Harvesting Energy by Solar Thermo-Electric Generation in Tropical Regions

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Abstract Thermos-electric generation (TEG) is a promising technique that transforms heat into electric energy even it has low conservation efficiency. In this work, the finite element method (FEM) has been used to determine the temperature distribution in the soil also a parameter that already used to present the effectiveness of the TEG was obtained. The temperature of the soil surface and temperature at any depth was obtained together with the temperature of a plate located above the TEG device which served as a hot source. The developed sum of the square of the temperature difference between the plate and different depths multiplying by the time interval of the soil is obtained and the maximum sum is searched for to see at which time and depth should the TEG be fixed to obtain the maximum output from the TEG device. From the result of this work, it is found that the maximum sum occurred in May and at depth of 0.3 m, and also a verified program has been built and tested and can be used successfully in other regions by changing latitude, weather conditions, and soil properties.

Keywords. Thermos-electric generation, soil temperature, heat transfer, weather condition.

1. Introduction

Thermo-electric generation (TEG) is a device that directly converts the heat into electrical energy through the Seebeck effect where the heat flows through an appropriately designed device that will produce voltage and current. The probable energy crises that may face the civilized world in the future bring more and more attention to this field of science also it is a matter of power-saving if one intends to gain electrical energy from lost heat in different engineering applications. Due to the high-temperature environment in the tropical region comparing with soil temperature there, the TEG device can be used to generate electric power from these temperature differences. In the literature, many works are devoted to this subject even that this transformation has low efficiency, but due to suitable weather conditions in that region, we focused on this type of power generation and studied the possible temperature differences for this device.
Many works devoted to this subject; Lawrence E E et al [1] studied the feasibility of the TEG device, they found that a starfish shape of the heat sink in the soil gave the best performance to the TEG device. Pedro Carvalhaes-Dias et al [2] studied experimentally a TEG device that could be used to collect energy with a heat sink buried at different depths and different latitudes. Eduard Massaguer et al [3] built a solar thermoelectric generator (STEGs) to validate their one-year cycle theoretical result. They found its promising feathers technology by harvest energy using these devices, especially for off-grid applications. Peng LI et al [4] studied the concentration of sunray on the hot side of the TEG where the conversion efficiency must be chosen properly depending on the cooling method and the properties of the thermoelectric materials. They suggested that a more promising result can be expected by the development of materials that have high efficiency in the transformation of heat into electrical energy.

TEG has many applications especially in the re-use of waste heat to generate energy such as that presented by Gongyue Tang et al [5], who studied the use of TEG in harvesting power from the temperature difference between lubricating oil inside the thrusters of a marine vehicle and cold seawater. They studied the effect of different TEG parameters and working conditions on the increasing temperature gradient to increase the output power. Recently, TEG is used to supply energy in very cold and hard access locations, where solar and wind energy, are not usually available and the required temperature difference could be induced by a source of heat such as a flameless catalytic burner [6]. Finally, a good survey can be found in reference [7] that presented the recent progress and application in TEG devices.

In this work, the FEM has been used successfully to predict the temperature distribution through the soil. The temperature of a horizontal plate that receives solar rays which were used as a hot source was also calculated and the summation of the square of the temperature difference multiplying by their time interval across each depth and through different months was obtained in the tropical arid regions to determine where and when their maximum sum could occur to increase the possible output from TEG device.

2. Theory
2.1 Temperature distribution through the soil

To determine the distribution of temperature through the soil taking into account the effect of the environment, the solution of the one-dimension transient heat equation is a must. The environmental weather conditions can affect the soil by the solar radiation, the convection heat transfer between soil and the air above, re-radiation from soil surface known as longwave radiation back to the atmosphere, and water evaporation loss from the soil.

The induced heat due to horizontal solar radiation can be calculated using the standards method suggested by ASHRAE [8] and is used here where the Irradiation and the absorbed heat can be calculated taking into account the location of the studied region, see [9-12]. The external convection between air and soil was used here as suggested by the experimental work of Garzolli et al [13] that depend on the speed of the wind which is taken to be 4 m/s. This can lead to obtaining the convection heat transfer coefficient ($h_o$) and the re-radiation of heat from the soil to the environment. Following Blast program [9-10] who suggest that the Instantaneous sky temperature ($T_{sky}$) is equal to environmental dry bulb temperature minus 6 K, the soil surface emissivity can be written as $\varepsilon_s = 9.2 \times 10^4 + T_{sky}^2$ [8]. also, heat transfer due to evaporation ($E_v$) was used as a boundary condition where a complicated process of water evaporation from soil can be simulated as suggested by ref [14] which depends mainly on meteorological conditions and soil water content. It was found that in an arid region, the average value of the water content was
equal to 0.22 in winter, 0.18 in spring, 0.17 in summer, and 0.19 in autumn as measured for Baghdad city which is obtained by reference [15].

All these parameters are incorporated in the FEM solution of the transient heat equation to obtain the temp. distribution in the soil. This method of solution (i.e. FEM or analytical methods) is very well discussed in references [16-34] that could be used to obtain the temperature distribution through the studied domain. Note that the thermal soil properties are taken from reference [35].

2.2 Plate temperature

The solar radiation that absorbs by the plate can be formulated mathematically as [36]

\[ I_l = \alpha_{sun} I_{sun} = Q_h \]  

(1)

Then

\[ I_l \pm q_{co} - q_{rered} - k_p \frac{(T_p - T_o)}{L} = 0 \]  

(2)

And for small temperature gradient across the plate due to its high thermal conductivity, rearrange yield

\[ f(T_p) = I_l \pm q_{co} - q_{rered} = 0 \]  

(3)

Where Newton Raphson method can be written as

\[ T_p,new = T_p - \frac{f'(T_p)}{f(T_p)} \]  

(4)

and eq.8 can be written as

\[ I_l \pm h_o (T_p - T_{co}) - \alpha_{low\ temp} \epsilon \sigma (T_p^4 - T_{co}^4) = f(T_p) \]  

(5)

Assume the emissivity of the Aluminium commercial plate is taken to be 0.09 and for polished copper, it is equal to 0.023[24]. Assume efficient heat pipe or very high thermal conductivity material is used where the temperature difference can be ignored, then its derivative with respect to \( T_p \) is

\[ \pm h_o - 4 \alpha_{low\ temp} \epsilon \sigma (T_p^3) = f'(T_p) \]  

(6)

For flat black lacquer Aluminum plate \( \alpha_{sun} = 0.96, \alpha_{low\ temp} = 0.95 \) [36], then the radiation equilibrium temp. for a plate exposed to solar flux and convection with the surrounding can be obtained using the Newton Raphson method where the solar energy absorbed must equal the sum of the re-radiation and convection heat transfer to or from the surroundings plus the conduction heat transfer to the system which is ignored while handling the iteration.

2.3 TEG device parameters

The electrical power delivered by a TEG named \( P_{elec} \) depends on \( \Delta T^2 \) and can be written as[2]:

\[ P_{elec} = \alpha_n \alpha_p \frac{R_L}{(R_L + R_{TEG})^2} \Delta T^2 \]  

(7)

where \( \alpha_n, \alpha_p \) are the Seebeck coefficients of the n and p elements of the TEG, \( R_{TEG} \) is the output impedance of the TEG, and \( R_L \) is the impedance of the external load.
The parameters that indicate at which best location for the hot and cold source of the device must be held on is as suggested by [2]

\[ \sum (T_p - T_{\text{depth}})^2 \Delta t \]  

(8)

Where \( T_p \) is the plate temperature, \( T_{\text{depth}} \) is the temperature at any depth and \( \Delta t \) is the time interval at which these temperatures are held on.

Fig1. Scheme of a TEG

3. Result and discussion

The temperature distribution through the soil is obtained from the built program that uses the FEM to simulate the heat transfer through the soil. The result of this work was compared with the theoretical and experiential data published by ref [22] with good nearby results. The temperature distribution through the soil was obtained by taking the effect of solar radiation together with the effect of environmental and water evaporation assume the weather conditions are taken from a local weather center. Also, the program is used to obtain the temperature of the plate taking the same aforementioned boundary conditions except that the effect of water evaporation is ignored. It is found that the temperature difference across the plate using Copper or Aluminum plate does not exceed 0.2 °C and 0.3 °C for Copper and Aluminum respectively. This is due to the high thermal conductivity of these materials. This small temperature difference enables one to use eqs. (4-6) in an iteration solution to obtain the temperature of the plate using the Newton Raphson method.

The environmental, plate, surface soil temperatures at different months and soil temperature at different depths are indicated in fig.2 (a,b,c,d). These figures show that the environmental, plate, surface soil temperatures were increased as they reach the noon of the sun and were reduced thereafter. It was found also that the time required for the plate to reach its maximum temperature after the noon of the sun is shorter than that of the soil due to the high absorptivity and diffusivity of the plate material comparing with that of soil. The temperature distribution shown in fig.2 is identical to the natural phenomenon where low-temperature distribution is observed in winter and the temperature is increased as the year moved toward spring and summer and is decrease
thereafter as the year moves toward autumn and winter. By obtaining the sum in eq.11, it is found that the maximum sum occurs in May at a depth of 0.3 m which is shown in figs 3,4.

Figure 3 shows the forward sum of eq.81 which is indicated as the height of the unshaded rectangle shown in fig 3 for each month of the year. The height of the shaded area presented the reversed sum (i.e. when the soil temperature is greater than that of the plate temperature). Their sum (forward and reversed) is presented by the total height of each rectangle shown in fig 3. It is also shown that the maximum sum occurs in May, this is due to the combined effect of environmental and soil temperature. This fig also shows that the reversed heat flow, which its influence is shown as the height of the shaded area, is small compared with the forward heat flow.
Figure 4 shows the variation in the total sum of eq.8 (i.e. forward and reversed) as the depth increased where the maximum sum is tested and it is found that it occurs in May at depth of 0.3 m. Figure 5 shows the temperature of the environment, plate temperature, the temperature of the soil at the surface, and at depth of 0.3 m in May when the sum in eq.8 seems to have its maximum value where the difference between the temperature of the plate and the temperature at depth of 0.3 m multiplied by time interval seems to have its maximum value, moreover, the difference is held for a long time (i.e. from 6:30 AM to 8:00 PM) more than other shining time shown in fig.2 (a,b,c,d).

Fig 3. The sum of temperature difference square multiplying by time interval for different months through the year, the shaded zone height indicates the reverse sum of square temperature difference. The white rectangle zone height indicates the sum for forward heat flow

Fig 4 The sum of temperature difference square multiplying by time interval for different depths in May, the solid line indicates the monthly sum as the depth increased, the long dashed line indicates the revised monthly sum, the small dashed indicates their total sum.
4. Conclusions

A numerical solution of a one-dimension heat transfer equation using FEM was used to determine the temp. distribution through the soil in the tropical zone also the temperature of a plate located horizontally in the space above the TEG device is obtained. The plate was regarded as the hot source in the device and an iteration solution is used to determine its temperature after it was tested by the built program and it is found that a very small temperature difference is established while using a material such as (Al or Cu). Searching for the maximization of temperature difference in TEG (in-depth and month) is the main aim of this work. We seek for the nearest depth to the soil surface where the maximum temperature difference between the horizontal plate that receives solar radiation and the in-depth soil temperature is found to occur at depth of 0.3 m.

The maximum temperature difference throughout the year is searched for where it is found to occur in May. This depends mainly on the location and the environment there. Other locations can easily be tested by changing the latitude and environmental weather conditions in the built well-verified program.

Fig 5. Environmental, plate, surface soil temp. and temp. at depth of 0.3m on 21 May

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