Thermoelectric Energy Harvesting as a Wireless Sensor Node Power Source

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ABSTRACT

Size and power requirements of wireless sensor nodes are gradually decreasing and this has allowed data collection across a range of spatial and temporal ranges. These nodes have power requirements that often necessitate batteries as an energy source. As the power requirements decrease for these sensors, alternative energy sources become more attractive. One such technology is thermal energy harvesting. Thermal energy harvesting requires a differential temperature between a heat source and a cool sink. As heat energy flows from source to the sink, energy can be harvested and utilized to power sensor nodes. By exploiting the temperature difference between a sun-warmed plate and a heat sink immersed in water, electrical energy can be harvested. The proposed concept utilizes a thermoelectric device to convert solar energy into electrical power. Initial experiments were carried out at the CSIRO Energy Centre for a variety of winter time intervals in 2009, with peak power outputs in the order of 50mW. Results indicate such a system could power a wireless sensor node continuously at ocean, lake and river water interfaces. We are presently in the process of evaluating the concept by powering a CSIRO Fleck™ wireless node to transmit water temperature and battery voltage data.

Keywords: energy harvesting, energy scavenging, thermal gradient, thermoelectric, wireless sensor network

1. INTRODUCTION

Wireless sensor networks are now beginning to increase in large scale deployment. Where previously networks might consist of fewer than 10 nodes transmitting hourly information, modern networks can have 100 or more nodes transmitting data on a minute by minute basis[1]. This scale change has led to a need to move away from primary batteries to secondary batteries, and utilise some form of energy harvesting to charge and recharge the secondary batteries. While this is often comfortably achieved by solar photovoltaics (PV), there is scope for other technologies to harvest energy where the solar resource is poor or non-existent. Examples of these locations include shaded areas, underground mining operations and under the forest canopy.

One technology that has been researched is the use of energy from the differences in temperature between two objects. Solid-state thermoelectric devices utilize the Seebeck effect, and are considered to be reliable and robust due to no moving parts. Originally TE devices were tested as part of the NASA unmanned spacecraft program and for the next 50 years there was relatively no increase in the energy conversion efficiency of thermoelectric devices. However recent advances in the composition of the devices have shown efficiency gains approaching twice those previously achieved [2]. This has sparked renewed interest in the development and use of thermoelectric technology. Recent work has shown it is possible to extract energy from natural thermal gradients using thermoelectric devices [3].

Typical power requirements for an individual node within a network are dependent on duty cycle and other aspects of the network design. For example the Fleck ™ series of nodes operates at 3.3V and consumes 30-40mA when transmitting, 15-20mA when receiving data and less than 1mA when idle. Nodes typically spend most of their time in the idle state, waking only occasionally, perhaps every few minutes, to transmit or receive information. With a well designed duty cycle a node will consume much less than 50mW. This power consumption does not include the power required by the sensors or other equipment attached to the node.

Water has a high thermal mass and also good convective heat transfer properties, which makes it ideal for use as a heat sink. The temperature of large bodies of water remains relatively constant during a day, regardless of large air temperature fluctuations. In this paper the difference in temperature between the water and ambient air is being used as a natural thermal gradient. Additionally, heat from sunlight can be captured by a blackbody to further increase the thermal gradient.

The experiments detailed in this paper investigate two aspects of collector design and use this information to power a wireless sensor node transmitting temperature information. The first design aspect is the size of the collector plate. Three sizes are used and the variation of power output is determined. The second variation is in the number of thermoelectric devices. These can be connected in series to scale up the voltage of the output energy to a size useable by modern electronics. A suitable voltage converter design is described. This circuit can increase the output voltage from the Seebeck device from 0.9V up to a more useable 3.3V.

Finally the thermoelectric generators are used to power a wireless node. This experiment has no batteries and collects enough energy to transmit temperature samples every two minutes while the temperature difference across the Seebeck device exceeds 10K.

2. EXPERIMENTAL DETAILS

In this section we will explain each of the elements of the experimental design, including the thermal energy harvester design, voltage boost circuit design, transmitting and receiving nodes and data storage. As shown in the block diagram in Figure 1, the experiment has a number of different elements that are utilised to collect energy from the thermal difference between air and water, and use this energy to transmit information over a 2 element wireless sensor network. The first stage is a thermal energy harvester which generates power using the Seebeck effect. This power is sufficient to run a wireless node like the CSIRO's Fleck™3B but has an insufficient voltage. Typical output voltages are less than 1V while the Fleck™3B requires at least 3.3V. The energy is taken into a dc-dc boost converter circuit where the voltage is increased to 3.3V.

The boost converter will only operate when the input is above 0.9V, but once operating will continue to work down to 0.7V. Once the boost is above 3.3V, the Fleck™3B turns on. The Fleck™ is programmed to send its onboard temperature and the boost voltage every 2 minutes. This transmission is received by a matched Fleck™3B, which converts the information to a serial string and sends the data to a Datataker™ DT85 data storage unit. In the following sections these elements will be described in detail.

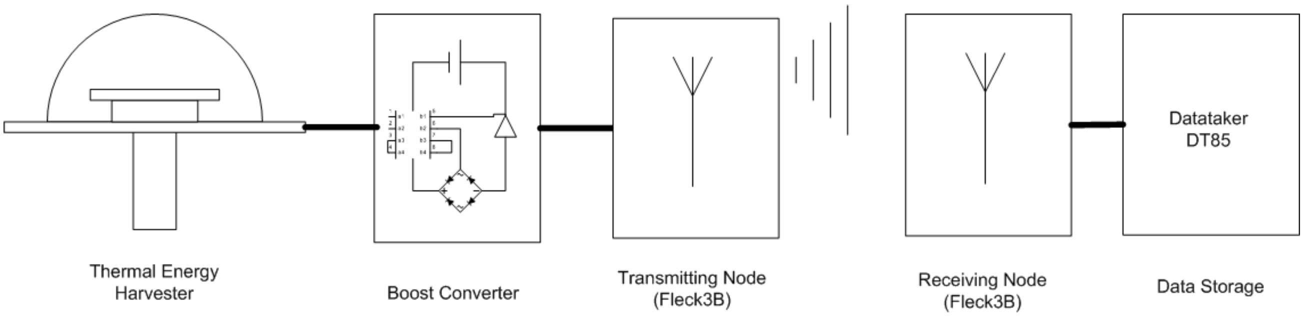

Figure 1. Experimental block diagram.

2.1 Thermal energy harvester design

There are three aspects being tested in this series of experiments. The first is the effect of the number of Seebeck devices sandwiched between the collector plate and aluminium heat sink and thus the ratio between collector plate size and Seebeck area. The second part of the experiment tests the effect of the collector plate area on the output power. The final part of the experimental procedure uses the power from the collectors to power a wireless sensor node and transmit information using energy collected from the thermal harvesting domes as its only power source.

The collector design is similar to those shown in [4, 5]. In those designs, a single Seebeck device was used to convert the temperature difference to electrical energy. For the first part of this experiment series aluminium plates have been added to the top of the heat sink to allow multiple Seebeck devices to be connected simultaneously. Figure 2 shows the design with one Seebeck device. The design uses a simple 40mm x 40mm square section aluminium block as the cold side heat sink. The Seebeck device was then placed onto the top of the heat sink using Arctic Silver™ heat paste. The large aluminium top plate was similarly placed onto the top of the Seebeck device. A foam collar was placed below the disk and that assembly slid through a hole in a circular acrylic disk. This acrylic disk has a number of fasteners around its periphery which mate with the acrylic dome which covers the device. The dome assembly was inserted into a foam raft and was able to float independently.

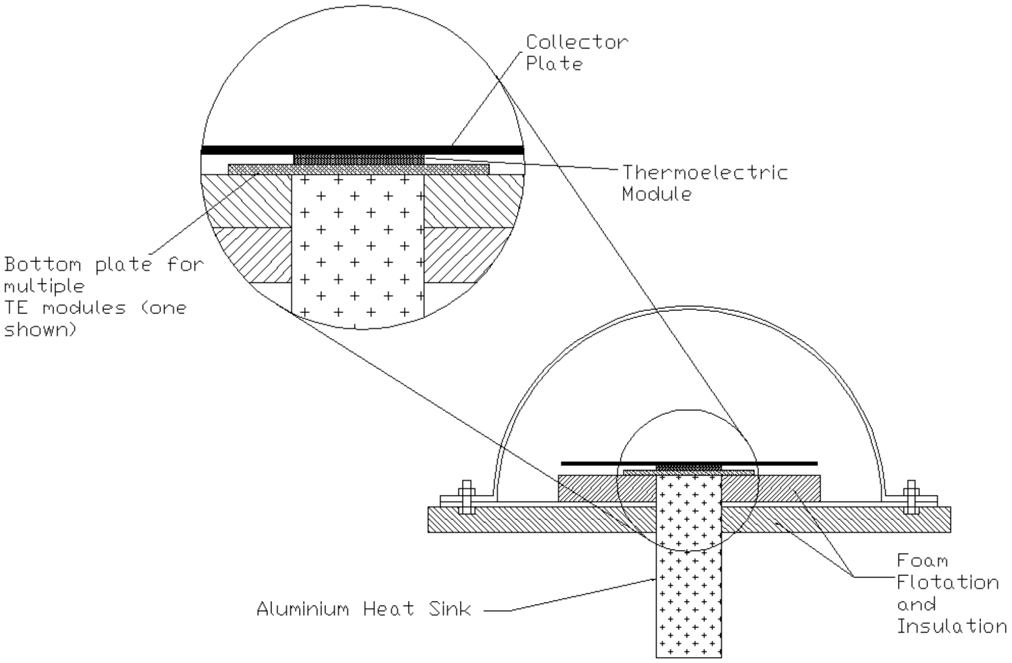

Figure 2. Experimental thermal energy harvesting collector design.

For the second part of the experiment the size of the collector plate is varied. The standard size is an aluminium plate, painted black, with a diameter of 200mm (area = 0.031m^2). The small disk has a diameter of 160mm (area = 0.020m^2), and the large disk has a diameter of 240mm (area = 0.045m^2). These changes have the effect of changing the ratio between collector and Seebeck area. The Seebeck devices are square and measure 40mm on a side the area ratios are as shown in Table 1.

Table 1. Collector plate to Seebeck area ratios.

Collector Plate (Diameter)	**Plate Area (m^2)**	**Area Ratio (%)**
Small (160mm)	0.020m^2	8.0
Medium (200mm)	0.031m^2	5.1
Large (240mm)	0.045m^2	3.5

The particular thermoelectric module chosen is commonly used to generate temperature differentials from input power however in this application we are using them in reverse to generate power from temperature differentials. For the first two parts of the test (collector size and multiple Seebeck devices), the output voltage was collected across two 12Ω resistors arranged in parallel for a total load resistance of 6Ω. This had previously been shown to be close to the maximum power point for these devices [4, 5].

2.2 Voltage conditioning circuitry

It was observed, that as the output from the Seebeck devices are typically less than 1V and rarely above 1.5V for the ambient conditions of these series of experiments, a dc-dc boost converter was required to raise the voltage to a useable level. The CSIRO Fleck™3B requires an input voltage in the range 3.3-8V to turn on. Once on the Fleck™3B will operate down to 2.9V. The boost converter used is based on the MAX756 switch-mode regulator IC. The circuit is shown in Figure 3.

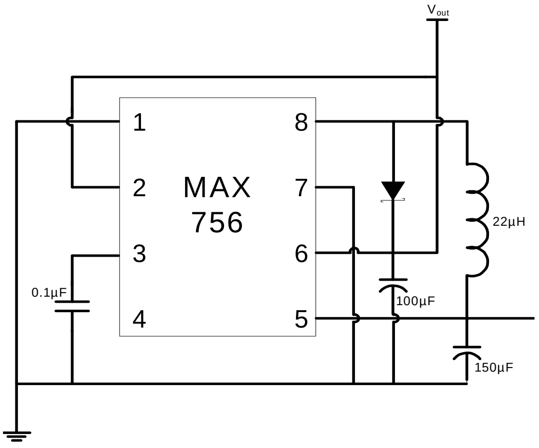

Figure 3a. Boost converter design.

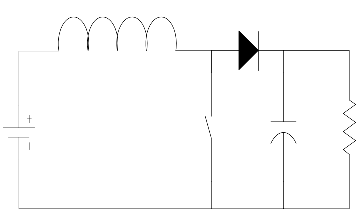

Figure 3b. Simplified boost converter design.

The MAX756 integrated circuit acts as a high-speed pulse-width modulation switching device, with pin 8 acting as the switch. A simplified version of the circuit is shown in Figure .

Assume at steady-state that the voltage across the capacitor is equal to the input voltage less the forward-bias voltage of the diode. When the switch is closed there is a low-impedance path from pin 8 to ground, so the input voltage is wholly dropped across the inductor, which causes a ramping current flow. When the switch is opened the inductor resists a change in the current flow, and so begins to ramp downwards, reversing the direction of the voltage drop, and acting as a voltage source, increasing the voltage across the output capacitor until the inductor is fully discharged.

By controlling the duty cycle of the switch the maximum voltage at the output can be maintained at any reasonable level, and if the capacitor is large the output voltage can be maintained at a relatively constant value. In the MAX756 the duty cycle is controlled by means of a feedback mechanism, which compares the output voltage to an internal reference, and varies the cycle accordingly. An input capacitor is used to smooth out quick changes in the input voltage.

The data transmission unit is shown in Figure 4a. The Fleck™3B unit with the whip antenna is connected directly to the voltage boost converter. The information being transmitted is the sample number (an incrementing number that resets to 1 whenever the boost converter is unable to continue powering the node), the node’s on board temperature (in degrees Celsius) and the output voltage (in millivolts) from the boost converter.

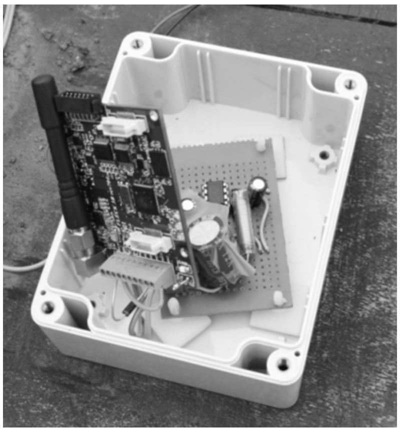

Figure 4a. Transmission node and boost converter

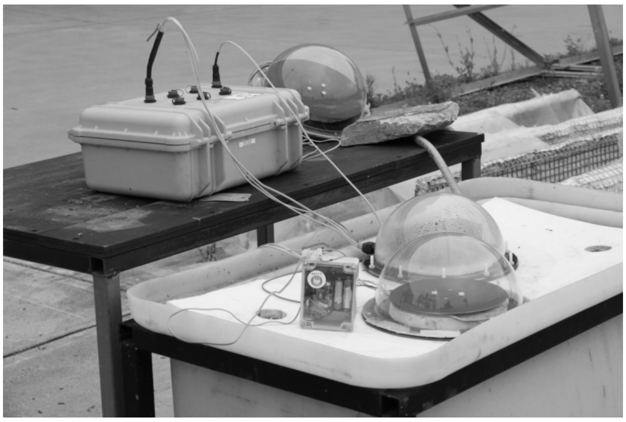

Figure 4b. Experimental setup: two domes, transmission box and data collection box

2.3 Data acquisition

In terms of data acquisition, each module captures temperatures using K-type thermocouples. The thermocouples are attached to the underside of the collector plate and the top side of the heat sink (thus giving the differential across the Seebeck device). A third thermocouple measures the air temperature inside the dome and the last measures the water temperature. Although K-types are not ideal for the temperature range expected for this experiment, it was felt that the availability and cost advantages were significant, and the expected accuracy more than sufficient. These thermocouples are connected directly to the Datataker™ DT85 data collection unit as shown top left in Figure 4b. The left hand cable entering the box measures the three dome temperatures and the right hand cable measures the water temperature. Shown in the foreground of Figure 4b is the tub of water used as the cold side heat sink. On top of the tub in the white foam raft are two collector domes and the data transmission box (see Figure 4a). The water tub has a volume of approximately 250 litres. The tub was chosen for its convenient access. The size of the tub introduced two main issues. The first was that the lack of turbulence in the water may lead to stratification of the temperatures, and thus lower than expected output, as the heat sink would now be in a layer of warm water. The second issue is that the thermal mass would mean that both the outside air temperature and the heat flow through the energy harvester would heat up the water. In order to use a larger body of water, other issues such as proximity, and thus convenience, and security of the experiment would need to be considered.

For the first two parts of the test (collector size and multiple Seebeck devices), the domes were connected to the data logging equipment. This equipment was housed in waterproof housing and logged data every 10 seconds. For the final experiment where the devices power a boost circuit, the thermocouples were attached to the data logging equipment, the output from the Seebeck device was connected to a separate housing, which contained the boost circuit and the transmitting Fleck™3B. When sufficient power was available the Fleck™3B would transmit. Upon reception the data logger stores the transmitted information (sample number, temperature and boost voltage) and logs thermocouple temperatures. If no power was available the boost circuit and Fleck™3B would not operate, however the data logger defaults to logging temperatures every 15 minutes. The information from the sending node is transmitted every two minutes when powered. The receiving node is housed inside the data storage box and transforms this data to a serial string and sends it to the DT85 storage unit. When this occurs it triggers the DT85 to take a temperature reading from the four thermocouples.

3. RESULTS

The results from the first series of experiments involving the variation of the number of Seebeck devices are presented on the next page in Figure 5 and Figure 6. Figure 5 shows the total power output from three different thermal energy harvesters with $0.031m^2$ collector plates and operating using either 1, 2 or 4 Seebeck devices. It shows a full 24 hour period starting from midnight and as to be expected the power outputs rise during the daylight hours peaking around midday in response to the incoming solar radiation. As can be seen the power output correlates very strongly with the solar insolation which was measured concurrently at a station less than 100m away and displayed in Figure 9. The slight dip in the output power shown in the 14th hour in Figure 5 but not seen in Figure 9 was due to a nearby wind turbine pole shadowing the experimental set up but not the pyranometer collecting solar data.

The effect the variation of the number of Seebeck devices has on the output power is illustrated in Figure 5. Here it can be seen that the more Seebeck devices conducting energy from the collector plate the greater the power output, with 19mW, 26mW and 37mW of peak power produced by the harvesters with 1, 2 and 4 Seebeck devices respectively. However, the output power does not increase linearly with the number of Seebeck devices operating between the top and bottom plates. The output power is not only proportional to the flow of heat energy through the Seebeck devices but also to the efficiency at which the heat flow is converted to electrical power. By increasing the number of Seebeck devices the surface area for conduction is increased allowing a larger heat flow. However the increased heat energy conducted from the top plate to the bottom sink has the effect of lowering the temperature difference between them which decreases the Carnot efficiency of the conversion process. This is evidenced in Figure 6 which is a plot of the temperature difference across the Seebeck devices. It shows that the dome with 1 Seebeck device attached consistently experienced the largest working temperature difference throughout the day and night with a peak of 21K occurring at noon and that the device with 4 Seebeck devices recorded the lowest working temperature difference with a peak of only 5.5K. It is believed that there is an optimum ratio between collector area and Seebeck device area which would allow good heat flow while maintaining large temperature difference to enable maximum power output. We seek to determine this optimum through further experimentation and/or model simulation.

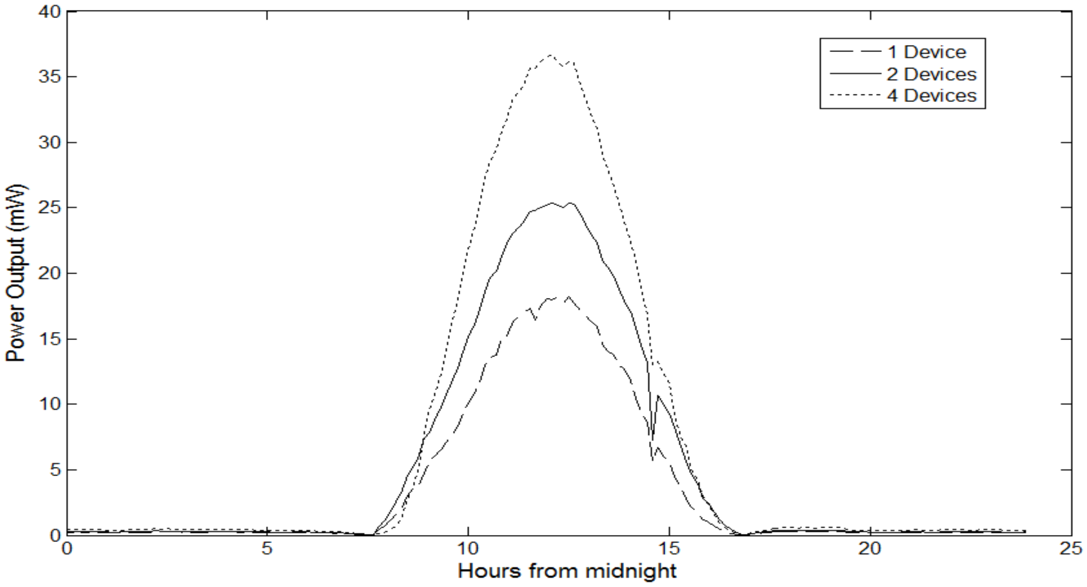

Figure 5. Power output from the varied number of Seebeck devices trial

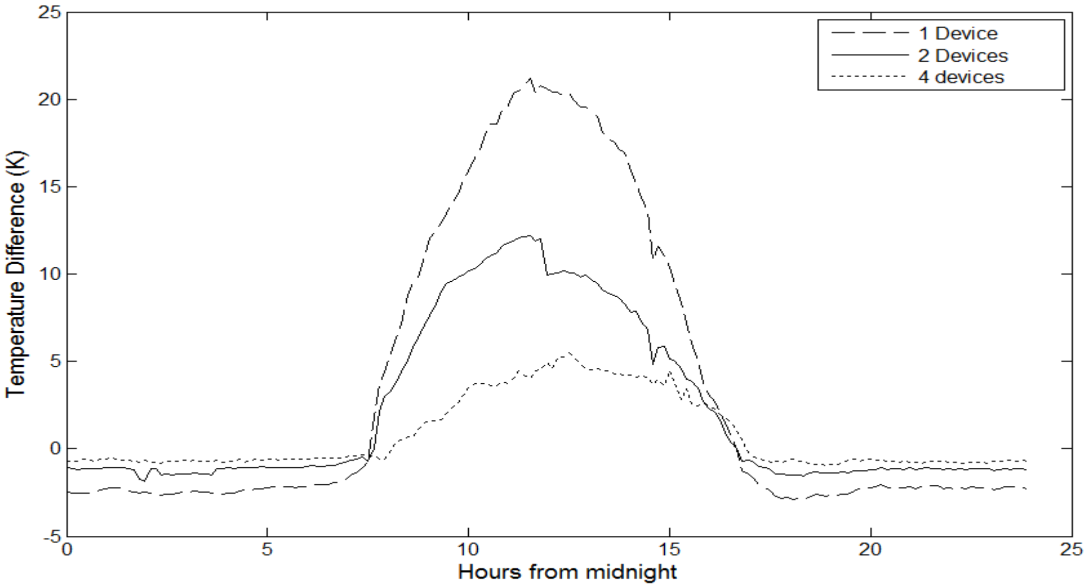

Figure 6. Temperature difference across Seebeck devices in the varied number of Seebeck devices trial

The power outputs from the trial investigating different sized collector plates are plotted in

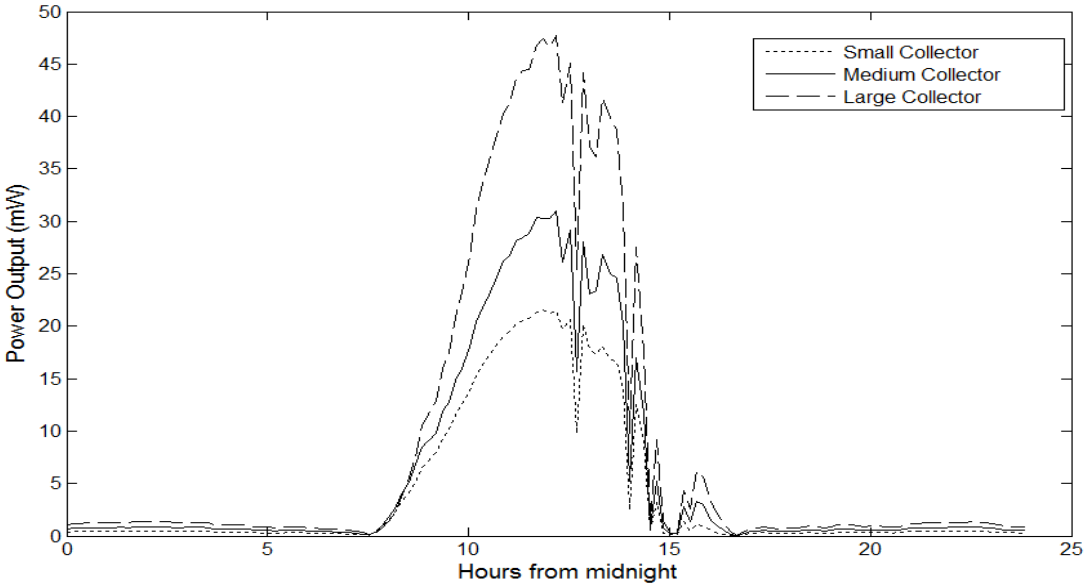

Figure 7. As the size of the collector plate increases so too does the output power with the large collector recording a peak power output of 48mW compared to 31mW for the medium collector and 22mW for the small collector. However when the power outputs are normalised against the size of the collector plates, to give the output power per unit area, it can be seen that the power flux is effectively the same for all 3 devices as shown in Figure8. The solar insolation for this trial is plotted in Figure10 where the values significantly drop and then spike back up in the afternoon due to passing cloud cover. The influence of this cloud cover on the harvesting device is also seen in Figure8 where the output power drops and spikes at the same corresponding time. Comparing Figure8 and Figure10 reveals that the harvesters output approximately 1W/m^2 for solar insolation of 640W/m^2 which relates to a conversion efficiency of less than 0.2%.

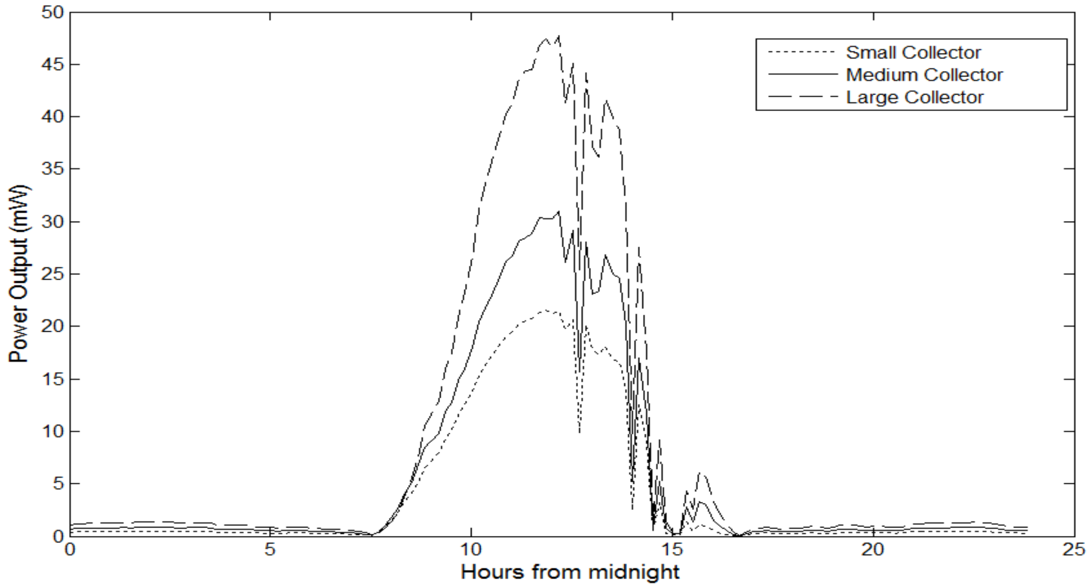

Figure **7**. Power output from varied collector sizes.

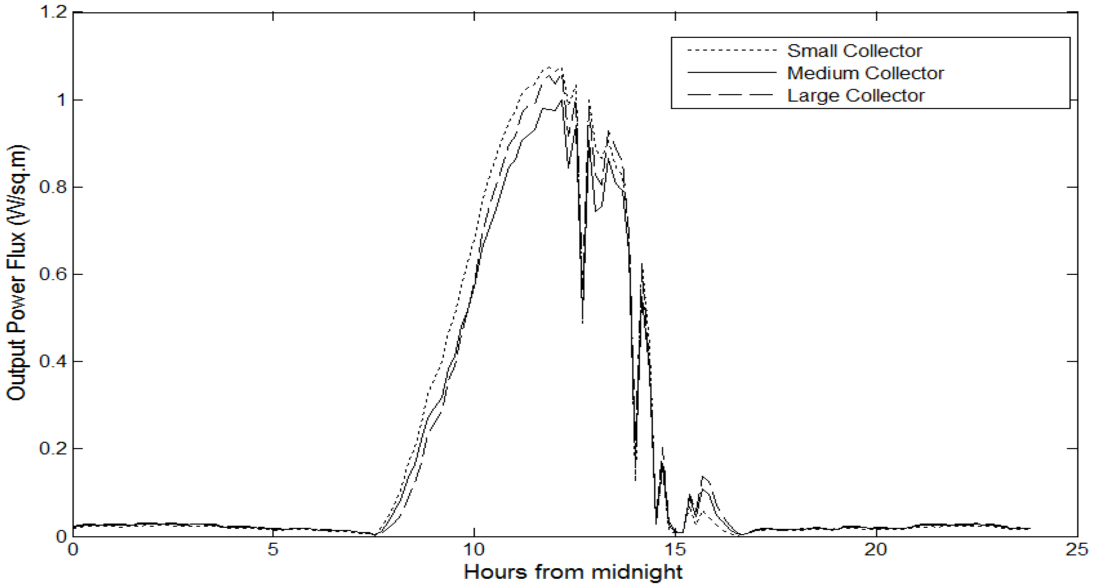

Figure 8. Normalised power output from varied collector sizes.

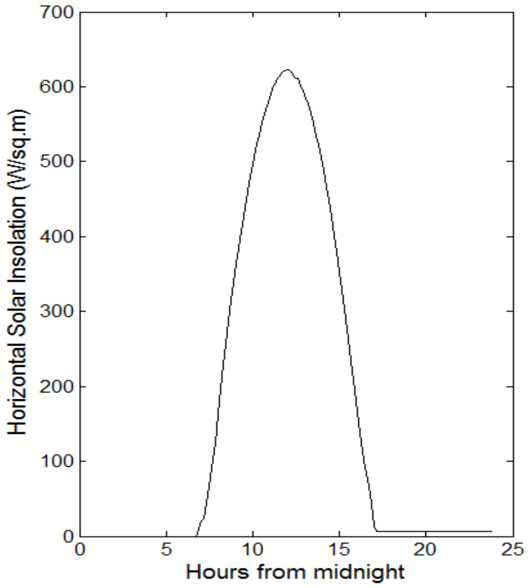

Figure 9. Solar insolation for varied number of devices trial.

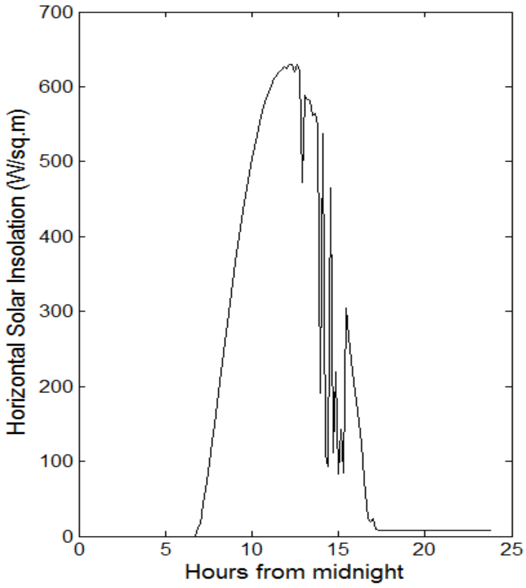

Figure 10. Solar insolation for varied collector size trial

The success which the design of the dome and collector plate have in increasing the temperature of the top side of the Seebeck device above the ambient air temperature is illustrated in Figure 11a. At midday the top side of the Seebeck device is heated 20K above the ambient temperature however, the dome design is also seen to hold its temperature overnight. During the night hours the ambient air is seen to drop about 10K below the water temperature, shown in Figure 1b, but the dome and collector plate remain much warmer, resulting in a small temperature difference and negligible power flow. However, it is believed that the advantage from the increased power during the day on the total daily energy output outweighs the drawback of decreased night time power.

The temperature of the water and the bottom heat sink is graphed in Figure 1b. The graph shows that the water temperature changes by over 20K across the day which is an artefact of the present experimental setup using a small volume of water as opposed to an actual body of water such as a lake, river or ocean, whose temperatures tends to remain relatively constant across the day due to large thermal mass. The graph also reveals the inefficiency of the bottom heat sink which should ideally be in thermal equilibrium with the water but instead is significantly hotter than the water during the day as the heat conducted from the top plate is not dissipated fast enough from the bottom heat sink to the water. This may also in part be due to the experimental set up whereby the water sat stationary in a tub unlike the real currents, waves and other fluid motions experienced in open water systems which would greatly increase the removal of heat from the sink due to convection.

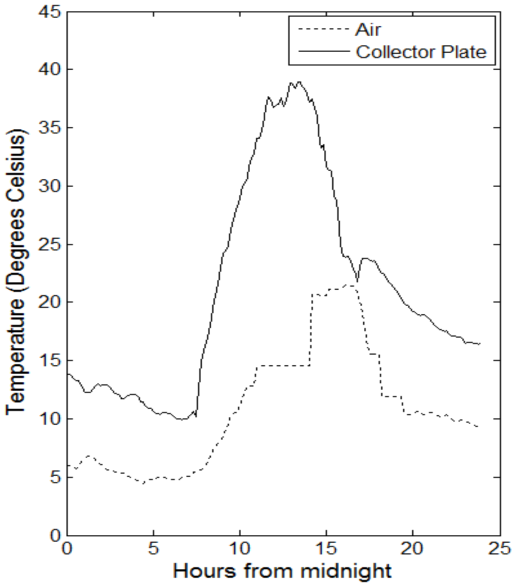

Figure 11a. Temperature of the ambient air and the collector plate

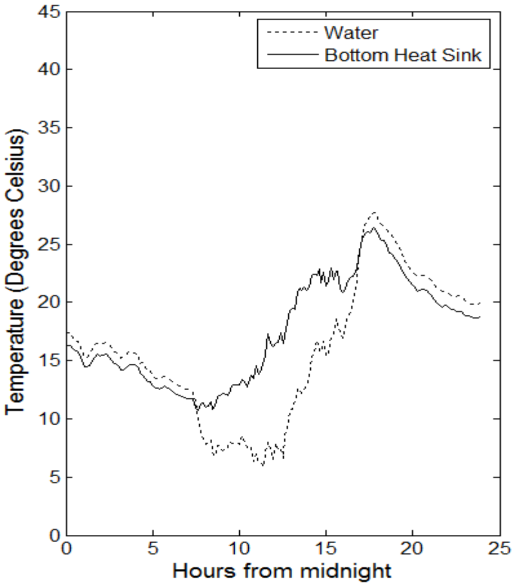

Figure 11b. Temperature of the water and bottom heat sink

The final experiment aimed to directly power a wireless sensor node from the output of the thermal energy harvester. The Fleck™ 3B node was programmed to measure temperature every 2 minutes and transmit the sample wirelessly to a nearby datalogger. It was left to run for almost 2 days from the 5th to 6th of January 2010 with the logger receiving over 280 samples in this time. In Figure 42 the temperature difference across the Seebeck device is plotted for the duration of the experiment with the secondary axis showing when samples were received by the logger. It shows that the output from the harvester was only able to power the node when the temperature difference exceeded 10K. The cause of the disrupted sampling on the second day when there appeared to be ample working temperature difference is unknown.

The results in Figure 12 reveal large portions of time when the direct output from the harvester was insufficient to power the sensor node. This problem can be rectified by including energy storage into the system. We are currently in the process of repeating the above experiment incorporating a secondary battery into the design allowing continuous data transmission by storing excess energy harvested during the day to power the node during the night and at other times when there is insufficient direct output power from the energy harvester.

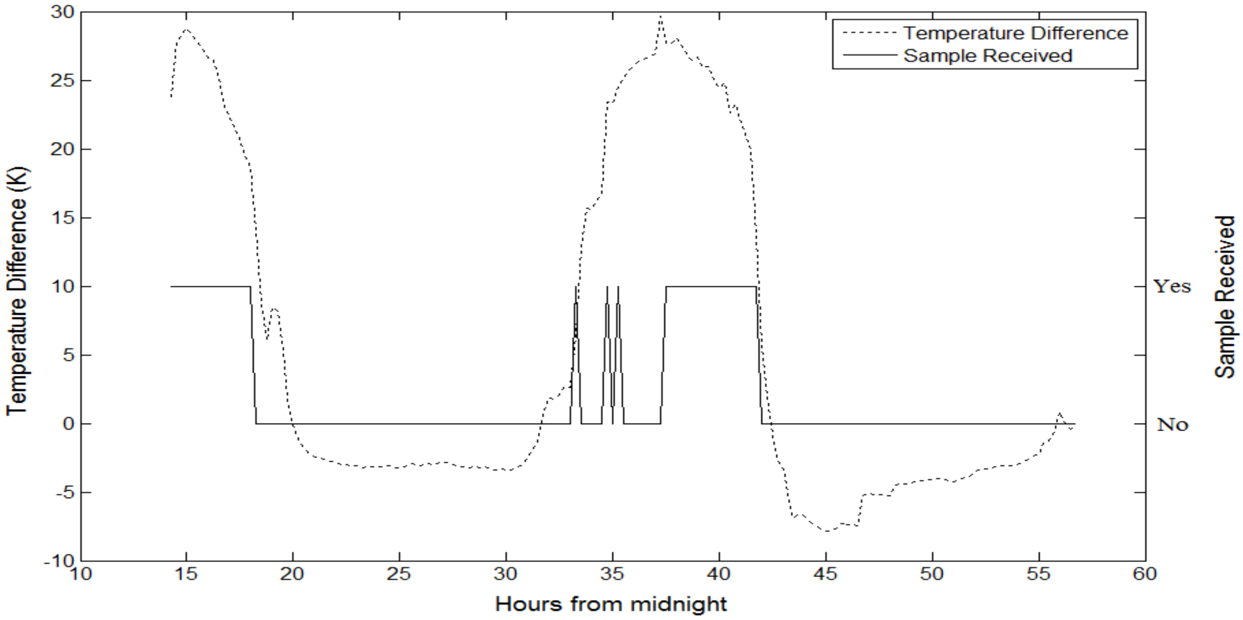

Figure 42. Results from the trial involving the direct powering of a wireless sensor node by the thermal energy harvester

4. CONCLUSION

In this paper two variables have been explored for their effect on the output of a thermoelectric based energy harvester. The first variation changed measured the effect of the number of Seebeck devices. These experiments found that increasing the number of Seebeck devices increased the heat flow and thus dropped the temperature difference across the device. While the output does increase with the number of devices it does not increase linearly. With one device the peak output was approximately 17mW. Two devices increased the output by less than 40%, and 4 devices increased the output by less than 100% over just one device. Critically, the use of multiple devices allows the output voltage to be stepped up to a useable level for voltage conversion circuits.

The second variation determined the effect of changing the size of the collector. As should be expected the increase in size directly affected the output of the system. However, when the output is normalised against area, the change in size had no effect on the output of the device. Comparing Figure 8 and Figure 10 reveals that each of the three sizes of collector disk has peak outputs of approximately $1W/m^2$ for solar insolation of $640W/m^2$ which relates to a conversion efficiency of less than 0.2%. Although lower than silicon based solar cells, these systems are aimed at locations where access to a solar resource is limited.

The final experiment aimed to use output of the thermal energy harvester to directly power a wireless sensor node without any energy storage. This experiment established that there is sufficient energy available to power a wireless node; however the system required temperature differences across the Seebeck device exceeding 10K. Although these temperatures are not normally available from ambient temperatures they can be achieved by amplifying ambient conditions with the use of black body collectors and domes to trap the emitted radiation. In order to achieve continuous sampling, energy storage will be required to allow transmission at night and on duller days. In order to extend the transmission times, sample periods could be extended from two minutes and as transmission power is by far the largest consumer of power, multiple samples could be sent at lower rates; for example six samples could be sent every hour rather than one sample every ten minutes.

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