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Prospects of Power Generation from Geothermal Energy Using Thermoelectric Modules

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ABSTRACT

This paper presents the prospects of power generation from geothermal energy using thermoelectric modules. A heat exchanger thermosiphon with a number of thermoelectric cells is proposed for this research. Thermosiphon heat exchanger is a passive device that can transfer heat from a hot reservoir to a cold reservoir. The heat from the geothermal source is transferred to the liquid in the thermosiphon. The liquid absorbs the heat and changes to vapour phase. The vapour then travels to the heat exchanger and transfers heat to the thermoelectric cells by condensation. Thermoelectric cells generate electricity when a temperature difference is created across these generators due to Seebeck effect. The hot and cold surface of these generators generates electrical potential and current flows when a load is applied. These thermoelectric cells are silent due to the absence of moving parts, scalable to meet any power demand and require no maintenance. The proposed system is able to generate electricity at an overall efficiency (thermal to electricity) of 8- 9%. The cost of power generation is in the range that can be competitive to other power generation plants. The proposed system can be used as an environmental friendly and sustainable alternative to other power generation systems.

1. INTRODUCTION

As earth itself is a reservoir of energy, geothermal energy has been developed and applied in electricity production and geothermal heating for either domestic or industrial purpose. Conventionally, the electricity production by using geothermal energy involves the transfer of hot water hot steam via production well to power the turbine and produce electricity before the water returned to the ground. As a result from energy crisis during 1970's, the pressure of searching for alternative energy sources rose and the renewable energy harvesting activity has become active since then. With the escalating demand of energy supply each year, the greenhouse gas emissions will keep on increasing in the long run (Khan et al., 2014; BP, 2013). Thus, the effort in fostering green, renewable energy will certainly mitigate the increasing trend of greenhouse gasses emission.

Renewable energy supplies around 17% of the global energy consumption (Panwar et al., 2011). On the other hand, geothermal energy comprises around 2% of the renewable energy generation (Pazheri et al., 2014). In the current global scenario, the US is the top country in utilising geothermal power generation in terms of plant capacity. Despite of the comparatively lower conversion efficiency of geothermal power plants compare with other conventional power plants, the energy costs for a geothermal power plant is among the lowest compared with other source of renewable energy (Fridleifsson, 2003). The highest conversion efficiency reported is around 21% at Darajat, Indonesia, which is a dry steam plant (Zarrouk and Moon, 2014). Furthermore, as surveyed, geothermal energy possesses the potential of producing 240GW of electrical energy (Pazheri et al., 2014). To date, biomass energy, solar energy, and wind energy constitute the major portion of scientific research with a growing number of research studies carried out. Geothermal energy, on the other hand, constitutes 5% of scientific studies in renewable energy, led by U.S. Geological Survey (Manzano-Agugliaro et al., 2013). In spite of a low research effort, some studies have been conducted on the prospective of developing geothermal power in (geologically) unusual places such as Pakistan (Abbas et al, 2014) and Saudi Arabia (Lashin and Al Arifi, 2014), in addition to the ongoing geothermal power plant developments such as in Turkey (Aksoy, 2014) as well as the study of a hybrid system combining solar and geothermal energy using organic rankine cycle in Australia (Zhou, 2014).

Hence, recognising the prospect of developing and making use of the geothermal energy, a heat exchanger module for the electric power generation from geothermal energy using thermoelectric cells (TECs) is proposed. Comparing with the conventional methods of generating electricity from geothermal energy using turbine and generator, the thermoelectric method requires fewer moving parts (reduction of mechanical devices) and easing the burden of carbon tax due to CO_2 gas emission. However, the major drawback of the thermoelectric system is its limited efficiency. The heat from the geothermal region is transferred from the ground using a thermosiphon. A thermosiphon is areliable and static, and requires no mechanical devices in transferring the heat by using the natural convection and condensation principles of a boiling working fluid.

2. THE PROPOSED SYSTEM- GEOTHERMAL TEC SYSTEM

2.1 The Structure

The proposed system is illustrated in Figure 1. The system consists of a thermosiphon heat exchanger, slightly inclined with an angle α, extended into a geothermal region in the earth in order to extract the heat from that region. The liquid under vacuum boils and undergoes phase change and becomes vapour. Due to the density variation, the vapour moves upward and exchanges heat with the stainless steel tube before being condensed and returned to the hot geothermal region.

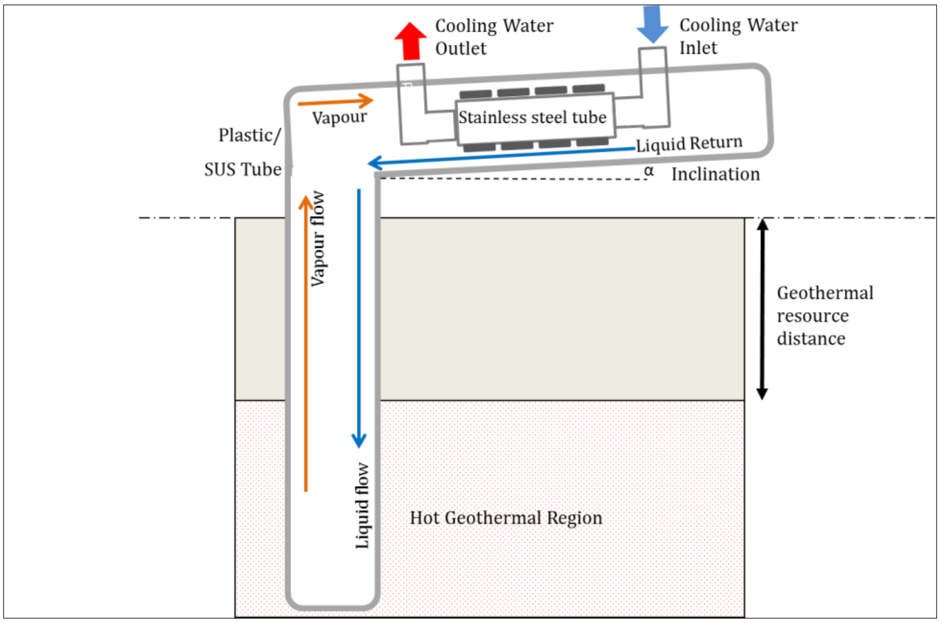

Figure 1: Overview of the proposed system.

The concept of the cooling system is shown in Figure 2, representing the system in which the TECs are attached. The TECs are attached on the outer surface of a polygonal stainless steel tube of diameter, D and length L (in the current example, a hexagonal tube is shown). In order to exchange heat with the hot vapour flowing from the geothermal region, the vapour is being cooled by the cold water flowing at a mass flow rate of $\dot{m}$ inside the stainless steel tube which serve as a heat sink. Hence, a temperature differential of ΔT is created across the TECs.

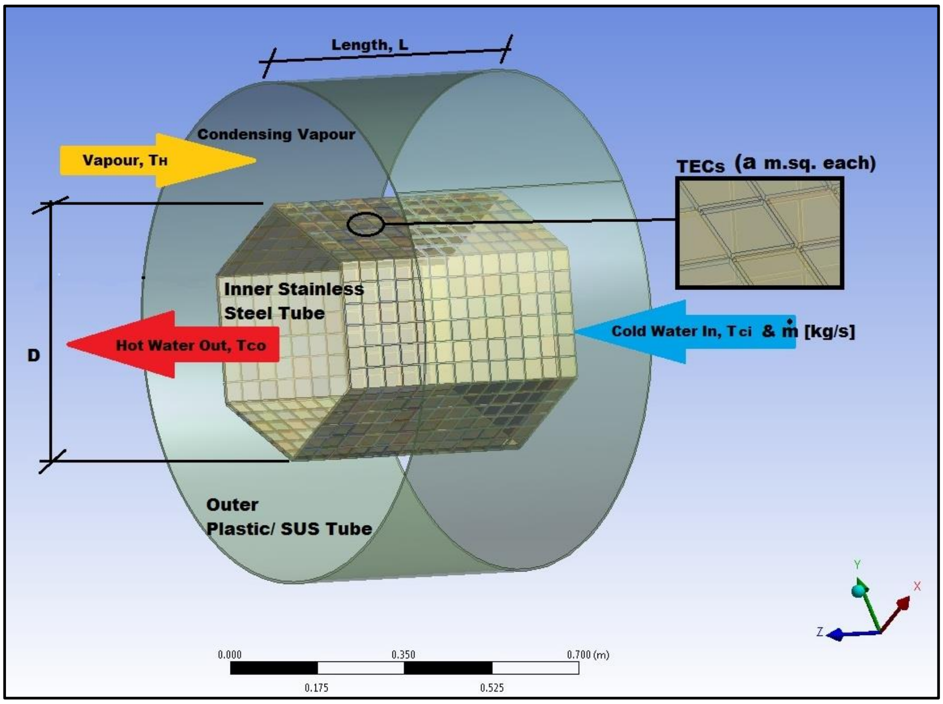

Figure 2: The heat exchanger system.

2.2 Thermal Analysis of the System

The TECs are attached on the surface of a polygonal stainless steel tube. Assuming the stainless steel tube is perfectly sealed and fully covered by the TECs, it results in a heat exchanger with an area of $A = N \times a$ which is the product of the number of TECs, N and the surface area of individual TEC of a . Thus, for a cross-flow heat exchanger system, the heat transfer across the heat exchanger is equivalent to:

$$\dot{Q} = UA\Delta T_{LMTD} \tag{1}$$

where ΔT_{LMTD} is the log-mean temperature difference for the heat exchanger, being defined as

$$\Delta T_{LMTD} = \frac{(T_H - T_{ci}) - (T_H - T_{co})}{\ln \frac{(T_H - T_{ci})}{(T_H - T_{co})}} \tag{2}$$

The overall heat transfer coefficient for the area of a, takes into account the thermal resistance of the stainless steel and TEC (Figure 3). Hence, the resulted overall heat transfer coefficient becomes $U = \frac{1}{R_{total} \times a}$. Alternatively, Equation (1) can be represented as:

$$\dot{Q} = \frac{N}{R_{total}} \Delta T_{LMTD} \tag{3}$$

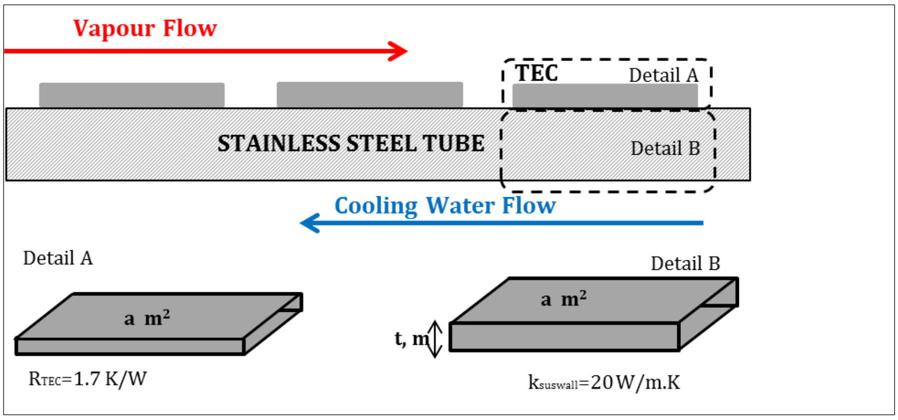

Figure 3: Close-up of the heat exchanger system.

2.3 The Electrical Power Generation

The power generated by each individual TEC, is defined as:

$$TEC_{power} = \beta \Delta T \tag{4}$$

From Equation (4), β representing the power coefficient, indicating the electrical power generated per unit temperature difference between the hot and cold sides of the TEC. Given that the heat transfer per module,

$$\dot{q} = \frac{T_H - T_C}{R_{total}}, \tag{5}$$

and due to

$$\Delta T = \frac{T_H - T_C}{R_{total}} R_{TEC} \tag{6}$$

we are able to redefine Equation (4) as follows:

$$TEC_{power} = \beta R_{TEC} \dot{q} \tag{7}$$

Note that in such a case, we should not confuse between ΔT which is the temperature difference of hot and cold surface of TEC and $T_H - T_C$ which is the temperature difference for hot vapour and cooling water. In the other words, typically, $\Delta T < T_H - T_C$.

3. CASE STUDY FORMULATION

In order to proceed with the parametric study of the system, we need to estimate the thermal resistance of the system. Besides thermal resistance from the TEC and stainless steel tube wall, we shall take into account the condensation resistance by the vapour, and the cooling water convection resistance.The total thermal of the resistance is,

$$R_{total}=R_{suswall}+R_{cond}+R_{conv}+R_{TEC}=\underbrace{\frac{t}{k_{suswall}}}_{R_{suswall}}a+\underbrace{\frac{1}{h_{cond}a}}_{R_{cond}}+\underbrace{\frac{1}{h_{conv}a}}_{R_{conv}}+R_{TEC} \quad (8)$$

By referring to the thermal characteristics of stainless steel tube as indicated in Figure 3 and assuming $t=0.05$ m and $k_{suswall}=20$ W/m-K, the estimated $R_{suswall}$ is equivalent to 0.15 K/W. The R_{TEC} value of 1.7 K/W is obtained from the result of laboratory testing by authors. Assuming the heat transfer coefficient for the flowing condensing vapour and the flowing cooling water as 2000 W/m^{2}K and 1000 W/m^{2}K, respectively, the R_{cond} and R_{conv} are equivalent to 0.3 K/W and 0.6 K/W. Consider a commercially available Bi_2Te_3 TEC with surface area, $a=0.04\times0.04=0.0016$ m^2. Summing up the thermal resistance by each component, the theoretical value for the overall thermal resistance flowing through each TEC is 2.75 K/W. Besides the aforementioned thermal resistance, other parameters and fluid properties are given in Table 1 below.

Table 1. Geothermal TEC system parameters and fluid properties.

Parameters	**Values**
TEC dimension, a	0.04 × 0.04 m^2
Cold water inlet temperature, T_{ci}	10°C
Cold water outlet temperature, T_{co}	Variable (15-100°C)
Geothermal temperature	220°C
Temperature difference across heat pipe	50°C
Vapour temperature	170°C
Heat from geothermal, $\dot{Q}$	20MW
Diameter of stainless steel tube, D	0.5m
Power coefficient, β	0.032W/K
Water: i. Specific heat capacity, C_P ii. Density, ρ iii. Dynamic viscosity, μ	4200 J/kg.K 1000kg/m^3 0.0010015 Pa.s

3.1 The Total System Power and Electric Efficiency

The total electrical power generated by the system, is:

$$TP=\beta\frac{N}{R_{total}}R_{TEC}\Delta T_{LMTD} \quad (9)$$

as derived from Equation (3) and (7). Meanwhile, the efficiency of the system, η which is an indicator for the amount of the total electrical power converted per unit heat input, is defined as follows:

$$\eta=\frac{TP}{\dot{Q}}=\beta R_{TEC} \quad (10)$$

From Equation (10), the efficiency of the system is only dependent on the thermal resistance of the TEC and the power coefficient of the cell. Figure 4 shows the theoretical total power output and the electric efficiency of the system, indicating that the maximum efficiency for the system is about 9%. With a maximum efficiency of 9%, a rough estimation of the electric power generated from the system is 1800kW.

In any Carnot cycle, the efficiency of the system is always less than the Carnot efficiency, given by:

$$\eta_{carnot}=\frac{T_{hot}-T_{cold}}{T_{hot}} \quad (11)$$

for the case of TEC, the maximum efficiency of the system is,

$$\eta_{TEC} = \frac{T_{hot} - T_{cold}}{T_{hot}} \frac{\sqrt{(1+Z_c\overline{T})}-1}{\sqrt{(1+Z_c\overline{T})}+(T_{cold}/T_{hot})} \tag{12}$$

and the value of $\overline{T}$ is the average of T_{hot} and T_{cold}. $Z_c\overline{T}$ corresponds to the dimensionless figure of merit of the TEC material. In the current case study, the $Z_c\overline{T}$ for Bi_2Te_3 is taken to be 0.8.

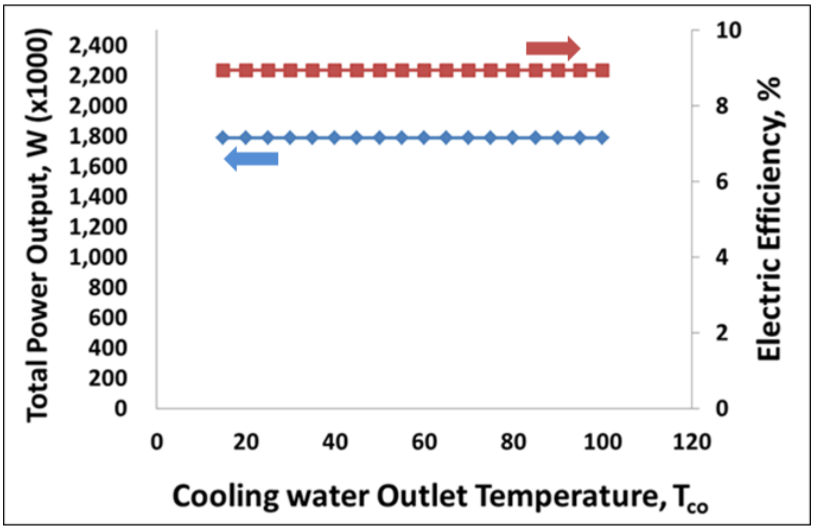

Figure 4: Total power output and the electric efficiency of the system.

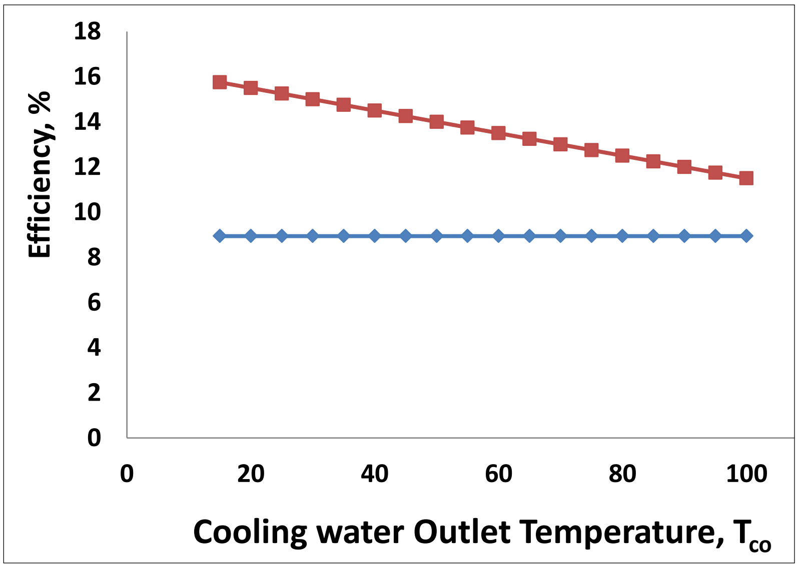

Figure 5: Number of TEC required against cooling water outlet temperature.

3.2 Number of TECs and Length Required

By using the relation stated in Equation (3),

$$N = \frac{\dot{m}R_{total}C_P(T_{co} - T_{ci})}{\Delta T_{LMTD}} = \frac{\dot{Q}R_{total}}{\Delta T_{LMTD}} \tag{13}$$

the graph for number of TECs against the cooling water outlet temperature is plotted. As the number of sides of the polygon increases, the surface area for the polygonal tube will approximate to the surface area of a circular cylinder with diameter, D. Hence, we can approximate the heat exchanger length by:

$$L = \frac{\dot{Q}R_{total}a}{\pi D \Delta T_{LMTD}} \tag{14}$$

As the cooling water outlet temperature increases, the number of TECs required increases as the effective temperature difference, indicated by ΔT_{LMTD} decreases. Hence, in order to exchange a fixed amount of heat input, more units of TEC are required and at the same time, a longer heat exchanger is needed. As shown in Figure (6) and Figure (7), depending on the cooling water outlet temperature ranging from 15-100°C, the number of TECs needed ranges from 350,000 to 520,000 (40mm × 40mm × 3.2mm dimension of each) or equivalent to a total heat exchanger length of 350m to 520m.

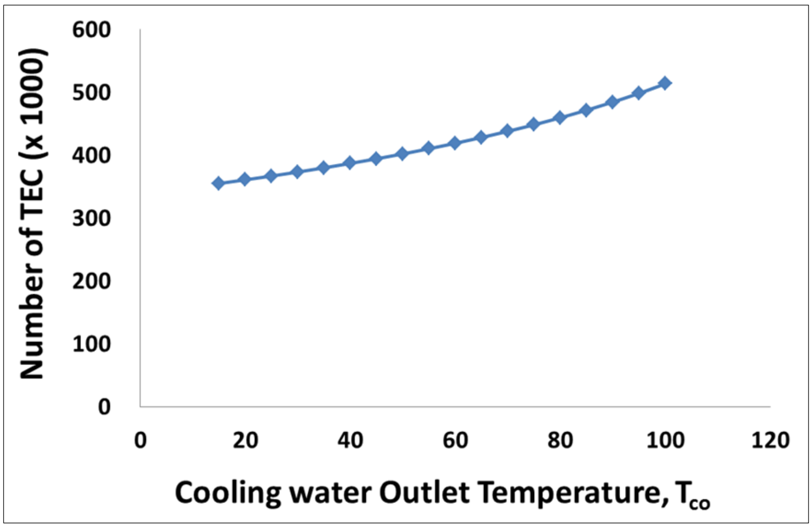

Figure 6: Number of TEC required against cooling water outlet temperature.

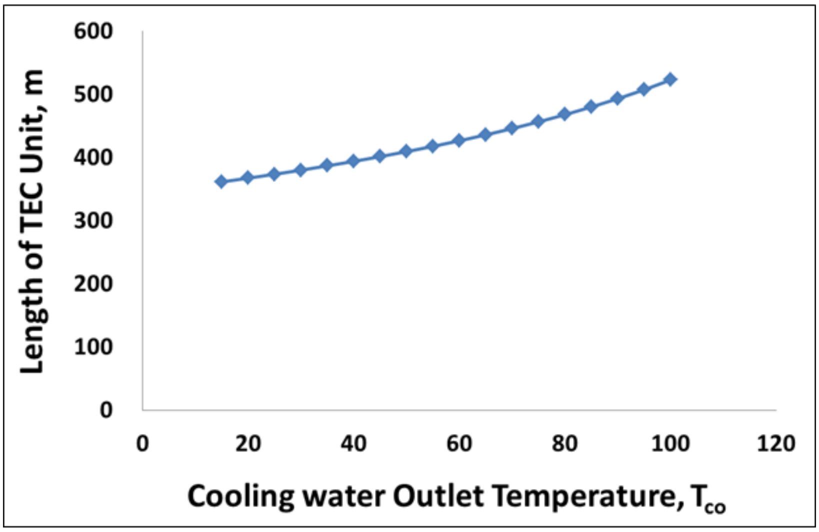

Figure 7: Length of the heat exchanger unit against cooling water outlet temperature.

3.3 Cooling Water Flow Rate and Pumping Power

By assuming a sensible heating process, the mass flow rate, volume flow rate and velocity of the cold fluid can be calculated by:

$$\dot{m} = \frac{\dot{Q}}{C_p(T_{co} - T_{ci})} \quad (15)$$

$$\dot{V} = \frac{\dot{Q}}{\rho C_p(T_{co} - T_{ci})} \quad (16)$$

$$v = \frac{\dot{Q}}{\frac{\pi}{4} D^2 \rho C_p(T_{co} - T_{ci})} \quad (17)$$

A pump is needed in order to compensate the losses in the cooling water tube, hence,

$$P_{pump} = \Delta P_{losses} \dot{V} \tag{18}$$

From Figure (8), the cooling water mass flow rate increases sharply when the $T_{co} \leq 20°C$. Such a large increment in the mass flow rate will require larger pumping power, in order to overcome significant pressure losses in the system. If the system is designed to accommodate the cooling water outlet temperature of 25°C, pumping power of 3.25kW is required (Figure 9). Further increment of cooling water outlet temperature will reduce the pumping power further.

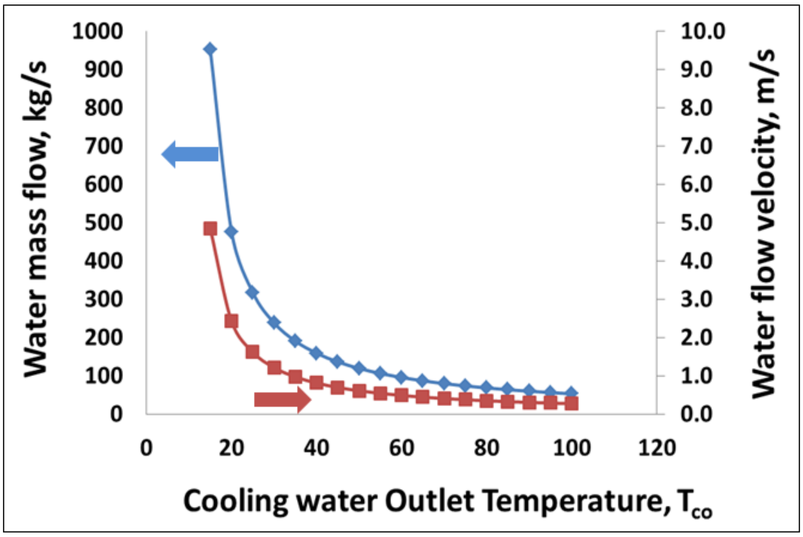

Figure 8: Water mass flow rate and water flow velocity required for given cooling water outlet temperature.

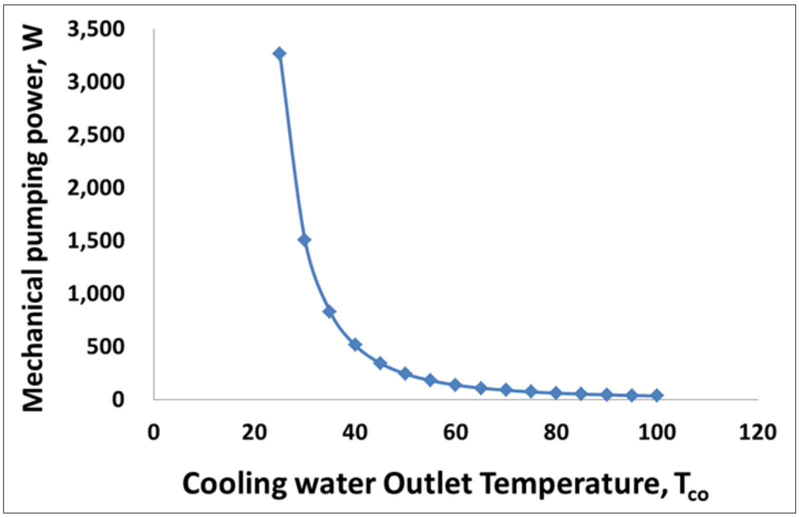

Figure 9: Mechanical pumping power required for given cooling water outlet temperature.

3.4 The Cost for TECs

The total cost of the setup, which is mainly attributable to the cost of the TECs, is approximate by:

$$TC = Nd = \frac{TP}{\beta \Delta T_{LMTD}} \frac{R_{total}}{R_{TEC}} d \tag{19}$$

and the cost per unit output power is:

$$\frac{TC}{TP} = \frac{d}{\beta \Delta T_{LMTD}} \frac{R_{total}}{R_{TEC}} \tag{20}$$

The total cost and the cost per unit output power escalates for higher cooling water outlet temperature, which is in accordance with the findings in Section 3.2. From the range of T_{co} studied, the cost per unit output power is within 1 USD/watt to 1.5 USD per watt (with single TEC cost of 5 USD).

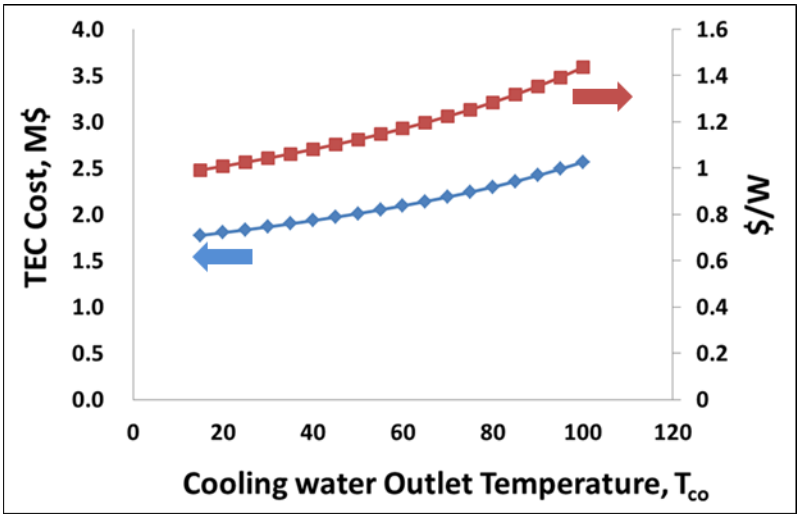

Figure 10: The cost of TECs and cost per unit power for the system.

3. CONCLUSION

A system of power generation from geothermal energy using TEC is proposed. The proposed system is designed in such a way that it is able to produce 1800kW of electric power, with an overall efficiency of 8-9%. Cooling water outlet temperature serves as a parameter on the sizing of the heat exchanger system for TECs in this study. Low cooling water outlet temperature will result in a large increase in mechanical pumping power although the number of TECs and the cost per unit output power will reduce. The cost per unit output power for the system proposed is around 1 USD/watt to 1.5 USD/watt.

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