Three Dimensional Modelling Integrated Thermoelectric Generator-Photovoltaic Thermal (Teg-Pvt) System Used COMSOL

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Abstract— **A Three dimensional steady state heat conduction thermo electric current model was created in COMSOL Metaphysics to study the performance of thermoelectric generator-photovoltaic-thermal (TEG-PVT) system. Four different cases were studied in the paper. In case 1, PV cells without concentrator was simulated while in case 2, concentrator ratio range from 2 to 5 was utilized In case 3, the convection heat transfer coefficient was varied between 6.2 and 14.2 W/m2K. The value of thermal insulation between Photovoltaic cells and TEG was decreased for case 4. The results indicate that having higher concentration ration results in more power generation while increases convection heat transfer coefficient between outside surfaces and atmosphere and lower thermal resistance between PV cells and TEG help keep the PV temperature at optimum level.**

Keywords—**TEG,PVT,FEA,CFD,COMSOL**

INTRODUCTION

Traditional thermodynamic steam cycles require large amounts of heat to convert the working fluid into a vapor form before it is passed through a turbine. That turbine drives a generator to create electricity. However, in low heat applications, it is inefficient to use a traditional cycle, such as the Rankine cycle, because there is insufficient heat to properly convert the working fluid to a vapor. The initial cost of the equipment necessary for a Rankine cycle, such as pumps and turbines, also makes traditional cycles unappealing due to the low rate of return. Thermoelectricity, however, requires relatively little upfront cost. The devices necessary are also small and the materials are less toxic. Unfortunately, they do not generate power on the magnitude of the traditional steam cycles due to the low efficiency levels of thermoelectric modules. Applying the Peltier and Thomson effects, thermoelectricity has been used frequently for thermal conditioning of electronics. By passing a current through a junction of two different conductors, a thermal gradient is created. On the other hand, if a thermal gradient can be maintained between two junctions of a thermoelectric (TE) module, then electrical power can be generated, also known as the Seebeck effect. As integrated circuits decrease in size yet increase in their power consumption and essentially power density, traditional cooling systems may become obsolete in their efforts to properly cool electronics for normal operation. While thermoelectricity has been proven for cooling uses, opportunities are arising to benefit from power generation. The power solicited may not be considerable, but waste energy is free, thereby increasing the potential for economic and efficient reuse of energy.

The advantages of TE devices to be able to both cool electronics and generate power can be leveraged to reduce data center operating costs. In Figure 1, the equipment heat loads as provided by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc. (ASHRAE) can be seen [1].

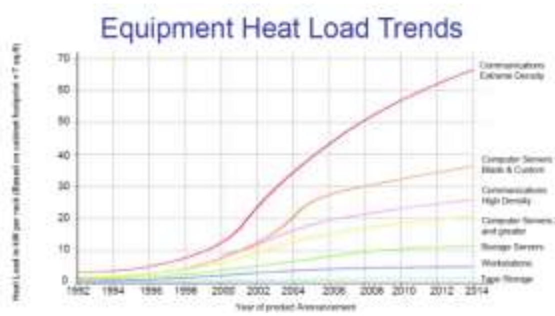


Figure 1- ASHRAE Equipment Heat Load Trends [1]

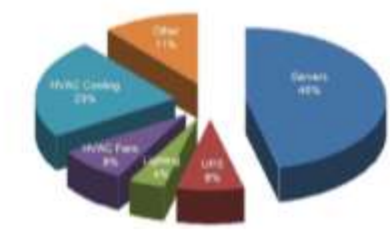


Figure 2- Average Data Center Power Allocation for 12 Benchmarked Data Centers [3]

This percentage may decrease due to alternative cooling methods with increased efficiency. The emphasis, however, is placed on the servers themselves and the efficiency of the electronics. Over 40 percent of electrical power consumption in data centers is spent on servers, and essentially all this power is rejected through waste heat. Since this waste heat is rejected to ambient and no longer used, it represents energy that is essentially free and can be potentially used as a green alternative energy source.

Problem Description

The objective of this project is to analyze the efficiency of applying TE devices to a data center to assess the practicality and feasibility of waste heat recovery. Data centers produce relatively low temperature waste heat when compared to other applications. The efficiency of the electrical conductors used in thermoelectric waste heat recovery can be used to assess the magnitude of power generation. Material selection is necessary to optimize the efficiency of the thermoelectric modules while maintaining an economic solution as well as selection of the optimum heat sink to make execution of TE devices in a data center realistic.

Literature survey

Several investigations and studies have been completed concerning the subject of materials for TE devices and recovering waste heat as a green energy source. Thermoelectric technology is used in countless applications to power small electronics, or harness enough energy from large heat producing sources to power smaller applications, such as using the waste heat from an automobile to power the internal computers. Most often, TE devices are investigated for their use as a cooling device by benefiting from the Peltier effect.
An analysis of thermoelectric cooling of personal computer circuits and waste heat power generation was conducted by C.A. Gould et al. [4]. This was conducted by mounting TE modules onto personal computer microprocessors and operating the computers over various levels of processing. For electrical power generation, a TE module was able to generate a small amount of power in microwatts.

Automobile manufacturers have also investigated the use of TE devices for waste heat recovery as explained by Meisner [5]. Following combustion, approximately 40 percent of gasoline is exhausted through waste heat. The auto industry is working to capture some of that waste heat through TE modules in the exhaust piping in order to power devices that normally drain battery life. The goal is to redesign the auto electronics to run on battery power as the primary power source rather than siphoning power generated by the combustion of gasoline. The role of gasoline combustion would then be to charge the batteries vice running the car. Thermoelectric modules can be used to supplement the gasoline combustion for usable energy and therefore increasing fuel efficiency.

Overall, efficiency levels of TE devices are rated much less than conventional heat engine cycles, thus granting minimal returns for generating electricity. Thus, data center waste heat recovery has not been extensively documented due to the low temperature of the heat rejected.

METHODOLOGY

In order to determine the feasibility and economic practicality of using thermoelectricity for large scale waste heat and energy recovery, the following approach will be adopted:

1. Establish a realistic data center based on published data and investigation. Then define normal operating parameters for operation including, but not limited to, electronics electrical power consumption, electronics heat rejection, electronics operating temperature, cooling approach, cooling load requirements, and cooling system power consumption.
2. Determine the potential thermal gradient between heat source and heat sink and relate to an appropriate thermoelectric module material selection to optimize efficiency with consideration to cost.
3. Based on cooling load requirements, determine the operating conditions for the cooling system.
4. Design cooling system loop using traditional heat exchange equipment to reject full electronics heat load and maintain constant cooling temperature.

Assumption: Cooling by way of the thermoelectric module will be neglected for this investigation since a current is not being applied to the thermoelectric module.

5. Analyze, assess, and make recommendations towards whether heat sink is appropriate to maximize temperature difference and energy recovery.
6. Investigate potential electricity generation based on chosen thermoelectric module and efficiency calculations, properties of the materials, environmental conditions of the electronics and cooling system, and figure of merit of the thermoelectric material.
7. Compare and analyze the model electricity generation for data center identified in Step 1 as well as the cost implications for using thermoelectric modules.

3.Thermoelectric Couple Basic Configuration

The thermoelectric effect can be defined by two processes, the Peltier and Seebeck effects.
The Peltier effect occurs when a voltage is applied to two connected electrical conductors made of different materials. When the voltage is applied, a circuit can be created that allows for continuous heat transport between the conductor's junctions [6].
The opposite also applies such that a voltage can be generated by applying a temperature difference to the two connected electrical conductors, which is known as the Seebeck effect. This temperature difference results in a transfer of thermal energy across the electrical conductors and causes charge carriers to also diffuse through the materials. These charge carriers can be either electrons, or electron deficiencies called holes, and move within the crystals of the materials by way of electron flow from the cold side to the hot side of the TE couple. The heat is transferred in the same direction as the charge carrier flow, from the cold side of the TE couple to the hot side. By leaving positively charged nuclei to collect on the cold side of the TE couple while the charge carriers move towards the hot side, a thermoelectric voltage is generated.

This results in the potential to generate an electrical current if a complete circuit can be created, as seen in Figure 3.

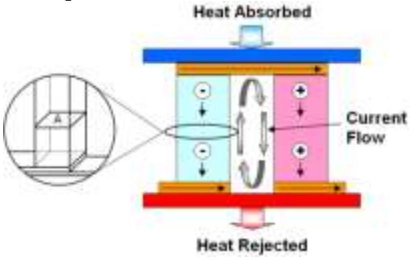


Figure 3- Example of Thermoelectric Junction

Typically, semiconductors are used in TE couples because they can be doped with additional electrons or electron holes creating species to increase the Seebeck coefficient. Normal metal conductors have smaller coefficients due to equilibrium of positive and negative charges in the material that would induce the thermoelectric voltage. A larger amount of charge carriers on the hot side of the material results in a higher thermoelectric voltage, and hence semiconductors are optimum for TE devices.

Meanwhile, a TE couple uses two dissimilar electrical semiconductors electrically in parallel because if the two semiconductors used to complete the electrical circuit are the same, then the charge carrier flow would negate itself. There will be equal and opposite charge carrier flow between the two semiconductors (each individual leg is commonly referred to as a pellet) rather than single direction charge carrier flow, which generates a current flow. Commonly used semiconductors are N and P types. N type semiconductors can be doped such that it has excess electrons, which move towards the positive side of the TE couple. A P type semiconductor is so doped as to have a positively charged carrier and is thus doped with holes, which move in a direction opposite to the flow of electrons. In both semiconductors, the charge carriers direct the direction of heat flow, which proceeds in the same direction as the charge carrier, but electrons and holes move in opposite directions. This allows for a continuous electrical current to be generated. Thermoelectric materials are gauged by their figure of merit, which represents their quality of performance, or efficiency, and is defined by the following:

$$Z = \frac{\alpha}{\rho\kappa} \qquad (1)$$

Where α is the Seebeck coefficient, ρ is the electrical resistivity, and κ is the thermal conductivity. The Seebeck coefficient is a material parameter used to determine the efficiency of a given thermoelectric material because it is a measure of the thermoelectric power of a material. This thermoelectric power, or thermopower, of a material measures the magnitude of voltage stimulated in response to a temperature difference across that material. The larger a thermoelectric voltage that can be induced combined with a higher Seebeck coefficient results in a higher efficiency.

Low electrical resistivity and thermal conductivity are necessary for a high figure of merit. The figure of merit is commonly multiplied by temperature because both the electrical resistivity and thermal conductivity are temperature dependent, therefore making the figure of merit temperature dependent. This also provides the dimensionless figure of merit. The figure of merit can also be defined based on the electrical conductivity σ as seen here:

$$ZT = \frac{\alpha^2 \sigma T}{\kappa} \qquad (2)$$

The maximum efficiency η of a TE device can be defined using the figure of merit, as well as the temperatures of the hot and cold junctions, TH and TC, respectively.

$$\eta_{\max} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}}$$

P and N type materials have different figures of merit and are averaged to determine a material's overall quality. To maximize the efficiency of a TE device, P and N type semiconductors are placed in series electrically, but are thermally in parallel, which creates a couple as seen below in **Error! Reference source not found.**.

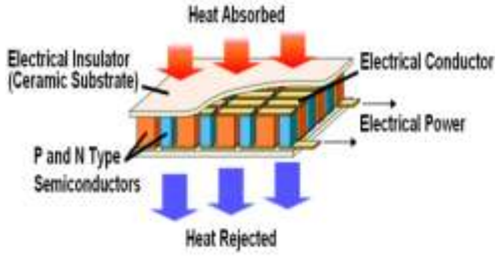


Figure 4- Multiple TE Devices Arranged in a Parallel Configuration

By linking multiple TE couples in series electrically, the TEG can operate at a larger voltage. Industry standards indicate that TEG modules can have on the magnitude of 71 or 127 couples operating at upwards of 6A.

4.Data Centre Cabinet Heat Load

The investigation of known data centre operators and electronics cabinet manufacturers was completed to determine a nominal heat load value for a single typical water cooling cabinet. After inspection of water cooled units by APC®, Black Box Networking Solutions®, HP®, Intel®, and Rittal®, the cooling capacity of the single cabinets is seen to range from 20 kilowatts (kW) to 37 kW for standard level high density electronics cabinets with negligible heat losses to ambient for each unit. Electronics cabinet manufacturers are constantly upgrading their technology to meet the cooling demands of modern electronics. Numerous other manufacturers also provide solutions to supplement current cabinet technology to improve the cooling capacity. For this project, the standard heat load of a single electronics cabinet is defined conservatively at 25 kW based on the above values Data Centre Air Flow Rate When employing air-to-liquid heat exchangers internal to the electronics cabinets, the ability of the heat exchanger to effectively cool the electronics is dependent on the volume of air throughput expressed in cubic feet per minute (CFM). By increasing the airflow across the electronics per a given time, the heat removal capacity increases. This is primarily controlled by the use of fans that supplement cooling coils in a heat exchanger. The size of the fans used directly correlates to CFM; the larger the fan, the more the airflow. However, as fan size, revolutions per minute (RPM), and the number of fan blades increase, so does the cost associated with the unit and vibration and acoustic noise levels. Also, fans have limits, because even as they increase in CFM, they cannot cool to lower than the surrounding temperature [9].

One way to determine the optimum amount of CFM necessary for the cooling load is to use the following formula that correlates the heat load, airflow, and temperature difference between intake and exhaust air temperatures in °F.

$$Watts = .316 \times CFM \times \Delta T \qquad (26)$$

This can be rearranged to solve for CFM:

$$CFM = \frac{Watts}{.316 \times \Delta T} \qquad (27)$$

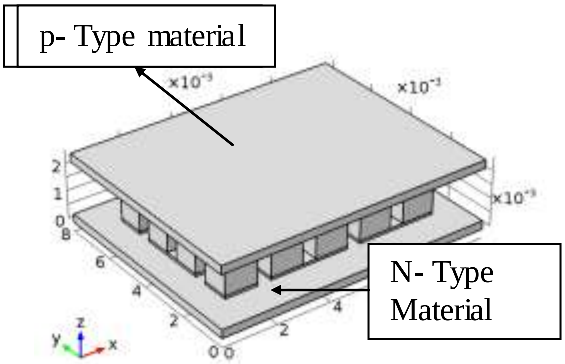
Typical data centers use a ΔT value of 20°-30°F. Applying the electronics heat load defined above of 25 kW to equation (27), the corresponding CFM values for each of these temperature differences is as follows:

Table 1- CFM Values for Given Temperature Differences with a 25 kW Heat Load

ΔT	**CFM**
20°F	3956
30°F	2637

5.Thermoelectric Material Selection

Based on the data center functional parameters defined above in Section **Error! Reference source not found.**, the materials for the TE device can be determined. The heat transfer equation seen below can be used to calculate the temperature of the electronics exhaust air.



$$Q = \dot{m} c_P \Delta T \qquad (28)$$

Where Q represents the cabinet heat load, $\dot{m}$ is the air flow rate, c_P is the specific heat, and ΔT represents the temperature difference between the exhaust temperature entering the air-to-water heat exchanger and the electronics intake air temperature. Rearranging equation (28) and substituting for ΔT , the exhaust air temperature, or essentially the hot junction temperature, is calculated here.

$$T_H = \frac{Q}{\dot{m} c_P} + T_C \qquad (29)$$

Where $\dot{m}$ for air can be defined as:

$$\dot{m} = \dot{V} \rho \qquad (30)$$

For this temperature level, the most commonly used semiconductor material choice is Bismuth Telluride (Bi_2Te_3). This material has a high figure of merit for the relatively low operating temperature range applicable to electronics cooling. **Error! Reference source not found.** shows a chart of the dimensionless figure of merit for various P-type semiconductors over a wide temperature range.

Thermoelectric Generator Implementation Using Comsol: Standard practice for connecting TEGs for the purpose of waste heat recovery is to use to directly connect the TEG to the heat producing object for the heat source, in this case the electronics packages. This can be completing using either solder or connecting screws. The TEG is then connected to a fin array that is used as a heat sink as seen in **Error! Reference source not found.**. A fan is regularly implemented to blow air across the fin array for convective cooling.

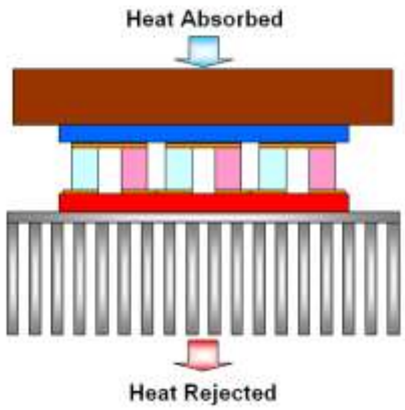


Figure 5- Standard Thermoelectric Module Configuration for Waste Heat Recovery

However, in this application the cooling air would only be operating at approximately 300K, thereby limiting the temperature difference across the TEG. Thus, for a liquid cooled cabinet, a way to implement the TEG would be to attach the modules to the heat sink, in this case cooling coils. The fin array would be placed on the upstream side of the cooling coil, thereby letting the hot air at approximately 316K operate as the heat source. The cooling coil, operating at 285K would then be the heat sink for heat rejection, seen in **Error! Reference source not found.**.

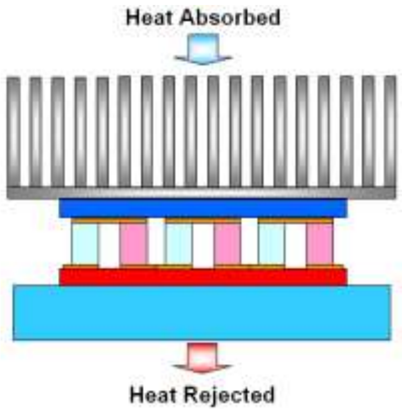


Figure 6- Thermoelectric Module Configuration for Liquid Cooled Cabinets

6.Results

The data center parameters defined in Section **Error! Reference source not found.** were applied to a typical TEG using the material properties defined in Section 0. First, a pellet of a TE couple was modeled using COMSOL Multiphysics as seen in Appendix B. This modeling showed that a single pellet of a TE couple, regardless of whether it was p- or n-type, can generate an approximate voltage of 0.015V when a thermal gradient of approximately 31K is applied. When extrapolated to a single 254-pellet thermoelectric module, low single digit voltages can be generated.

After validating the ability to generate a voltage, a practical energy generation scenario was calculated as seen in Appendix B. Applying the equations described in Section **Error! Reference source not found.** to the operating temperatures of the data center defined in Section **Error! Reference source not found.**, the number of TE modules and optimum configuration were determined. In this application, in order to generate a power output of approximately 18W, operating with a 12V output and 1.5A current, approximately 65 TE modules were required for the TEG. The module chosen was a typical 127-couple, 6A module. In order to maximize efficiency of the TEG, the modules were connected in a series-parallel configuration to attempt to equal the resistance load. This resulted in a configuration of 4 parallel strings of 13 modules placed in series.

The heat input to a single TE module is approximately 38W, and approximately 2500W for the TEG. The resulting efficiency of the TEG was approximately 0.7%. Modelling of a Bismuth Terruride TE pellet using COMSOL Metaphysics software.

Pellet size, 1mm x 1mm x 6mm, with 0.1mm copper electrodes on either side.

Property	**Symbol and Unit**	**Bismuth Telluride**	**Copper**
Thermal conductivity	k- W/(m·K)	1.6	350
Electric conductivity	σ- S/m	1.1e5	5.9e8
Seebeck coefficient	S- V/K	P: 200e-6 N:-200e-6	6.5e-6

The bottom of the pellet was maintained at 0V and the top of the pellet maintained at 316.82K. The voltage for the top of the pellet was varied until the operating temperature difference was achieved.

Table 2 - Resultant Temperature, Current, and Power for Varying Voltages

Across a Single Bismuth Telluride 1mm x 1mm x 6mm Pellet

Voltage (V)	Temperature (K)	Current Density (A/m2)	Current (A)	Power (W)
0.05	350	6.65E+05	0.6654	0.03327
0.04	355	5.04E+05	0.50432	0.020173
0.03	360	3.58E+05	0.35813	0.010744
0.02	365	2.26E+05	0.226	0.00452
0.018	370	2.01E+05	0.20119	0.003621
0.016	375	1.77E+05	0.17688	0.00283
0.015	380	1.65E+05	0.16492	0.002474
0.0148	385	1.63E+05	0.16255	0.002406
0.014	390	1.53E+05	0.15309	0.002143
0.012	395	1.30E+05	0.12979	0.001557
0.01	400	1.07E+05	0.10699	0.00107

Table 3 - Resultant Temperature, Current, and Power for Varying Voltages Across a Single Bismuth Telluride 2mm x 2mm x 6mm Pellet

Voltage (V)	Temperature (K)	Current Density (A/m2)	Current (A)	Power (W)
0.05	350	6.65E+05	2.6616	0.13308
0.04	355	5.04E+05	2.01728	0.080691
0.03	360	3.58E+05	1.43252	0.042976
0.02	365	2.26E+05	0.904	0.01808
0.018	370	2.01E+05	0.80476	0.014486
0.016	375	1.77E+05	0.70752	0.01132
0.015	380	1.65E+05	0.65968	0.009895
0.0148	385	1.63E+05	0.6502	0.009623
0.014	390	1.53E+05	0.61236	0.008573
0.012	395	1.30E+05	0.51916	0.00623
0.01	400	1.07E+05	0.42796	0.00428

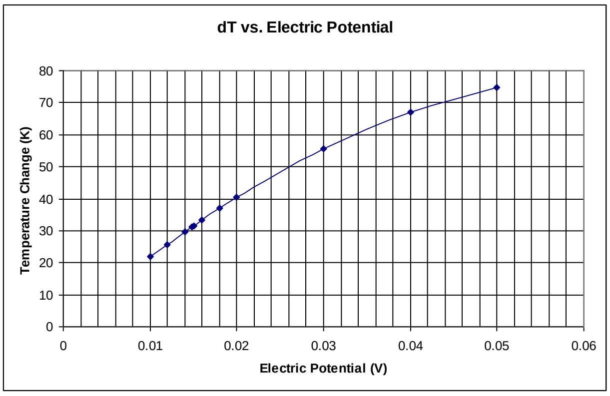


Figure 7- Change in Temperature Across TE Pellet Based on Electrical Potential

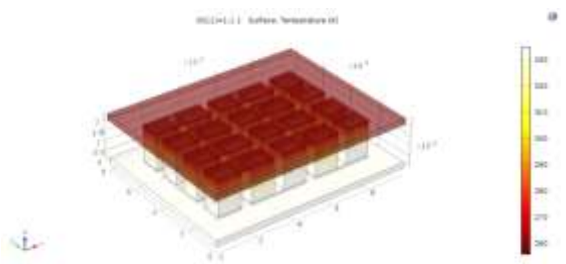


Figure 8- Surface Temperature Across TE Pellet

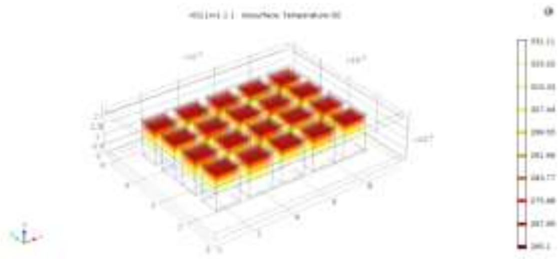


Figure 9- Electric Potential Across TE Pellet

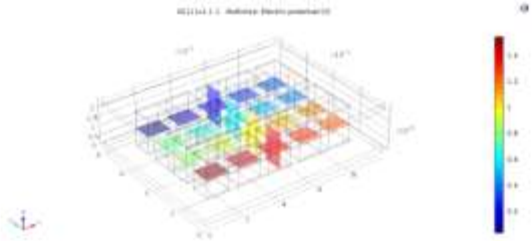


Figure 10- Current Density in TE Pellet

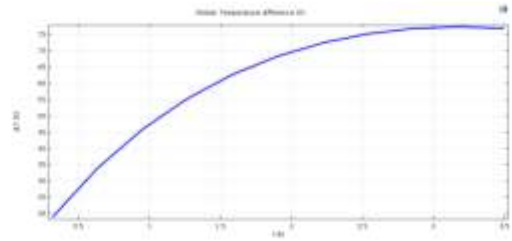


Figure 20- current density Vs Coefficient of temperature

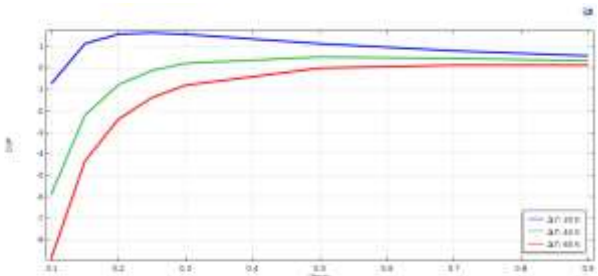


Figure 21 Coefficient of Performance

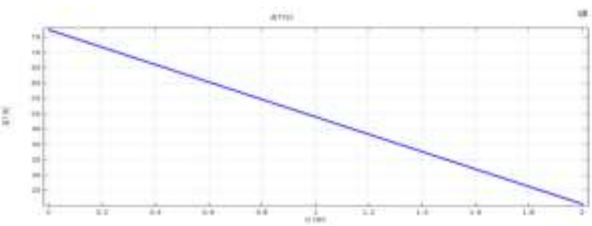


Figure 22 Coefficient of Performance

7.Conclusion

A standard data centre was defined using real world practical components and functional operating conditions. A TEG was created based on the operating conditions of that data centre, primarily focusing on the operating temperature of the servers, cooling air temperature, and cooling system heat sink. While an infinite amount of configurations exist that may better define an operational scenario, this investigation provided an evaluation of a typical data center and a simple application of thermoelectric. Unfortunately, as seen in Appendix B, and discussed in Section 0, the approximate efficiency in using TEGs for waste heat recovery for low temperature data centres is below 1%. As stated earlier in Section **Error! Reference source not found.**, the power output is directly related to the square of the temperature difference.

8.Future scope

In this application, a temperature difference of approximately 30K was achieved while trying to optimize that temperature difference. With increasing heat densities in liquid cooled electronics cabinets, the effort of producing approximately 18W from a 25000W cabinet is not practical. Given the costs of standard model thermoelectric modules, this can result in thousands of dollars in order to implement a 65 module TEG. While the power generation is feasible, the costs of implementing such a system make it ineffective. A return on the initial investment would not be achieved before the servers themselves became outdated. While thermoelectric are appropriate for applications with low power devices, where moving devices are not desired, and physical size is a concern, they do not have the efficiency desired to make an impact on a data center level. The temperature difference created between standard operating electronics and standard cooling systems is not large enough. Typically, a temperature difference of greater than 100°C is desired for measurable returns.

Thus, thermoelectric devices can be used for waste heat recovery, but they have minimal efficiency and prove to be not cost effective for data centres.

References

The following published works will be used as guidance and references in performing this study:

[1] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Datacom Equipment Power Trends and Cooling Applications, ©2005.

[2] U.S. Environmental Protection Agency ENERGY STAR Program. Report to Congress on Server and Data Center Energy Efficiency Public Law 109-43, 2 August 2007.

[3] Koomey, Jonathan G., Ph.D. Estimating Total Power Consumption by Servers in the U.S. and the World. Lawrence Berkeley National Laboratory, 15 February 2007.

[4] Gould, C.A.; Shammas, N.Y.A.; Gainger, S.; Taylor, I.; Thermoelectric cooling of microelectronic circuits and waste heat electrical power generation in a desktop personal computer. Staffordshire University, Beaconside, Stafford, UK. Elsevier B.V. 2010.

[5] Meisner, Gregory P. Advanced Thermoelectric Materials and Generator Technology for AutomotiveWaste Heat at GM. General Motors Global Research and Development, Warren, MI. January 2011.

[6] Saied, Widah. Essentials of Thermoelectric (TE) Cooling, With an Emphasis in Thermal Control of Electronics. San Jose State University. www.engr.sjsu.edu.

[7] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Liquid Cooling Guidelines for Datacom Equipment Centers. Atlanta. ©2006.

[8] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2011 Thermal Guidelines for Data Processing Environments – Expanded Data Center Classes and Usage Guidance. ©2011.

[9] Pentair Technical Products. Overview & Design of Data Center Cabinets, Anoka, Minnesota. 2010.

[10] Bar-Cohen, A., Solbrekken G. L., and Yazawa, K. (2005). Thermoelectric Powered Convective Cooling of Microprocessors, IEEE Transactions of Advanced Packaging, 28(2).

[11] Ferrotec (USA) Corporation. Thermal Reference Guide. 2012, http://www.ferrotec.com/technology/thermal/thermoelectric-reference-guide/.

