Survey and Analysis of Digital Thermoelectric-Generator-based Power System

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SURVEY AND ANALYSIS OF DIGITAL THERMOELECTRIC-GENERATOR BASED POWER SYSTEM

Abstract

This paper is an attempt to report the modeling, design and build analysis of thermoelectric module (TEM) with realistic conditions for electrical power generation. It gives an insight to static and dynamic modeling with temperature dependent parametric variations and computation of various TEM parameters for modeling power generators.
This paper demonstrates the undergraduate engineering technology student-driven research at our university in this arena. It depicts the application of the multi-agent approach which allowed the student team to take full control of the project from inception to completion. The team developed and built a microprocessor based prototype thermo-electric generator for waste heat recovery (module and heat exchanger), computed and analyzed the optimal power delivery by judicious material selection.

The dynamic model developed under MATLAB and COMSOL MultiPhysics environment with a consideration of its dependence on materials and temperature will be explored. The micro-controller manages and regulates other systems components. The autonomous device control by a micro-controller gives the flexibility to estimate the efficiency, power, voltage and current parameters and help validate the efficacy of the developed model under dynamic operating conditions resulting in optimum thermo-electric power generation.

The ultimate design goal is to capture possible latent potential heat energy that tends to get lost from normal industrial mechanism processes thereby save energy and promote the modular design for satellites and space applications. It furnishes an alternative route for green energy with renewed design emphasis on semi-conductor technology instead of traditional analog mechanization. Finally, the results of the survey analyzing this learning methodology will also be discussed. This will go a long way in motivating engineering technology students to conduct potential future research, and reinforcing the best practices for life-long learning.

Background

Engineering departments are often confronted with the necessity to update laboratory exercises and equipment with the latest emerging technological trends within tight budget constraints. Another challenge faced by departments pertains to satisfying the Engineering Technology Accreditation Commission (ETAC) criteria for capstone senior project experience within the electronics and computer engineering technology curriculum.

A group of four engineering technology students came up with the proposal to develop, design and test the Parasitic Digital Thermoelectric Generator (P-DTG) Power System, which employs autonomous device control by an Arduino based microcontroller.

Thermoelectric generators (TEGs) are renewable energy devices made up of semiconductor components that directly convert the temperature difference between surfaces into electrical energy. The efficiency of a TEG depends on the thermoelectric materials. The main advantage of TEG is that it uses green energy.

COMSOL MultiPhysics software was initially used as a platform to conduct thermal budget and feasibility of the materials. COMSOL have a standard set of materials in their library which can be customized to some extent according to the user's requirements. Before simulating the chosen module, the properties of materials need to be assigned for each geometry in thermoelectric model.

Implementation

The Students proposed to create an alternative route for green energy with renewed design emphasis on Digital Parasitic applications that will employ Thermoelectric Generator Peltier (semi-conductor) instead of traditional analog mechanization. Initial faculty feedback on students proposed capstone senior project had mixed feelings. Faculty was concerned that after having taken a course [2] in HCS 12 microcontroller programming, why students want to use a different microcontroller for their senior project. The student's response was that there is a dual incentive in venturing in this project. They will not only fulfill the requirements of senior project completion but also will be adequately prepared to take Arduino Programming Certification [8] Exam conducted by BrainMeasures.

Arduino Programming certification offered by BrainMeasures covers the following topics:

- Introduction to Arduino
- Overview of programming, the basics of performing the programming process
- Overview of Arduino Programming
- Understanding about Arduino Programming environment
- Understanding about microcontrollers basics
- IDE environment for Arduino
- Creating Arduino Programs
- Effectively using the Arduino IDE environment
- Different menus and tools for efficient programming in Arduino IDE
- Sketching and interfacing with electronic circuits for Arduino Program
- Role of object oriented programming
- Learning basics of C programming
- Commands, structures, constructors, loops and strings in C programming
- Using C for Arduino programs
- How to effectively implement the data structures for Arduino Programming
- Functions and their effective use for Arduino programs
- Concept of pointers in object oriented programming
- Data storing procedure and codes in programming
- Use of libraries and built in codes
- Digital input and output procedure with Arduino

- How to effectively interfaces with analog systems and devices using Arduino Programming
- Understanding about interrupts
- How to use and test external interrupts
- What are pin change and timer interrupts

Once the students began working on their senior project they used the internet resources, tutorials on their own and in few months they developed the expertise far beyond what is expected for the above certification exam. Students demonstrated that Arduino offered a friendly environment to perform certain tasks and conceptual roles that refer to using a more conceptual framework when organizing the ideas about different processes and things. Arduino Programming has introduced new features for writing codes that are deemed as user friendly with unification of procedural and object-oriented portion of the language.

Microcontroller and Subsystems Operation

Figure 1 shows the Arduino sketch displaying the Parasitic Thermoelectric Generator Component Diagram. The Arduino Uno micro-controller interfaces with 5V relay module channels switches and control components for applications such as 12V CPU Fans, 5V voltmeter, 5V low current Temperature Sensor, Grounding safety switch for 22V Peltier w/ 1A fuse load and Grounding safety switch for LM2596s Voltage regular. It is powered by a 12 V Battery that gets charged from a 22V max Peltier DC source.

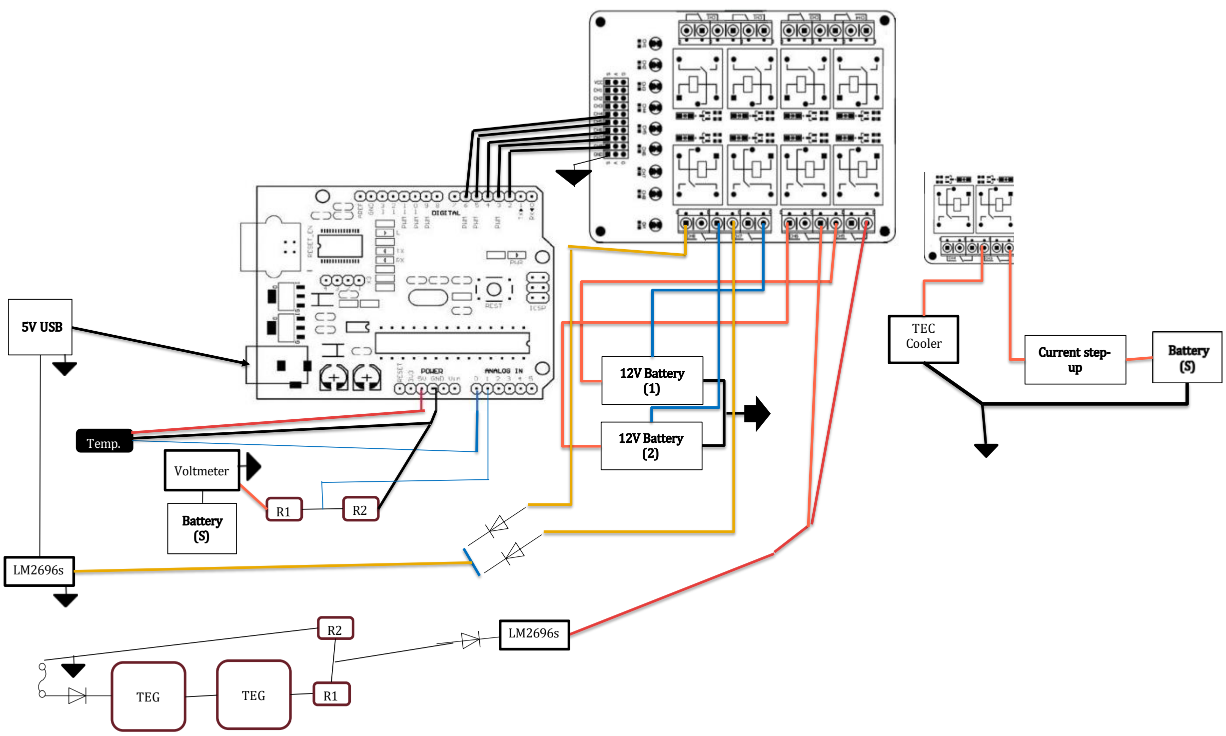

Figure 1. Arduino Sketch with Parasitic Thermoelectric Generator Component Diagram

This scalable design demonstrates the high performance, cost efficient modular design concept as shown in the flow chart depicted by Figure 2 and the hardware block diagram as depicted in Figure 3. A current amplifier is being used to increase power efficiency cycle from batteries, for TEC to work at optimal levels and furnishing higher current as compared to the rest of the circuits. The intent is to prevent current to increase to 5 amperes and protect the draining of 12 volt battery and functioning at 1 ampere rating. The non-integration of a current amplifier will drain the battery source at a faster rate than it would take to charge it.

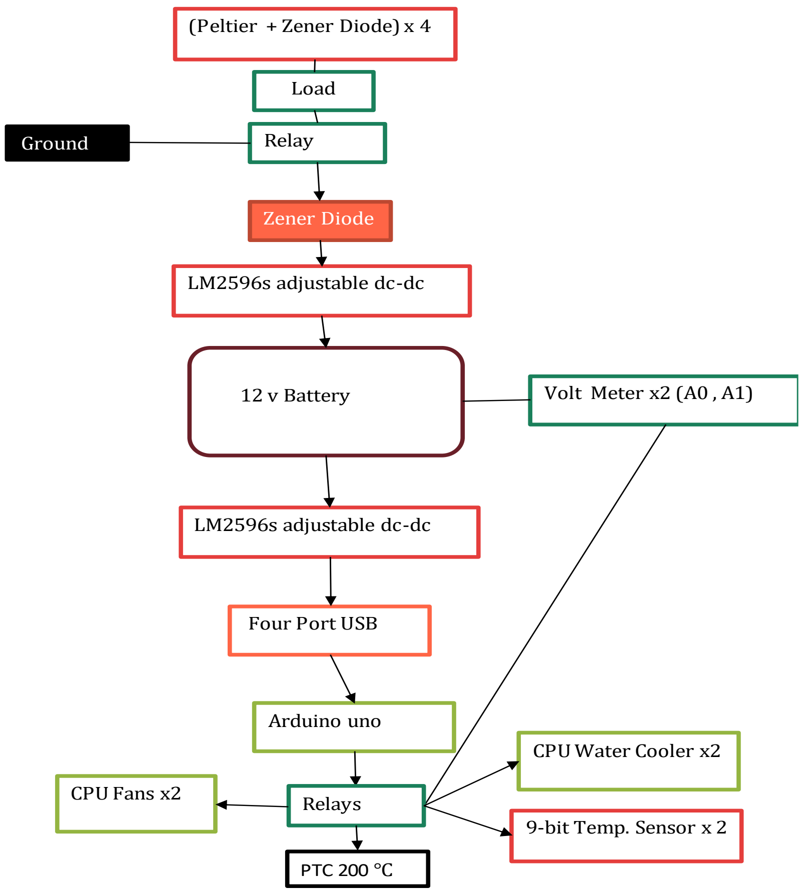

Figure 2. Hardware Block Diagram and Schematics

The Arduino microcontroller functions to supervise the TEC Power Heat Pump systems and provides sufficient cooling for the TEG Peltier hot side. Voltage Regulators are being used to step down initial high voltage levels from TEGs Peltier voltage output, and steps down high voltage from battery to low voltage circuits thereby preventing high voltages from burning sensitive circuit parts. The current design incorporates the microcontroller (MC) with a 3.3V or 5 V power supply system that can regulate P-DTG system components at optimal efficiency level by using simple relay or transistor based switch and provides isolation of high power from low power circuits. Subsystems include battery charging, back-up power supply, cooling system, sleep mode and protection system. The relay system in turn helps the microcontroller to self-regulate the system without any human intervention.

Battery charging subsystem systems is a dual power system that is monitored with programmable voltage sensors which functions as a switch in the situation for charging or discharging: fully chargeable even at low power levels and shuts-off to avoid overheating. Microprocessor interfaces with temperature sensor thereby monitoring heat levels of TEG Peltier and sub-circuits within operational temperature limits.

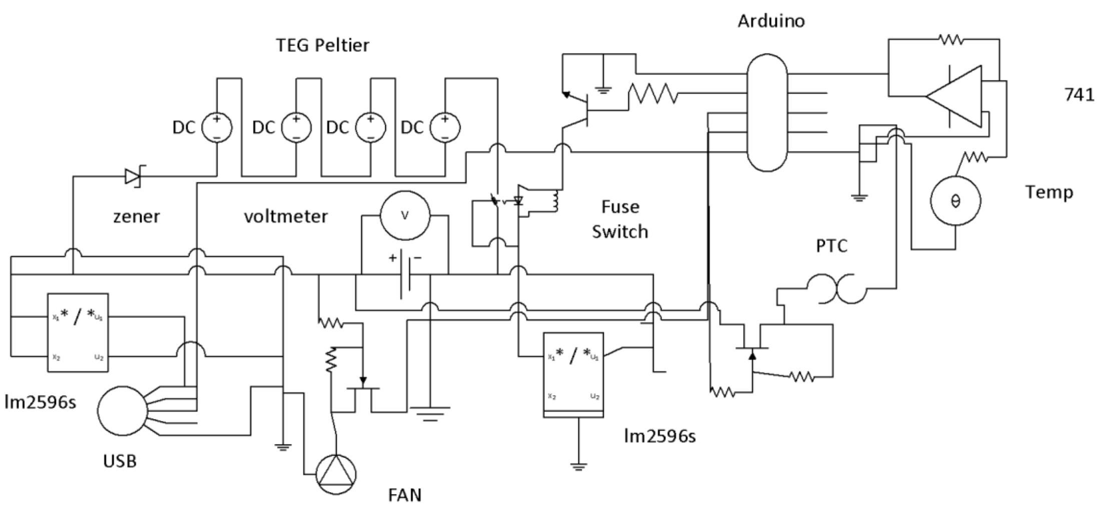

Figure 3. Prototype Test Set up Diagram

Observations

This project successfully depicted a highly efficient [1]and parasitic relationship between TEG application via heat transfer and its complementary TEC effect. Via unique experimental setup, the students have created a novel application, which reduces the need of traditional analog and moving parts, and accomplishes miniaturization and noise reduction. It furthermore contributes to cost reduction, modular design and easy maintenance.

Figure 4 shows a picture of Image of encased prototype Parasitic Digital Thermoelectric Generator System. As part of the prototype experimental testing, it was noted that in order to incorporate TEC cooling utilizing Seeback effect, we need a high current amplifier system that would capture enough digital voltage without compromising our battery (energy) resource. Power and current generation must be separated from power storage, in order to preserve power levels throughout the whole circuit.

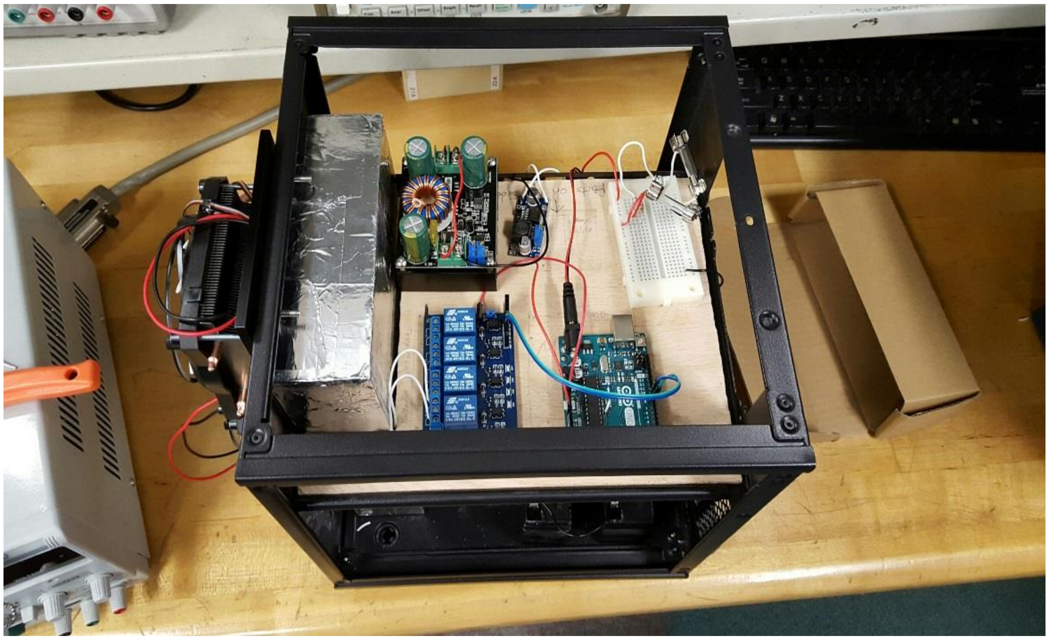

Figure 4. Image of encased prototype Parasitic Digital Thermoelectric Generator System

Testing Results

During initial testing of TEG power systems, it was found that Peltier employed, produces only seven volts due to the ineffective CPU cooling as such not preventing the hot side from bleeding through the cold side. Initial readings showed that the difference between the two sides was 20℃. Further deliberation revealed that the combination of thermoelectric cooler (TEC) along with CPU fans produced a cooling surface of 10℃.

Figure 5 displays the NI Multi-Sim based simulation snapshot of prototype circuit. It was observed that ΘSA = thermal resistance of our TEG between the heat sink and the air (cooling) got overwhelmed by the ambient temperature (TA) of the air immediately surrounding the package, thereby decreasing power dissipation of the IC in accordance with the thermal resistance between the junction and case of the TEG, resulting in elevated ΘSA_{max}. This meant that a more effective way to cool the Peltier TEG was needed. On a positive note we were now selecting more effective methods of cooling at -4 ℃ versus 10℃ at the cooling plate.

Consequently, an effort was made to design a robust cooling unit that can provide superior cold temperatures and offset the heating coil temperature bleed. This issue was resolved when further experimentation with TEC created a viable cooling system for our TEG's power generation. Testing results of TEC cooling units were promising. It demonstrated a stable increase of 3.7 volts with low end temperature reading at 75 C resulting in increase in efficacy by more than 50%. Next task was to incorporate a three stage TEC cooling unit which can provid efficient cooling, and stable voltage at a lower temperature setting of 200 C versus 300 C.

Design changes mandated the use of load of 20kΩ resistor and 1 amp fuse and helped create a stable DC power source preventing burning out. LM2596s voltage regulator steps down 22V to 5Vs and powers BJT switch to the relay Fuse. The logic control uses state 0001 as open and 0010 as closed, 5v is ground and application (red probe) is off. Relays switches were added before fuse to shutdown 22 volts and the relay switch K5 was added to the voltage-regulator and help shut down static build up. Figure 5 gives a snapshot of MultiSim simulation results.

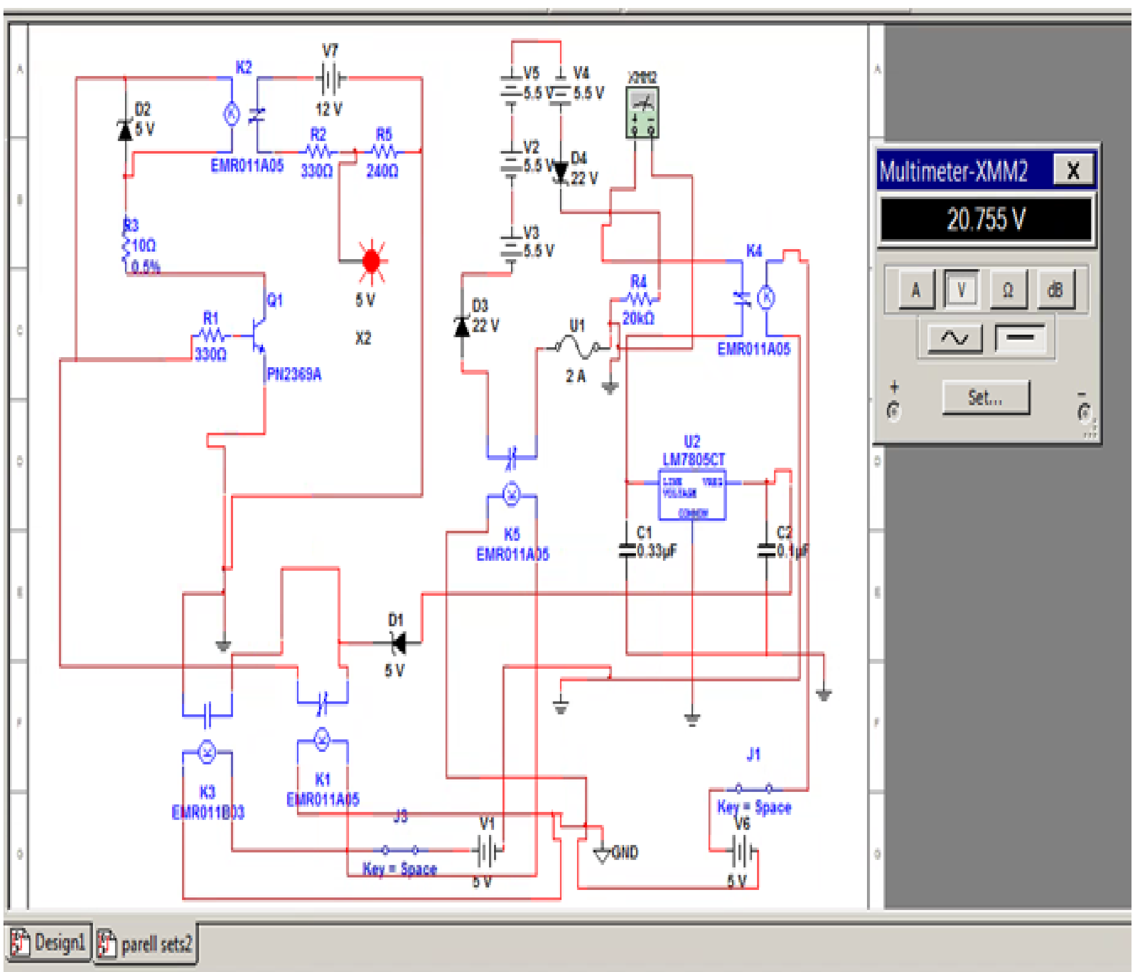

Figure 5. NI MultiSim based simulation snapshot of prototype circuit

This completes our discourse on analysis of digital thermoelectric Generator based power systems, which the student designed using Arduino microcontroller programming control and COMSOL Multiphysics modeling and simulations.

Lessons Learnt

The main point is that every great design starts with a brilliant idea, but translating that idea into actions requires planning. So before one can write any code, or design any system, one has to take the time to explore the possible techniques and technologies. The main challenge for non micro-controller based TEG systems is that the utilization efficiency of the energy is low, a large amount of the generated energy may be wasted. Hence there is a potential need for an energy management system which can acquire, store and deliver energy efficiently, with minimum energy wastage. With proper mentoring, capable tutelage, and guidance, these burgeoning and talented young students will contribute to the best practices in implementing future system design and apps development.

Results

So far we have used this series of modular design projects only on two sets of students. The first experimental set of students have given us some limited feedback. Overall the student critique was positive but some of them feel they were overwhelmed by too much information. Here is a small representative sample of the student critiques:

- "I had no clue about COMSOL MultiPhysics modeling earlier but now I feel comfortable and at ease."
- "I think I know the basics of C and Arduino interface programming but still far from mastery of the subject."
- "It is too much to learn, but I can think and analyze better than before."

Concluding Remarks

Currently we are in the process of utilizing the multi-agent approach which allows the student teams to take full control of the project from inception to completion. .The students demonstrated an enhanced understanding of the alternative route for green energy with renewed design emphasis on Digital Parasitic applications that employs Thermoelectric Generator Peltier instead of traditional analog mechanization. We have collected no data to quantify if this approach will be satisfactory with all our capstone senior project students, since the new batch of students have just started taking their senior project capstone course sequence.

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Appendix A

Waste Heat Recovery

Industrial waste heat refers to energy that is generated in industrial processes without being put to practical use. Sources of waste heat include hot combustion gases discharged to the atmosphere, heated products exiting industrial processes, and heat transfer from hot equipment surfaces. Some of the most widely used waste heat recovery technologies are in Figure A1. The study proposes to generate electric power by providing waste heat or unharnessed thermal energy to built-in thermoelectric modules that can convert heat into electric power.

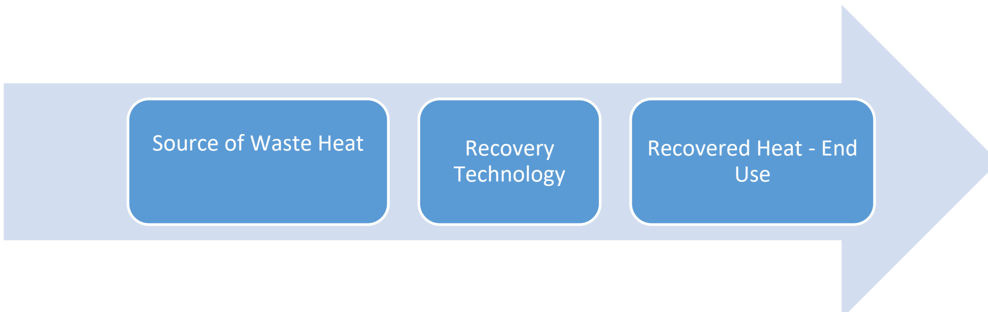

Figure A1. Three essential component required for waste heat recovery [11]

The thermoelectric modules are the basic building blocks that constitute thermoelectric power generators or coolers. Figure A2 depicts the arrangement of the different constituents of a thermoelectric module. Modules essentially are a matrix of semiconductor thermoelectric couples which are connected electrically in series and thermally in parallel. The four main different constituents of a thermoelectric module are as follows:

1. Thermoelectric elements (legs)
2. Ceramic substrates
3. Metal interconnects
4. External electrical connections

Thermoelectric coolers (TEC) are solid-state heat pumps that operate according to the Peltier effect: a theory that claims a heating or cooling effect occurs when electric current passes through two conductors. When a voltage is applied to the free ends of two dissimilar materials creates a temperature difference, with this temperature difference, Peltier cooling will cause heat to move from one end to the other. This will allow us to include more TECs in parallel, and will help increase the cooling surface. Current design emphasis is on finding an economical alternative solution which employs cooling of TEC with cooling fans units and thereby will be more practical for even cooling the TEGs.

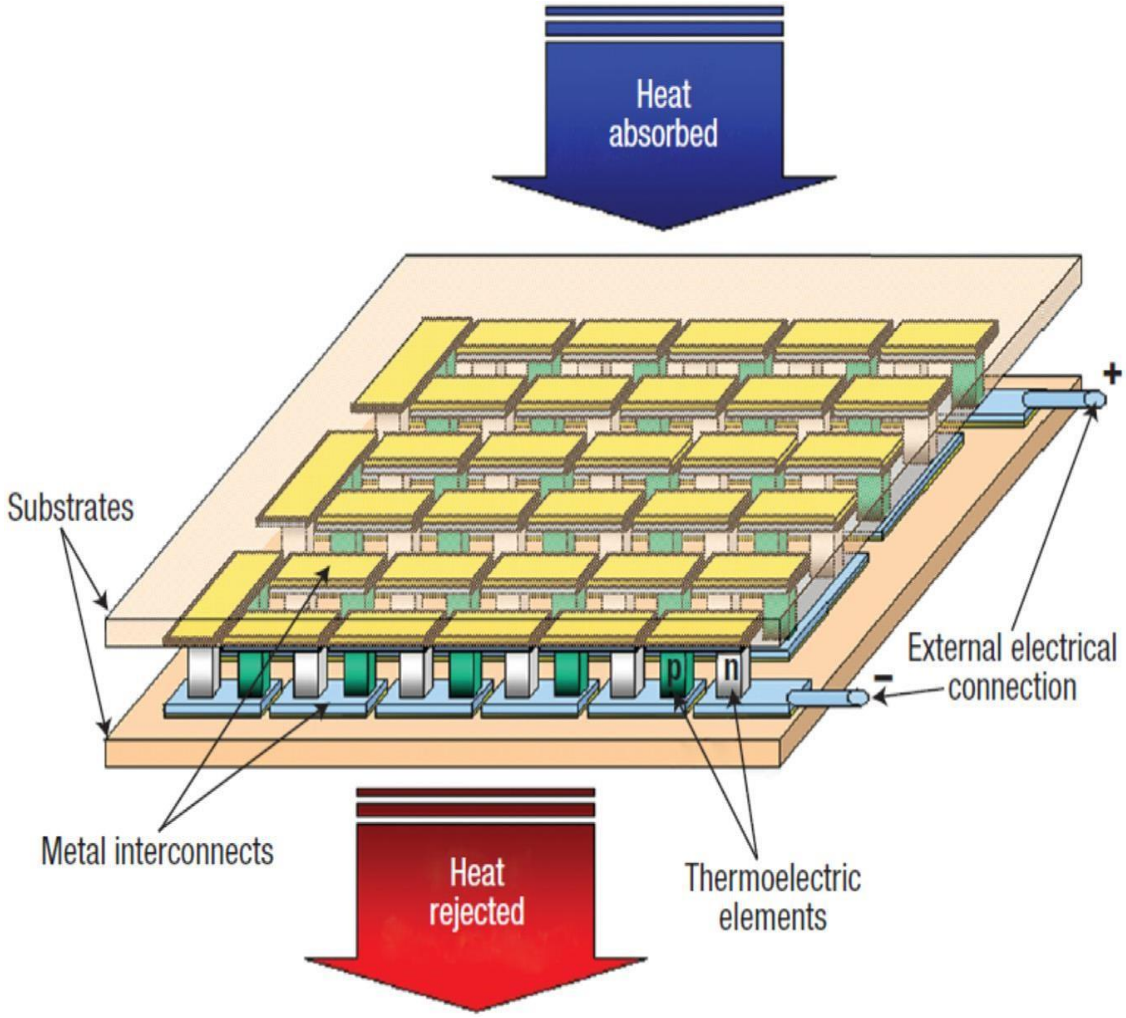

Figure A2. Constituents of Thermoelectric module [7]

The pioneer scientist Thomas Seeback in 1821 proposed and demonstrated that establishing a thermal gradient between two dissimilar conductors can produce electricity. This temperature gradient contributes to the diffusion and flow of charge carriers between the hot and cold regions and in turn creates a voltage difference. Thirteen years later Jean Peltier verified the reverse effect that running an electric current through the junction of two dissimilar conductors could, depending on the direction of the current, cause it to act as a heater or cooler. Figure 35 shows its thermal network, It consists of thermal resistances between the heat source between the heat source and Thermoelectric module (TEM), thermal resistance of TEM, and thermal resistance between the TEM and the heat sink [11].

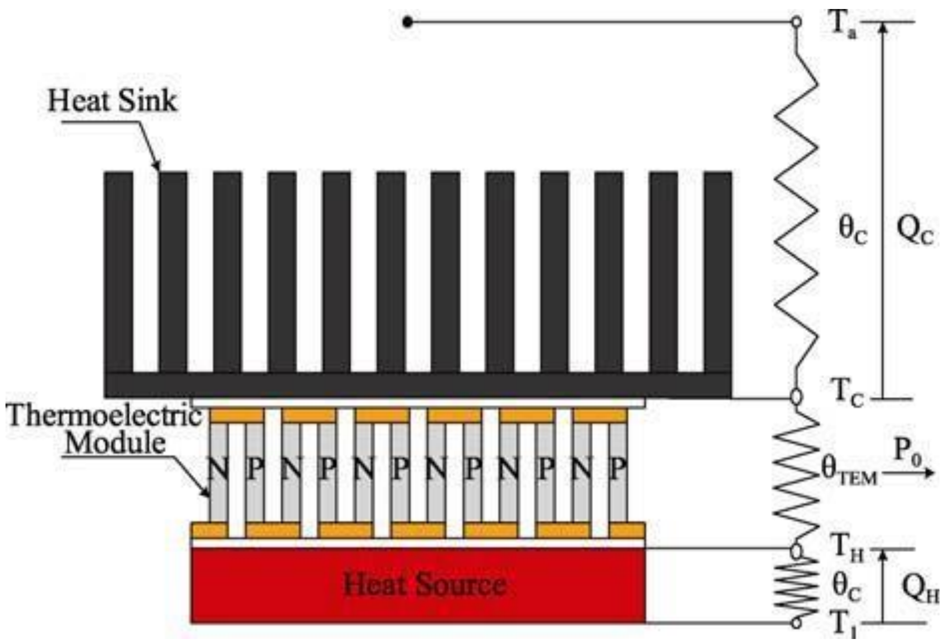

Figure A3. Structure and thermal resistor network of thermoelectric generator

Thermodynamic Principles

We make use of basic equation for radiation, when two objects at different temperatures are within close proximity of each other, and how heat is exchanged between them. When this occurs the electromagnetic radiation is emitted from one object and transmitted to the other object surface. The hot object being the TEG will experience a net heat loss from the TEC as a cold object, and a corresponding net heat gain as a result of the temperature difference. The TEC's Digital Thermoelectric Heat Pump design [4] takes advantage of this passive heat load in the following fundamental equation which describes radiation heat loading as follows:

$$Q_{rad} = F^* e^* s ^*A ^*(T_{amb}^4 - T_c^4)$$

where as Q_{rad} = radiation heat load (watts), F = shape factor, e = emissivity, s = Stefan-Boltzman's constant (5.667 X 10^{-8}w/m^{2}K^4), A = area of cooled surface (m^2), T_{amb} = Ambient temperature (Kelvin) and T_c = TEC cold ceramic temperature. Rearranging, we get

$$T_C^4 = -\frac{Q_R}{F \cdot e \cdot S \cdot A} + T_{Aamb}^4 ,$$

This equation clearly depicts that creating an efficient Heat Pump relies on maximum amount of radiation heat load divided by Stefan Boltzman's Constant and terms denoted by emissivity, area of cooling surface, shape factor and added ambient temperature to create latent heat in cooling the hot side of the TEG, thereby energy is released or absorbed. To create this TEC Heat Pump, we simple enhance voltage and high current. Normally the TEC would heat-up due the natural resistance element of the semi-conductor material in accordance with Peltier Effect, however when we add a heat sink and high velocity fans, it provides efficient heat transfer to and from the TEC. This in turn forms a heat pump [5] application, where the adjacent side becomes a cold surface which provide the proper element to create the thermodynamics differential needed to sustain the Seebeck effect for the TEG, which relates to the term T_C^4 in the radiation formula which corresponds to T_c term in the Seebeck's formula. This explains how TEC can be integrated into the cold differential side of the TEG.

The important parameters regulating thermoelectric cooler application are discussed next. The hot surface temperature (Th), the cold surface temperature (Tc), and the heat load to be absorbed at the cold surface (Qc). The TEC hot is where heat is released when DC power is applied. This in turn would be attached to the heat sink or another TEC-to-TEC-to-heat sink thereby creating a 3 stage cooling unit. The idea is to superimpose cooling area of the hot side, and increase the transfer of latent heat. Qh signifies the heat released from the hot side of the thermoelectric (watts), to cold surface Qc. This in turn results in enhancing the dynamics and performance coefficient of the thermoelectric device, TEG.

Power dissipated at the silicon level produces heat that must flow through the IC packaging material, to the case, through the thermal interface between the case and the heat sink, to the heat sink, and finally into the surrounding air. These parameters combine to define the junction temperature.

$T_J = T_A + P(\Theta_{JC} + \Theta_{CS} + \Theta_{SA})$

where

T_J = silicon junction temperature of the IC-a specification

T_A = ambient temperature (of the air *immediately* surrounding the package)

P = power that the IC must dissipate

Θ_{JC} = thermal resistance between the *junction* and the *case*. This too is a specification of the IC.

Θ_{CS} = thermal resistance between the *case* and the heat *sink*.

Θ_{SA} = thermal resistance between the heat *sink* and the *air*.

Rearranging the basic thermal equation to solve for the maximum allowable heat sink thermal resistance gives:

$$\Theta_{SA\,max} = \frac{T_{J\,max} - T_{A\,max}}{P_{IC\ worst\ case}} - \Theta_{JC} - \Theta_{CS}$$

In still air, the temperature of the layer of air immediately surrounding the heat sink may be considerably higher than the air only a few centimeters away. This raises T_A, thereby forcing to obtain a larger heat sink with a lower thermal resistance.

Power Systems Analysis

The emphasis is on the power delivery system which takes full advantage of the unique Peltier design principle. It incorporates a typical thermoelectric module comprising of an array of semiconductor tablets that have been arranged into a grid layout in a way that will polarize positive or negative (P/N) charges and thereby creating a voltage. It implies that power is generated by Thermodynamic property due to temperature difference between the cold (heat sync) & hot side (thermo-sync). P-DTG Power System's TEGs thereby produces electricity and utilizes thermodynamic element of generating positively charged particles which is consistent with TEG's Seebeck Effect:

$Q_p = \pi I = \alpha \mathrm{T} I;$

in which the phenomenon process Thomas Seebeck Effect in two junctions due to conductivity of materials and temperature difference create a voltage within the semiconductor.

$V_s = \alpha(T_h - T_c);$

As such this will generate power by thermodynamics temperature gradient between the cold side (heat sync) and hot side (thermo-sync). In Power Generation formula, Seebeck voltage V_S value is further illustrated as shown below:

$$P = I^2 R_L = \left(\frac{V_s}{R_i + R_L}\right)^2 R_L = \left(\frac{\alpha(T_h - T_c}{R_i + R_L}\right)^2 R_L.$$