Usage of thermoelectric generator for water surface drones

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***Abstract*— This report discusses a design of using peltier array as thermoelectric generator for motoring an autonomous water drone to test water quality in lakes and rivers. An efficient solar collector plate on the top-facing surface of the drone is designed and is set to achieve a temperature difference of 30 to 50 degrees Celsius relative to the water body underneath. The energy harvested from this temperature difference will power sensors for monitoring the health of lake or river water ecosystem. Aspects such as the peltier array, physical exterior and electrical designs for this drone are described in this report.**

I. INTRODUCTION

Worldwide over 780 million people do not have access to clean drinking water [1]. Pollution and high levels of dangerous bacteria are often the cause of unsafe water. The Yangtze river, the longest river in China, provides 20% of the countrys water but is polluted with fluoride to the point of being undrinkable without treatment [2]. These dangerously high levels of fluoride can lead to bone disease in children. In Nepal, the fresh mountain water is often contaminated with E.coli from livestock that live upstream. Some strains of E.coli bacteria cause kidney failure, which leads to death. Levels of chemicals and organisms in water can vary day to day depending on air pollution, runoff from rain water and some days being significantly more dangerous than others.

Despite efforts in many of these places to improve water quality, many times the issue is too severe and funding is too low for anything substantial to be done. Communities who rely on unclean water sources are often aware the water source is not safe but they have no other options. By providing daily measurements to these communities they would be able to determine when drinking water should be collected. To accomplish this task, our team has designed an autonomous water drone. Water drones has been the subject of many engineering research because of their ability to constantly monitor the water with little continuous effort, and the ability of robots to navigate. This water drone is powered by peltier elements and equipped with a pH sensor. The water drone is to be placed in a river, navigate autonomously, and read pH levels. The water drone will then send a signal indicating the pH level. The goal is to inform communities who rely on rivers for drinking water when the water is suitable to drink.

II. PROPERTIES OF PELTIER ELEMENTS

The foundation of this project are peltier elements. A Peltier array acts as a power source to provide power to the motor and sensor. The functionality of peltier elements are introduced in this report with a special focus on the thermoelectric generator. Furthermore, the electrical characteristics of a peltier element are described and explained.

A. The effect of temperature difference

The peltier element is a thermoelectric device which can be utilized for two different functions [3]:

- It can be a thermoelectric cooler/heater, which converts electrical voltage in a temperature difference. As a result, one side is hot and the other one is cold.
- It can be a thermoelectric generator (TEG), which converts temperature differences in electrical voltage.

For this project the function as a TEG is crucial, since it is the power source for the whole setup.A peltier element contains several n-type and p-type-semiconductors, which are alternately connected via a metal-bridge on the top and bottom side [3]. The connection between two semiconductors with different energy levels of the conduction band is fundamental to the thermoelectric function. The semiconductors are joined in parallel thermally and in series electrically. The two ceramic plates isolate the whole system.

The generation of electrical voltage is called Seebeck effect. Due to the temperature difference between the plates, electrons receive thermal energy at the hot side and a thermal gradient is present. The electrons are energized and flow towards the cold end. As a result, the cooler side has a higher density of charge carriers than the hot side; for n-type electrons and for p-type holes [3]. Since charge separation exists, an electric field is built up. If it is connected with a conductor, direct electrical current (DC current) flows through this circuit [3]. The direction of the electrical current is the opposite of the electron flow.

B. Electrical characteristics of the peltier element as a TEG

There are three main parameters of a TEG module [4] :

1) The Seebeck-coefficient $\alpha = \alpha_p - \alpha_n [\frac{V}{K}]$, which depends highly on the thermoelectric material used in the semiconductors. It is a measure for the magnitude of the voltage, induced by the temperature difference. α_p represents the coefficient of the p-type semiconductor and α_n is the coefficient of the n-type semiconductor.
2) The resistance $R_{in}[\Omega]$ includes the resistance of the p-n semiconductors and the resistance of the contact used to connect the TEG to the load.
3) The internal thermal resistance $\theta_m[\frac{K}{W}]$ and the contact thermal resistance $\theta_C[\frac{K}{W}]$. Both are used to describe the heat flow in the module.

In general, the output voltage depends mainly on the temperature difference. To implement the TEG module in an equivalent circuit, both thermal and electrical characteristics need to be included [4]. However, in this project the focus is on the application and not on the analysis of the TEG module. Furthermore, a constant temperature gradient is assumed, since the distance between the two plates is not changing and apart from the warming up and cooling down phase of the top side, both sides have constant temperature during a specific time period. The contact thermal resistance is neglected to simplify the analysis of the electrical behaviour [4].

Taken all the above points into account, following relations can be formulated:

$$V_{module}|_{\theta_c=0,\Delta T'=constant}[V] = \alpha\Delta T' = \alpha\Delta T \quad (1)$$

$$R_{module}|_{c=0,T'=constant}[\Omega] = R_{in} \quad (2)$$

$\Delta T = T_H - T_C[K]$ is the temperature difference between the bottom side of the top and the top side of the bottom. $T_C[K]$ and $T_H[K]$ are the actual temperature, which are seen by the module. $T' = T'_H - T'_C[K]$ is the temperature difference of the outer part. $T'_C[K]$ and $T'_H[K]$ are the external temperature of the hot side and cold side. Since θ_c is zero, ΔT is equal to $\Delta T'$.

With both formulas and the assumptions, it is possible to create an equivalent electrical circuit for the TEG: an ideal DC voltage source V_{module} with an internal resistance R_{module}.

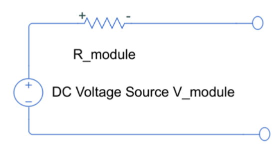

Fig. 1. Equivalent circuit of the TEG

III. Setup of the Drone

The final objective for this device is to become an automated water sensor drone for lake or river surfaces. A schematic for this envisioned device is provided in the sketches below.

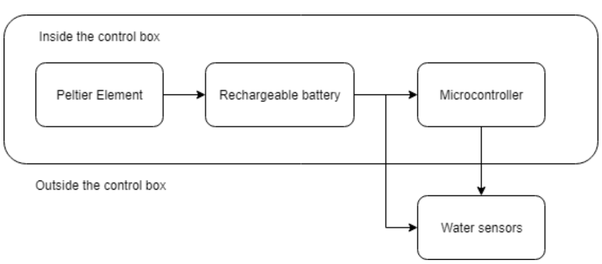

Fig. 2. Schematic of drone systems

A. Physical setup description and rationale

Figure 2 describes the concept of the drone. The energy generated from the Peltier elements is stored using a rechargeable battery, which then powers the water sensors at a time interval. A microcontroller helps to manage this time interval and to record the measured data.

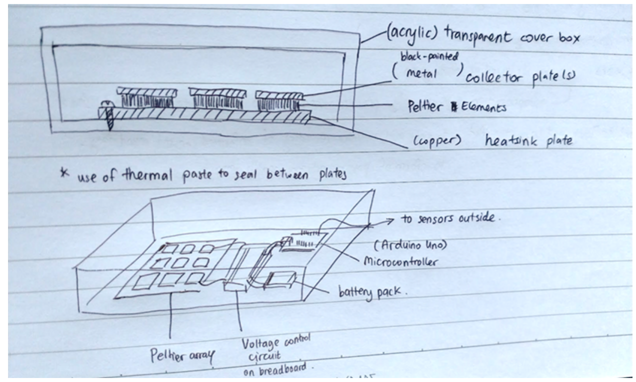

Fig. 3. Illustration of the drones control box. Suggested materials for the parts are written inside brackets.

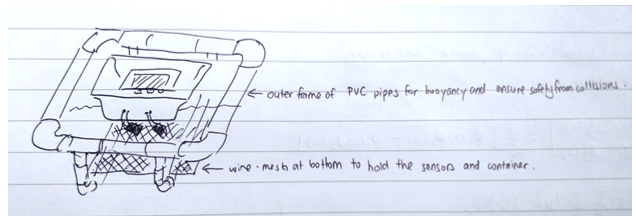

Fig. 4. Possible drone frame that provides additional buoyancy and collision protection

The collector plate and heatsink plates are attached to different sides of the peltier elements using a thermal paste, and they need to be good thermal conductors. The collector plate also require an absorptive surface to sunlight to have a larger temperature under solar heating. Selective coating of copper or aluminum plate using black chrome or black copper is ideal [5], but under cost constraints black matte paint would be a suitable replacement.

A water-tight and transparent container containing peltier elements (used as a Seebeck generator) will provide protection for the circuitry from water, as well as protecting the collector plate from wind and water to prevent heat loss from convection or water evaporation. The top-side surface can also work as glazing that reflects radiation from the collector plate.

Lastly, the control box and sensors are kept afloat by an external frame that protects the control box from collisions, as well a providing additional buoyancy. A frame constructed of sealed PVC pipes containing air is a simple and cheap solution, that can be reconstructed into different dimensions if the size of the control box changes.

B. Electrical setup description and rationale

The equivalent electrical circuit of the whole system contains three main parts:

- The TEG module, which is the main power source.
- The rechargeable battery, which is used to deliver power to the system if the TEG module does not deliver

enough power when there is no sunlight (cloudy day or during night).
- The sensor unit with a central controller. This unit monitor the different water parameters and is controlled by an Arduino, which is used on low power mode while measurements are not needed.

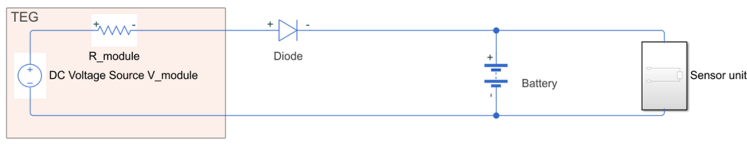

Fig. 5. Electrical circuit of the system

The sensor unit and the TEG module is connected in parallel to the battery. As in section 2 described, the TEG module is a DC voltage source with an internal resistance . There are two general cases for the electrical behaviour. First, the TEG module provides enough power to run the sensor unit. In this case, the load is the parallel connection of the battery and the sensor unit. During this time, the battery is also charged. The second case is, if the TEG module does not provide enough power. The battery is now the DC voltage source and ensure that the sensor unit is running. In order to prevent that the battery charges the TEG module, a diode is connected between the positive pole of TEG and of battery. Thus, a current flow is prevented, since the diode is reverse biased. The possible reverse current, which flows through the diode and is equal to the saturation current of the diode, is in the range of micro amperes. Consequently, this current can be neglected, and it does not affect the TEG module.

For the choice of the rechargeable battery various aspects need to be considered. The battery ought to be a low voltage battery, due to the fact, that the output voltage of the TEG module differs over the day and can be relatively small. Additionally, the battery need to have a high tolerance to overcharging, since the charge is not controlled and it is not possible to maintain the output voltage over a long time period.

IV. Collector plate sunlight heating experiment

A. *Experimental conduct*

This is the initial test for the collector plate, constructed from 0.4 mm thick Aluminum sheet, and then coated with black acrylic paint. There are two objectives to this experiment:

1) Determination of the maximum temperature achieved by black acrylic coated aluminum collector plate. This provides indication of the plates light absorbance performance.
2) Determination of voltage generated with respect to the temperature difference, to then determine the number of peltier elements is needed in an array to reach charging voltage.

The setup can be seen in figure 6. In the figure above, the peltier element is located in between two aluminum sheets,

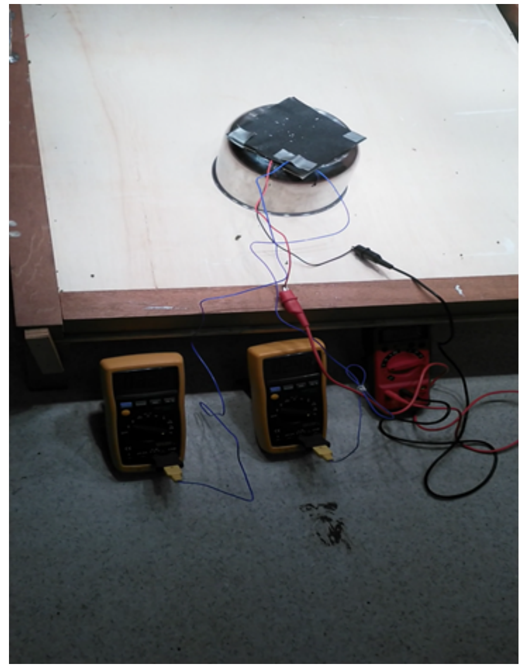

Fig. 6. Artificial sunlight heating experiment. Two multimeters (in yellow) are used to measure the temperatures of the two aluminum plates, while one other multimeter measures the output of the Peltier element. Maximum temperature recorded for black acrylic-coated aluminum is 52 degrees Celsius.

which are gripped together by tape on the borders of the plates. The bottom surface is physically in contact with a metallic bowl to keep it relatively colder than the top surface. Temperatures are measured for both aluminum sheets and the current generated by the peltier element is analyzed.

There are three significant imperfections in this setup compared to the peltier element in the drone as described in section 3.1 above. This setup should have poorer thermal conduction between the plates to the peltier element, as thermal paste was not yet available for use. Inability to keep the temperature of the heat sink plate is another major difference to the drone, as the metallic bowl does not have high enough heat capacity to keep a roughly constant temperature. Whereas the drone is expected to have a constant temperature on the heat sink plate due to being cooled by a large body of water underneath. The third imperfection is that this experiment is conducted under artificial sun condition, without fluctuating sun intensities that can be present in the field due to clouds or time of the day.

These three imperfections of this experiment does not negatively affect this experiments first objective; determination of the maximum temperature of the collector plate assumes as little heat loss to the surrounding due to conduction or wind convection, as well as maximum sun intensity. The artificial sun condition is ideal for identifying the absorbance ability of the black-coated aluminum. However, the imperfections presents an issue for achieving the second objective, as the voltage generation of the peltier elements become different when it is not under an actual sun, and has no thermal paste to effectively transfer the collector plates heat.

Thus this experiment cannot accurately determine how many peltier elements is needed, though it does provide an estimate of how many is needed.

B. Results and discussion

Four sets of sun heating experiments are conducted under varying conditions, as detailed in table 1 below.

The maximum temperature reached by the collector plate is about 52 degrees Celsius, reached in about 7 minutes. The heat absorbance from the collector plate is very poor compared to commercial solar heaters that can reach to over 100 degree Celsius.

Two issues were identified that may cause this low maximum temperature. First, the surface of the black acrylic coating is to some extent reflective. This is an indication that the paint used is not ideal for heat absorbance. Different coating must later be tested for achieving a higher maximum temperature. Second is that the collector plate is thin, and has a large surface area per volume ratio. This led to the plate losing heat faster from emission and wind convection. A thicker plate, while addresses the immediate concern of large surface area per volume ratio, can introduce a different heat loss due to resistivity in metal. Further experimentation will need to be conducted regarding the thickness of the collector plate.

A separate issue is to be noted regarding the short amount of time to reach maximum temperature. This is indicative of low heat capacity of the collector sheet. Upon experimentation with varying sunlight due to weather conditions, it can be expected that the voltage generated by the peltier array fluctuate significantly. Thus a plate with a higher heat capacity, for example by having a thicker metal plate, will be required.

Voltage output of the peltier element(s) is approximately 100 mV when the temperature difference is approximately 22 degree Celsius. A number of assumptions is needed for determining the number of peltier elements to be assembled in an array. First is that the solar collector is efficient and able to maintain a 70 degree Celsius collector plate temperature, in comparison to 23 degrees of warm lake water. As voltage generated scales linearly to temperature difference, each peltier element can generate 200 mV of voltage. An estimated nine peltier elements is needed for supplying 1.8 Volts, a voltage with some margin for fluctuations and schottky diode voltage drop to charge a 1.2 V battery. This estimation of nine peltier elements would be a guideline for designing the size of the drone.

Meanwhile, connecting two peltier element in series as done in experiments 3 and 4 generates an output voltage that is lower than the expected twice the voltage output of one Peltier element. A major reason identified is that physical contact between the connector plate to the multiple peltier element cannot be guaranteed without using thermal paste. Future experiments to confirm effectiveness of arranging a peltier array requires this thermal paste.

V. PV cell vs. Peltier Elements

Photovoltaic (PV) cells are usually the best choice for utilizing energy from the sun. PV cells have been drastically improved over the years to increase efficiency. Thus, it is important to compare the PV cells with the Peltier elements as power source for the water drone. Generally PV cells have a higher efficiency and higher output voltage than peltier elements. However, it is important that PV cells do not have a high tolerance against water; being in a high-moisture environment will help to accelerate delamination of polymer-metal contacts and the degradation of the PV cells [6]. This gave peltier thermoelectric generator a key advantage of much longer lifetime in water-based environments.

VI. Conclusion and Future Plans

This report has attempted to illustrate the use of thermoelectric generator in the design of autonomous self-powered water surface drone. Energy generation through Seebeck effect finds a particular application on lake surfaces as the water reservoir acts as a massive heatsink. This thus presents a different method of converting solar energy into electricity, other than using photovoltaic cells. A simple sunlight heating experiment is then conducted, from which the operating conditions of an efficient peltier array can be better understood.

More work needs to be done in the design of the drone. Design of solar collector plate requires figuring out appropriate cost-effective absorbing black coating, as well as figuring the suitable thickness of the plate. Choice of battery and sensor power requirements will also require further design deliberation.

All in all, it is possible to get enough power from the TEG to run the water drone. However, components need to be chosen, which are running under low voltage conditions and the control need to be programmed in the way, that the charge of the battery is efficient and that almost no power is wasted.

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