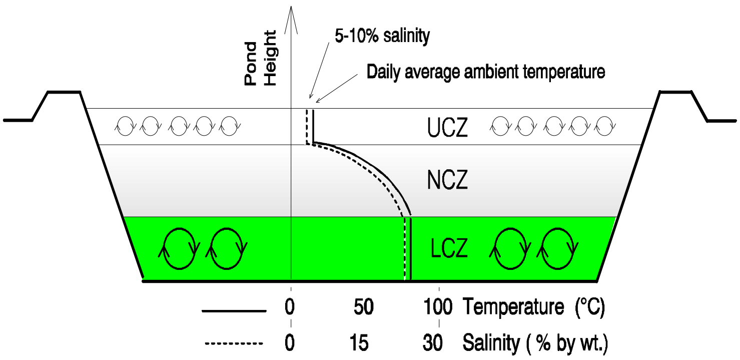

Fig.1.The salt gradient solar pond configuration

Extensive research has been also carried out to utilize the thermal energy produced by solar ponds to produce electric power [2]. The best showcase for such power generation was the project near the Dead Sea in Israel where 5 MW electric power was produced using a Rankin Cycle heat engine from a 210,000 m^2 salinity gradient solar pond having a depth of 4.5 m [3]. Although generation of electricity from large solar ponds has been successfully demonstrated, for power generation from small scale solar ponds there has not yet been a practical and viable proposal. A solar pond does not have to be larger than a few hundred square meters to be able to produce enough heat that after conversion can satisfy the electricity demand for an energy efficient house (say 2 to 5 kWh per day). While construction and maintenance of a solar pond of this size is not a problem, In the present research it is shown that by combining thermosyphons and thermoelectric cells, it would be possible to utilize the temperature difference existing between the top and the bottom of a solar pond and produce electric power in a fully passive way, i.e. no moving parts. In such a scheme, the heat is transferred by the thermosyphon from the lower region of the pond to the 'hot' side of thermoelectric cells which maintains a good thermal contact with the top of the thermosyphon tube. The 'cold' sides of the cells are in contact with the cold environment of the top layer of the solar pond. The above proposal utilizes thermosyphons, which are highly effective devices for heat transfer [4], and thermoelectric cells, which can effectively convert a temperature difference to electric potential and generate power [5]. Both of these devices do not have any macro scale moving parts and are thus fully passive. Although at present, the efficiency of conversion of heat to electricity by thermoelectric cells is still low (2% for a 50°C temperature difference) and at its best is 10 to 20 percent of the Carnot efficiency for the same temperature difference, the availability of the cells and their simplicity suggest that these devices may be very suitable candidates as small and simple energy converters in applications such as small solar ponds.

2. Theoretical Analysis

2.1 Thermosyphon

The gravity assisted thermosyphon is an effective heat transfer device that utilizes latent heat of the working fluid, flowing under the influence of gravity, to transport heat from the source to the sink. As the latent heat of vaporization is relatively high, the thermosyphons can transfer large quantity of heat with very small end to end temperature differential and thus low thermal resistance. In the thermal analysis of the gravity assisted thermosyphon corrections from ESDU [7] were used. The total thermal resistance – Z_t [K/W] from heat source to the heat sink for thermosyphon is related to the actual overall heat transfer - $\dot{Q}_{oa}$ [W] as below:

$$\dot{Q}_{oa} = \frac{\Delta T_{eff}}{Z_t} \tag{1}$$

Where, ΔT_{eff} [K] is effective temperature difference between heat source and heat sink and defined by:

$$\Delta T_{eff} = T_{so} - T_{si} - \Delta T_h \quad (2)$$

In Equation (2), T_{so} [K] is heat source temperature, T_{si} [K] is heat sink temperature and ΔT_h [K] is mean temperature difference due to hydrostatic head which is given as:

$$\Delta T_h = \frac{(T_p - T_v)F}{2} \quad (3)$$

Where, F is the filling ratio and defined by:

$$F = \frac{V_l}{A_{ts} L_e} \quad (4)$$

V_l [m^3] is volume of working fluid, A_{ts}[m^2] is internal cross section area of thermosyphon pipe and Le [m] is evaporator length. T_p [K] the saturation temperature at the bottom of the pool is given by

$$T_p = T_v + \left(L_e F \frac{dT_s}{dH} \right) \quad (5)$$

In Equation (5), T_v [K] is the temperature of the vapour in the adiabatic and condenser section T_s [K] is the saturation temperature of the boiling liquid and H [m] is the hydrostatic height of the liquid in the evaporator.

$$\frac{dT_s}{dH} = \frac{T_s g}{L} \left[\frac{\rho_l}{\rho_v} - 1 \right] \quad (6)$$

Where, g [m/s2] is acceleration due to gravity T_v [K] is determined from

$$T_v = T_{si} + \left(\frac{Z_7 + Z_8 + Z_9}{Z_t} \right) (T_{so} - T_{si}) \quad (7)$$

Where Z_t is the overall thermal resistance of the thermosyphons, it can be represented by the idealized network of thermal resistances Z_1 to Z_{10} as shown in Fig 2.

2.1.1 Thermal Resistances

The individual thermal resistances as depicted in Figure 2 that make up the total thermal resistance from the heat source to the heat sink in the gravity assisted thermosyphon system is now discussed in detail.

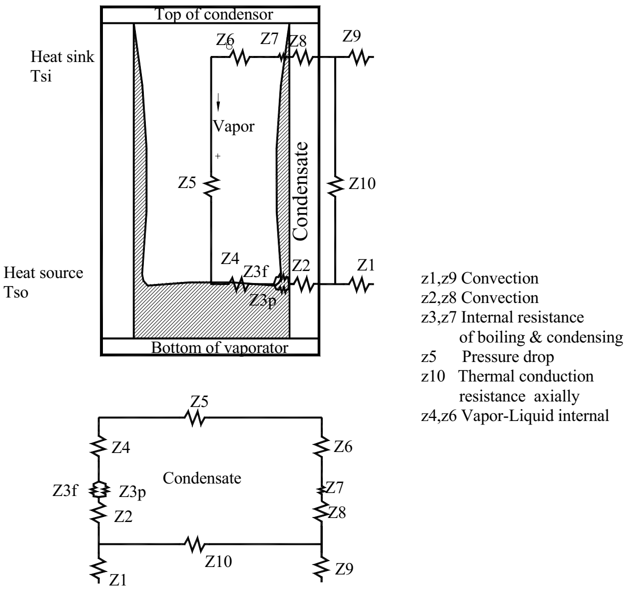

Fig.2.Thermal resistance and their locations.

Z_1 and Z_9 are thermal resistance between "heat source and the evaporator external surface" and "heat sink and condenser external surface" respectively. These can be expressed as:

Z_4 and Z_6 are the thermal resistances that occur at the vapor liquid interface in the evaporator and the condenser respectively.

Z_5 is the effective thermal resistance due to the pressure drop of the vapor as it flows from the evaporative to the condenser. The value for Z_5 is quite small as compared to Z_3 and Z_7.

As the magnitude of Z_4, Z_6, Z_5 and Z_{10} is negligible therefore these are generally neglected in the analysis. Thus the overall thermal resistance is given by:

$$Z_t = Z_1 + Z_2 + Z_3 + Z_7 + Z_8 + Z_9 \quad (8)$$

2.2 Thermoelectric Generator

In remote areas, where the electric grid is not available and the sun shines year round, combined power generation modules based on the small scale solar pond, thermosyphon and Thermo Electric Generator (TEG) is one of the viable candidates for providing daily electricity demand in such areas. A TEG has the advantage that it can operate from a low grade heat source such as waste heat energy. It is also attractive as a means of converting solar energy into electricity. The schematic diagram of the TEG is shown in Fig 3. It consists of two dissimilar materials, n-type and p-type semiconductors, connected electrically in series and thermally in parallel.

Heat is supplied at hot side at temperature (T_{hs}) while the other end is maintained at a lower temperature (T_{cs}) by a heat sink. As a result of the temperature difference, current (I) flow through an external load resistance (R_{ex}). The power output depends on the temperature difference, the properties of the semiconductor materials and the external load resistance.

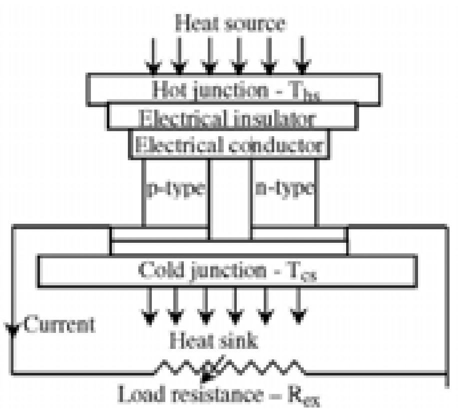

Fig.3. Schematic diagram of the Thermo Electric Cell

Each thermoelectric element is assumed to be insulated, both electrically and thermally, from its surroundings, except at the junction to hot/cold reservoir contacts. The internal irreversibility for the TEG is caused by Joule electrical resistive loss and heat conduction loss through the semiconductors between the hot and cold junctions. The Joule losses generate internal heat equal to I^2Ri where I [A] is electric current generated by thermoelectric generator, R_i [Ω]is total internal electrical resistance of the thermoelectric generator. Conduction heat loss is $k_{teg}(Ths - Tcs)$ where, k_{teg} [W/m.K] is thermal conductivity of thermoelectric generator. The external irreversibility is caused by finite rate heat transfers at the source and the sink.

3.Proposed System Description

The schematic of the proposed power generation unit is shown in Fig 4. Here a thermosyphon, which is basically an evacuated copper tube charged with water as the working fluid, is held vertically and is long enough to connect the bottom convective zone of the pond to the top convective zone. In the same figure a typical temperature profile is also given. It is seen from this profile that the temperature is low and uniform in the top zone. This uniformity is caused by the wind-induced wave actions near the top. In this zone the temperature follows closely the daily average ambient temperature. In the middle layer of the pond, where the convective currents are suppressed because of the existence of a strong salinity gradient, the temperature rises continuously until it reaches a maximum near the interface with the lower layer. In the bottom layer the temperature is also uniform as in the top layer. The mixing in the bottom zone is primarily due to the absorption of solar radiation by the dark bottom of the pond, and the convection currents that are thereby induced. Therefore the non convecting middle layer, which is sometimes called the gradient layer, separates the upper zone (cold) and the bottom zone (hot). Some typical thicknesses for these three layers are: 0.2m to 0.6m for the top layer, 1m to 2m for the middle layer, and 0.5m to 5 m for the bottom layer.

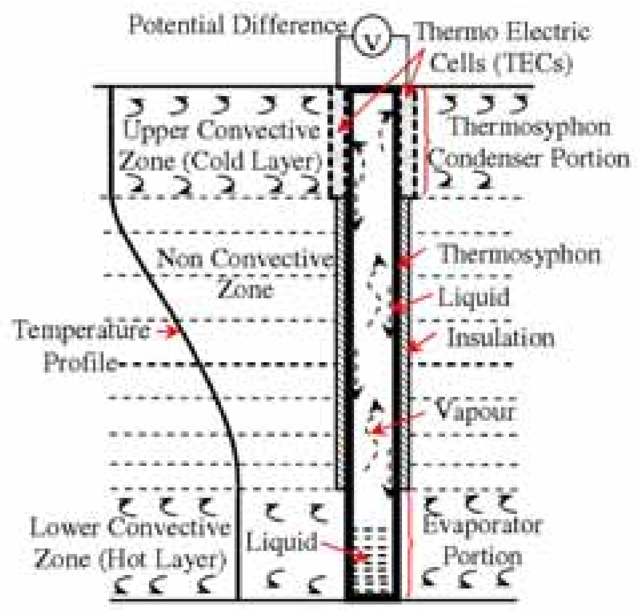

Fig.4. Schematic showing the concept of generating electric power from salinity gradient solar pond using a combination of thermosphon

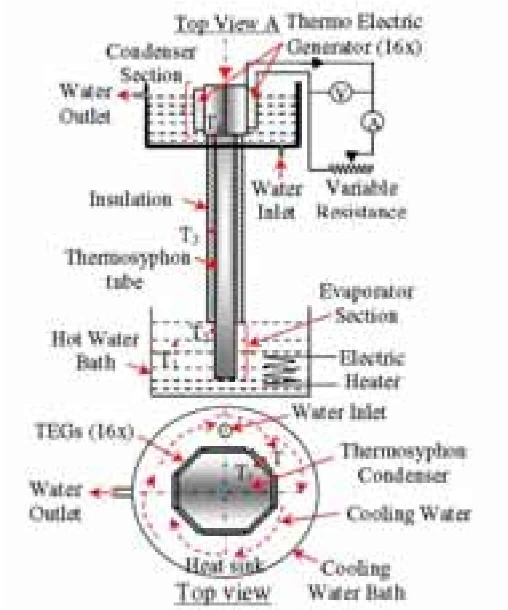

Fig.5.Tests assembly to simulate the operation of the combined of thermosphon and thermoelectric cells under solar pond conditions

The middle section of the thermosyphon (adiabatic section) is insulated to prevent heat losses from the thermosyphon to the surrounding water in the gradient layer, which is at a lower temperature than the bottom layer. The thermoelectric cells are attached to the top part of the thermosyphon (condenser section) with a good thermal bond. The other side of the cells is cooled by the cold and convective currents available in the top convective zone. Therefore the required temperature difference for power generation is created on the two sides of the thermoelectric cells.

3.2 Working

The working fluid is continuously evaporated in the evaporator and the resulting vapor travels upward because of the lower pressure in the condenser section caused by a lower temperature. The vapor is then condensed releasing its latent heat, which is transferred to the sides of the thermo electric cells attached to the thermosyphon. The resulting condensate travels downward because of gravity. As a result the two sides of the cells are maintained at different temperatures, and hence an electric potential difference is generated across the cell. On applying an external electric load, an electric current is produced and electric power generated. The produced electric power can be directly used for applications requiring direct current, or converted into alternating current if needed. The electric energy thus produced can be also continuously stored in batteries to provide power to intermittent loads, which may have a higher demand than the capacity of the thermoelectric cells for a period of time.

4. Laboratory Testing and Results

In order to test the viability of the proposed system of power generation some preliminary tests were performed. Suitable thermoelectric cells that can be used for power generation were obtained from Kryotherm Ltd, Russia [7]. These cells are 40 mm by 40 mm and have a thickness of 3.9 mm. Sixteen TEG cells were subjected to temperature differences of the order that can exist between the top and the bottom of solar ponds. It was shown that for a temperature difference of 20°C a voltage of 1.1volt could be created under no electric load condition. Attempts were made to produce power under the applied temperature difference. It was found out that a power of 0.12 W can be generated with a voltage of 0.51 volts and current of 0.24 Amps. No attempts were made at this stage to measure the energy efficiency of the cell.

Indoor laboratory tests were also carried out on a combined system of thermosyphon and thermoelectric cells to simulate the operation of the system when installed in the solar pond. For these purpose a thermosyphon was made from a 100 mm diameter copper tube with a total length of 2m. The thermosyphon was charged with water as the working fluid. The schematic of the prototype and the test rig is shown in Fig 5. As seen in the figure the thermoelectric cells are attached to the top part of the thermosyphon. This is the part that will be in the top convective zone of the solar pond which is the heat sink. As shown in the Fig 5, the lower section is heated by a hot water reservoir. This results in the heating of the inner side of the thermoelectric cells through the thermosyphon. The outer sides of the cells are cooled by flowing water that simulates the cooling effect of the top layer of the solar pond. Fig 6 shows the test results on the Thermosyphon Thermoelectric Module (TTM) for different heat source temperature (i.e. hot water bath temperature, T_2). On the figure, the temperature difference achieved across the TEG (ΔT_{TEG}) when the water bath temperature is changed from 50 to 90 °C is mentioned (with the top curve corresponding to the 90 °C). It can be seen from the graph that the power generated by the TTM module increase with the increase in the temperature across TEG which tracks the increase in the temperature of the hot water bath. Here, the temperature of the hot water bath simulates the temperature of the bottom dense layer of the solar pond. For each setting of evaporator temperature (T_2), the maximum power point for the TTM system was achieved by changing the external resistance - R_{ex} (or load). For evaporator surface temperature of 90°C, maximum power of 3.2 W was generated by the TEG units. It should be noted that the temperature across the TEG does not increase in the same proportion as the water bath temperature due to the limited cooling on the cold side of the TEG.

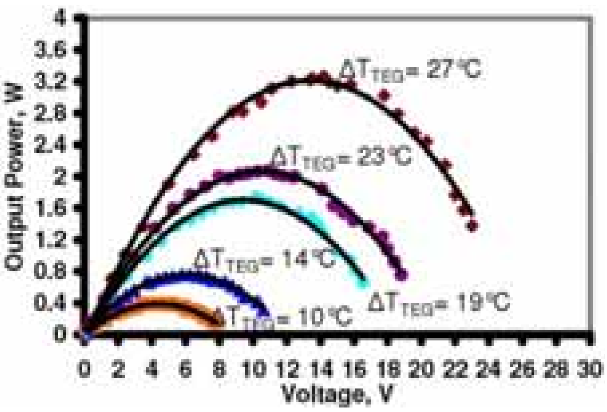

Fig.6. Dependence of output power on ΔT across TEG and external resistive load

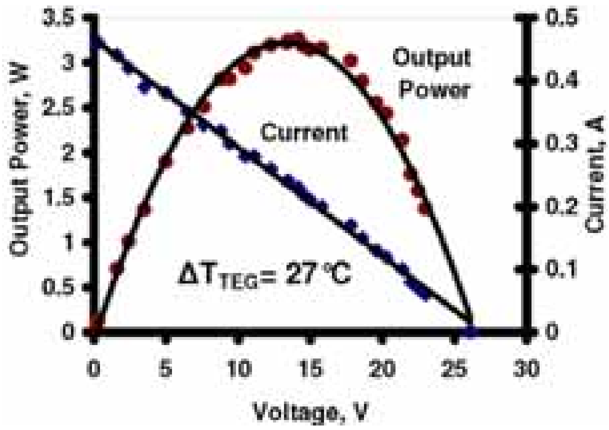

Fig.7. V-I Characteristics and Power Output for 90°C Hot Bath Temperature and 27°C ΔT across TEG respectively

Fig 7 shows the V-I characteristics of the TEG units for hot water bath temperature of 90°C and temperature difference of 27°C across TEG. In this case, the open-circuit voltage and the short circuit current values of 26 V and 0.4 A respectively were obtained. As seen from the Fig 7, the power curve is parabolic in shape with maximum power point of 3.2 W obtained at 13.4 V and 0.24 A. In contrast to photovoltaic cell, the maximum power point of the thermoelectric module is always obtained at half the open circuit voltage due to the linear $I - V$ characteristics. This emphasises the importance of internal resistance in determining the performance of thermoelectric device.

Attempts are made to utilize the existing data available for off-the-shelf thermoelectric cells and design a thermosyphon heated thermoelectric module (TTM) that can be used as a building block for power generation from salinity gradient solar ponds. For this purpose use is made of the commercially available cells such as TGH-199-1.4-0.8 produced by KRYOTHERM [7]. These cells are 40 mm by 40 mm and have a thickness of 3.9 mm. According to the manufacturer these cells can produce 3.2 W at a voltage of 2.6 V if the cold side is maintained at 50°C and the hot side at 150°C. The stated efficiency for these conditions is 3.8 %. Under solar pond conditions the efficiency would be lower than this. By using a number of the above cells in series one would be able to design a TTM suitable for battery charging (12 V) using the heat from the bottom of the solar pond. The output power of the unit can be between 10W to 20W under normal conditions of the pond. The rate of heat transfer through each TTM is estimated to be about 1 kW for a 10 W unit; that is, the energy efficiency of the conversion is around 1%. A number of the above TTMs can form the power supply system for a small house. For example for a small energy-efficient house, the needed electrical energy can be as low as 2 kWh per day. Since the TTM works day and night then a total number of 10 units would be required to power the house. It should be noted that a suitable coating needs to be applied to the TTM to protect the device against the salt environment.

5. Conclusion

It has been shown that by combining thermosyphon and thermoelectric cells it is possible to produce a fully passive and simple power supply system for remote area applications using the temperature differences that exists in a typical solar pond. These devices will be most suitable for small-scale applications of solar ponds for power generation. The thermosyphon-heated thermoelectric module is easy to manufacture and mostly uses off-the-shelf components.

References

[1] Akbarzadeh, A, Andrews, J, and Golding, P.2005. Solar Pond Technologies: A Review and Future Directions, Chapter 7, Advances in Solar Energy, EARTHSCAN.
[2] Tabor, H and Doron, B. 1986. Solar Ponds- Lessons learned from the 150 kW(e) power plant at Ein Boqek, Proc. of the ASME Solar Energy Div., Anaheim, California.
[3] Ha, B. Ormat Turbines, Arava Solar Pond Inaugurated, Sunworld, (1984)Vol 8 (1). 18
[4] Dunn, P. D, and Reay, D. A. (1994). Heat Pipes, Pergamon, Fourth Edition
[5] Rowe, D. M. 1995. CRC Handbook of Thermoelectrics, CRC Press
[6] Engineering Data Science unit No. 81038, Heat Pipes – Performance of Two-Phase Closed Thermosyphons, ESDU International Publishing, London, UK, (1983).
[7] KRYOTHERM, 6 Aerodromnaya Street, Saint-Petersburg, 197348, Russia, Tel.: (812) 394-1310, Email: info@kryotherm.ru, http;//www.kryotherm.ru