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Development of Thermoelectric Generator for Automotive Current Generation System

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Abstract: The aim of this project is to develop and study the potential of renewable energy source through heat waste recovery by the application of thermoelectric generator (TEG). TEG system offers direct conversion of energy from heat waste into electrical powers. Main objectives are to obtain fundamental theory and characteristic of thermoelectric in automotive system, evaluating thermoelectric generator compatible for powering up automotive electrical system and also to develop an alternative to alternator function for commercial value. The model of thermoelectric generator system is designed in Solidworks and Ansys Workbench is used for simulation purpose. Parameters involved in this project are temperature input, temperature at thermoelectric generator module hot side, temperature at thermoelectric generator module cold side, temperature difference, voltage output, seebeck coefficient and thermoelectric generator efficiency. Minimum and maximum input temperature is 100℃ and 325℃ respectively. Results of this simulation is focused on voltage generation with efficiency achieved as key findings. Lowest voltage produced from the simulation is 3.50V at 4.29℃ of temperature difference and highest voltage generated is 9.72V at 93.43℃ of temperature difference. Lowest recorded efficiency is 1.10% and highest efficiency is 6.07%, giving a 4.97% difference between lowest and highest efficiency value. This study can help future researchers to improve development of thermoelectricity in automotive applications.

Keywords: Thermoelectric, Automotive, Energy Recovery

1. Introduction

Energy demand is increasing steadily accompanied by population growth. One of the most used energy sources around the world is oil, which is a non-renewable energy. According to International Energy Agency, global oil production is estimated to have fallen by 6.6 million barrels per day, which records the largest drop since post war era. Hence, it can be seen that the supply response has been underwhelming to justify the increasing demand. Oil demand and supply as of 2020 is shown in figure 1.

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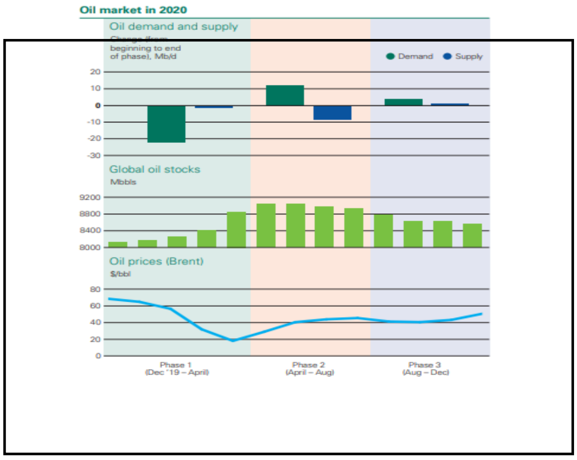

Figure 1: Oil market in 2020

This study practically targets the usage of oil in automotive industry since 48.6% of all oil consumed in 2020 was related to motor vehicle functions, as referred by Organization for Economic Co-Operation and Development. About two thirds of energy in gasoline used in motor vehicles is wasted as heat. This is due to the internal combustion engine which has the maximum efficiency of almost 25% while losing 75% energy in the form of heat waste from exhaust gases and engine coolant. The energy usage chart is shown in figure 2.

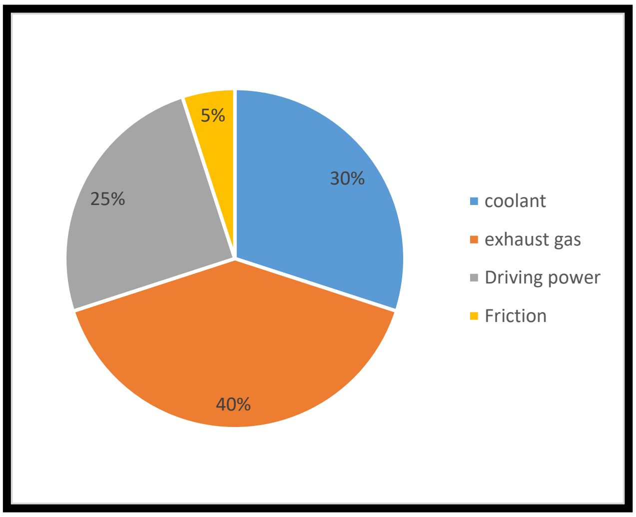

Figure 2: Automotive energy usage chart

1.2 Energy Recovery with Thermoelectric Generator

The 75% of energy discarded as heat waste however, can be recovered by converting it into other form of energy such as electricity, which can be achieved through thermoelectricity. Thermoelectric is a concept that converts heat into electricity, particularly through usage of thermoelectric generator (TEG). TEG harvests heat waste from the surrounding and converts it into electrical energy which can be used to power up appliances, which can potentially exploit heat waste generated by a motor vehicle.

Thermoelectric generator consists the element of thermoelectricity, where the heat is used to directly generate electrical powers. This process of turning heat into electrical power is called as Seebeck effect, a phenomenon discovered by Thomas. J Seebeck in 1820s [8]. In this phenomenon, the temperature differences between two dissimilar electrical conductor or semiconductor produces a voltage difference between two materials. Therefore, bigger temperature difference can generate larger voltages.

Implementation of TEG system in automotive can be challenging due to its low efficiency. This efficiency performance is affected by input conditions, such as temperature difference between hot side and cold side. Thus, suitable TEG placement in motor vehicle for TEG needs to be determined to utilize the best possible outcome by largest temperature difference.

1.3 Previous Research of Thermoelectricity on Automotive

The application of TEGs to the recovery of medium temperature waste heat from a low-power stationary diesel engine was examined by Haidar [11], despite being an incomplete system. Other than that, past researchers [12] demonstrated a TEG system mounted on a stationary diesel plant with six cylinders and as many distinct exhaust gas outlet channels, claiming a maximum power output of 1350 W despite the limited number of experiment results being disclosed.

BMW was the first automobile manufacturer to build a TEG system, which produced 600 W of electrical power in an on-vehicle [13]. However, while the system has a high power output and good thermal performance, the very low output voltage of roughly one volt reduces overall system efficiency due to the problems of dealing with low voltage and high current.

1.4 Project Objective and Scope

The project consists of following objectives:

- To obtain fundamental theory and characteristic of thermoelectric in automotive system
- To evaluate thermoelectric generator compatible for powering up automotive electrical system
- To develop an alternative to alternator function for commercial value

Scope for the project is as follow:

- Design of thermoelectric generator model in Solidworks
- Steady-state and thermoelectric simulation based on input in Ansys Workbench with element size of 0.005 to achieve variance target output and efficiency
- Analyze the performance of thermoelectric generator as a current alternative for automotive system at ambient temperature of 28℃

2. Materials and Methods

To design a thermoelectric generator modeled for automotive exhaust, parts and components involved were determined first.

2.1 Parts and components

- 304 stainless steel exhaust muffler. Specifications is shown in table 1.

Table 1: Specifications of exhaust muffler

Material	304 Stainless Steel
Inlet size (inch)	2
Outlet size (inch)	2

Body Diameter size (inch)	8

- Thermoelectric generator module or Peltier module. Specifications is shown in table 2.

Table 2: Specifications of Peltier module

Model Name	TEC1-12706
Material	Bismuth Telluride
Max operable temperature (℃)	300
Max Voltage output (V)	17.2
Resistance (Ohm)	1.8
Tolerance (%)	10

- A unit of 12 finned Aluminum Heat Sink.

2.2 Methods

Overall process taken to design and simulate thermoelectric generator for automotive exhaust system is shown in figure 3.

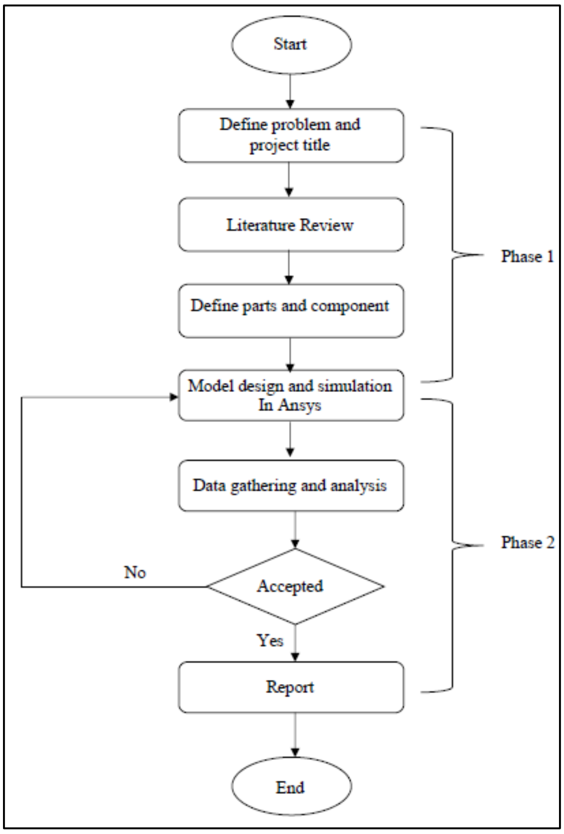

Figure 3: Flowchart for PSM 1 and PSM 2

According to parts and components listed in previous section, a complete model for TEG powered automotive exhaust is redesigned. Finalized model is shown in figure 4.

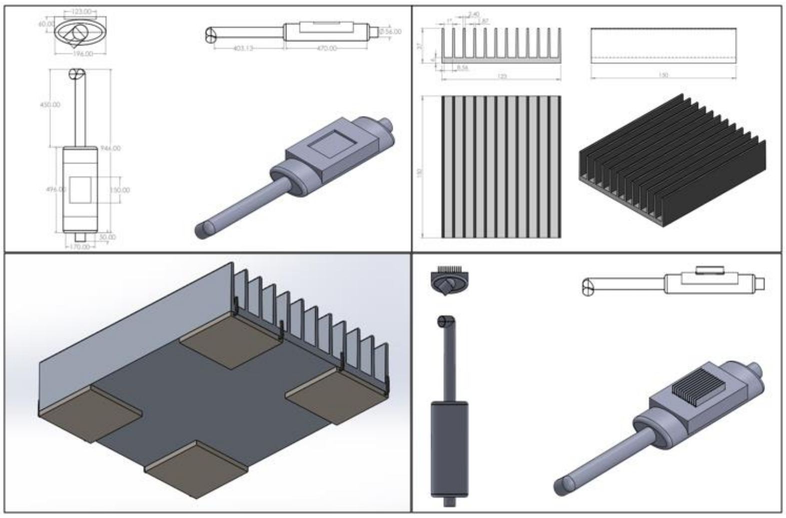

Figure 4: Modeling of automotive TEG system

Source of heat is supplied by exhaust muffler and source of cold air is supplied by convection through heat sink. Cooling process depends on ambient temperature which is 28℃ in this case. Peltier module is stacked in between hot and cold source temperature. Temperature from exhaust muffler to Peltier module is defined as T_h and temperature between heat sink and Peltier module is defined as T_c. Availability of both heat and cooling produces a temperature difference, ΔT, which is needed to produce electricity from waste heat.

2.3 Equations

Referring to previous parameters, the equation for Carnot efficiency is stated as the following:

$$\eta_{max} = \frac{[T_h - T_c]}{T_h} \times \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T}} + \frac{T_c}{T_h}} \qquad Eq. 1$$

Z and $\bar{T}$ is defined as the following [10]:

$$Z = \frac{s^2}{kR} \qquad Eq. 2$$

Where s is Seebeck coefficient, k as thermal conductivity and R as electrical resistivity. Combining the two equation gives $Z\bar{T}$ value. Seebeck coefficient is the value of voltage over temperature differences as follow:

$$s = \frac{V}{\Delta T} \qquad Eq. 3$$

With parameters defined, simulation was set up on Ansys. Ansys Workbench was used to carry out steady-state thermal simulation. Steady-state thermal simulation is done to gather data about temperature value across the model material. Once data about temperature is acquired, thermoelectric simulation can be executed by the previous data input. Successful simulation should give value of temperature at hot side, temperature at cold side, temperature difference and voltage output. Then, Seebeck coefficient can be calculated using eq.3 and efficiency is gained by using eq.1.

Simulation is run with temperature ranging from 100℃ to maximum operable temperature of 325℃. This is repeated with three sets of constants which is T_i, T_h and T_c. Thermal conductivity was set to $1.5Wm^{-1}k^{-1}$ and electrical resistivity is set to 1.8 Ohm.

3. Results and Discussion

Data acquired from simulations is arranged into corresponding table. Value acquired from simulation is temperature and voltage, while Seebeck coefficient and efficiency is acquired by calculation using eq.1, eq.2 and eq.3

3.1 Results

Tables for simulation and calculation results are attached in appendices. In appendix D, overall results were arranged based on value of ΔT in ascending order. Lowest temperature difference is 4.15℃ and highest is 93.43℃. From the table, plotted graph of voltage vs temperature is shown in figure 5.

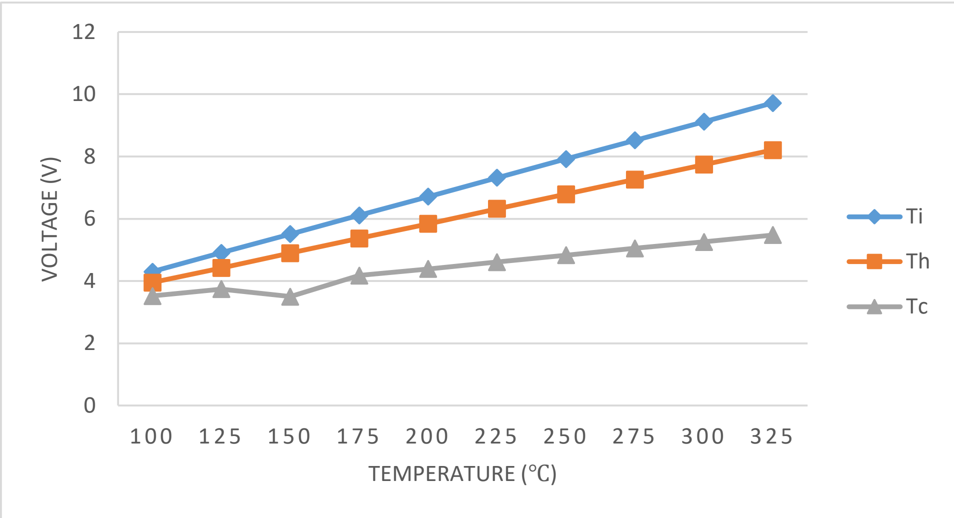

Figure 5: Voltage vs temperature graph

From table in appendix A, overall graph for output against temperature difference is shown in figure 6.

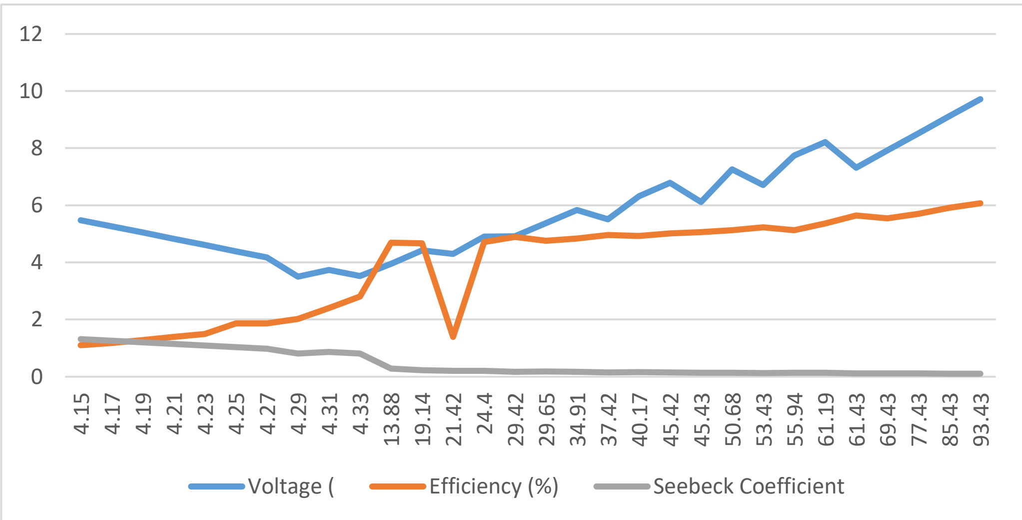

Figure 6: Voltage, efficiency & seebeck coefficient across temperature difference

3.2 Discussions

From the figure 5, lowest temperature difference recorded was 21.42℃ while the highest is at a temperature difference of 93.43℃ when T_i is set as a constant value. Lowest voltage produced that was recorded from simulation is 4.20V while the highest is 9.72V. The voltage produced starts to spike when there is a temperature difference, which in this case begins at 21.42℃. Then, voltage produced starts to increase steadily along with temperature difference before reaching peak end at 93.43℃. Thus, the voltage produced, V, is linear with the value of temperature difference, ΔT. Average voltage produced is 7.014V and average temperature difference is 57.43℃. Using the relation between average voltage produced and average temperature difference, seebeck coefficient for the entire system is 0.122 V/℃. Lowest and highest efficiency recorded was 1.39% and 6.07% respectively. Drastic increase was recorded when temperature difference is at 29.42℃, with an efficiency of 4.89%. Then, efficiency starts to gradually increase along with temperature difference which peaks at 5.64% before slightly decline to 5.54%. Efficiency then starts increasing up to 6.07%, which is the highest in this case.

Lowest temperature difference recorded in this set was 13.88℃ while the highest is at a value of 61.19℃. voltage produced with T_h as constant starts with 3.95V at 13.88℃ and has been increasing steadily until a peak of 8.21V at 61.19℃ was reached. Similar to previously recorded sets, the voltage produced tends to spike when there is a temperature difference, which in this case begins at 13.88℃. As the temperature difference increase, the voltage also increased linearly. Average voltage calculated from this variable is 6.08V and average temperature difference is 37.54℃. Relationship between voltage and temperature difference gives a seebeck coefficient of 0.162 V/℃ for this system. Lowest efficiency recorded was 4.67% at 19.14℃ temperature difference while highest efficiency achieved is 5.36% at 61.19℃ temperature difference with this setup. It is observed that the efficiency starts as 4.69% at 13.88℃ temperature difference before dropping to 4.67% at temperature difference of 19.14℃. Afterwards, the efficiency gained in this system starts to stabilize and increasing steadily before ending at the peak of 5.36%. Compared to previous constant, this sets of simulation starts at higher value of efficiency and is more stable but the peak efficiency value achieved is theoretically lower than T_i as constant.

When T_c is set as constant, the value of temperature difference decreases due to high temperature of cold side, hence causing lower temperature difference. Graph is arranged in ascending order to learn the relation between voltage and temperature difference. Lowest voltage produced when T_c was set to constant is 3.52V at 2.81℃ and highest voltage generated is 5.48V at 1.10℃. Average voltage produced is 4.46V while average temperature difference is 4.24℃. Seebeck coefficient for this entire system is 1.052 V/℃. Gradual lower voltage decline in the graph is because of the relatively low temperature difference when compared to other sets of simulation with different constants. From observation of the table, potential value of voltage that can be generated is dependent on temperature at hot side of TEG. Hence, voltage still can be generated when temperature is increasing but efficiency will drop if the value between temperature differences is relatively low. Lowest temperature difference and efficiency is 4.15℃ and 1.10% respectively. Percentage of efficiency is affected by temperature difference. Highest temperature difference gained from this simulation condition is 4.33℃ with an efficiency of 2.81%.

Lowest voltage generated from the entire system is 3.5V at 2.02% efficiency with temperature difference of 4.29℃ . Lowest efficiency is 1.1% which is able to generate 5.48V at 4.15V temperature difference. Highest voltage generated and efficiency from the entire data is 9.72V at 6.07% efficiency with temperature difference of 93.43℃. When calculated, average efficiency is 3.9% over entire sets of results. Average voltage generated over entire sets is 5.85V.

As for seebeck coefficient, highest recorded was 1.32 V/℃ while 0.104 V/℃ is the lowest. Seebeck coefficient drops as the temperature difference increases. Average seebeck coefficient of the entire system is 0.455 V/℃. These values are in positive which is still within acceptable range. Therefore, the feasibility of the system was demonstrated by the data of simulation based on commercially available

Peltier module in the market TEC1-12706. The results presented indicates a positive thermoelectric generator performance over increasing temperature difference, in which the voltage generated also increases if temperature rises occur at the hot side of thermoelectric generator.

4. Conclusion

In conclusion, implementation of Peltier module TEC1-12706 into automotive exhaust system are able to generate voltage from waste heat. From eq.1, efficiency is affected by temperature, seebeck coefficient, thermal conductivity and electrical resistivity. Thermal conductivity and electrical resistivity in the simulation is $1.5Wm^{-1}k^{-1}$ and 1.8 Ohm. Seebeck coefficient is value of voltage output over temperature difference. Through these values, efficiency is determined. Potential efficiency may vary with different sets of constant but when the data is compiled, efficiency of this system are able to achieve up to 6.07% which is an additional of 0.07% when compared to previous research (Harun, 2016) that uses the same Peltier module to generate voltage. Understanding of theory and fundamentals of thermoelectric generator helps in determining parameters involved during the simulation process. According to referred source materials [12], standard voltage needed to power up a car engine is 12.6V. Highest data achieved by this simulation at steady-state is 9.72V which is 23% lesser than the theoretical value. From the data collected, lowest and highest efficiency is 1.10% and 6.07% respectively, which is a 4.97% of difference from lowest to highest efficiency value.

The availability of voltage in output from setup of simulation shows that implementation of TEG in automotive has the potential to generate sufficient electricity, thus is possible to be an alternative to electricity generated by mechanical load such as alternator if the efficiency increases along with temperature difference. TEC1-12706 module is a commercially available Peltier module which can be acquired at low cost, therefore lower maintenance cost compared to mechanical alternator. However, limitations for this system is the relatively low starting efficiency due to the concept of being temperature dependent. By finishing this project, a simulation to generate electricity through automotive exhaust heat waste has been completed and data has been achieved, hence meeting the objective to obtain fundamentals, evaluate and develop a thermoelectric generator simulation for automotive exhaust system.

Limitations of this project is the maximum operable temperature of Peltier module TEC1-12706 which has maximum operable temperature up to 325℃. To improve findings in the future, fabrication can be made based on proposed model to achieve a more accurate results, since real time application can involve time dependent variable and simulation results can be referred. As previously stated the ideal voltage to be supplied in automotive electrical system should be 12.6V and maximum voltage achieved from simulation is 9.72V. This can be solved by increasing the number of Peltier module used or by using module with higher melting point so that maximum temperature limit can be exceeded, creating potential to generate higher electricity over higher temperature difference in the future. Other improvement that can be suggested is to use Computational Fluid Flow Dynamics (CFD) as a medium for simulation to achieve more accurate data supported by additional parameters such as time, flow of heat, ambient wind velocity and automotive rotational speed per minute (rpm) in relation to exhaust temperature. This suggestion requires a higher computer specifications to be able to run the simulation successfully. Other than that, using cold side of automotive radiator as a source of coolant for TEG cold side can increase the temperature difference due to consistent cooling performance compared to cooling supplied by ambient air.

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Appendix A

ΔT(°C)	T_h(°C)	T_c(°C)	**Voltage (V)**	**Seebeck coefficient (V/°C)**	**Efficiency (%)**
4.15	329.15	325.00	5.48	1.32	1.10
4.17	304.17	300.00	5.26	1.261	1.18
4.19	279.19	275.00	5.05	1.205	1.28
4.21	254.21	250.00	4.83	1.147	1.39
4.23	229.23	225.00	4.61	1.090	1.49
4.25	204.25	200.00	4.39	1.033	1.86
4.27	179.27	175.00	4.18	0.979	1.86
4.29	154.29	150.00	3.50	0.816	2.02
4.31	129.31	125.00	3.74	0.868	2.40
4.33	104.33	100.00	3.52	0.813	2.81
13.88	100.00	86.12	3.95	0.285	4.69
19.14	125.00	105.86	4.42	0.231	4.67
21.42	98.85	77.43	4.30	0.201	1.39
24.40	150.00	125.60	4.90	0.201	4.71
29.42	123.35	93.93	4.91	0.167	4.89
29.65	175.00	145.35	5.37	0.181	4.76
34.91	200.00	165.09	5.84	0.167	4.84
37.42	147.85	110.43	5.51	0.147	4.96
40.17	225.00	184.83	6.32	0.157	4.93
45.42	250.00	204.58	6.79	0.149	5.02
45.43	172.36	126.93	6.11	0.134	5.06
50.68	275.00	224.32	7.26	0.143	5.13
53.43	196.86	143.43	6.71	0.126	5.23
55.94	300.00	244.06	7.74	0.138	5.13
61.19	325.00	263.81	8.21	0.134	5.36
61.43	221.36	159.93	7.32	0.119	5.64
69.43	245.86	176.43	7.92	0.114	5.54
77.43	270.36	192.93	8.52	0.110	5.70
85.43	294.86	209.43	9.12	0.107	5.91
93.43	319.36	225.93	9.72	0.104	6.07

References

[1] B. Klaus and P. Horn, Robot Vision. Cambridge, MA: MIT Press, 1986 (Example citation for books)

[2] D. Rowe, Thermoelectric handbook: macro to nano, CRC Press, 2005.

[3] S. Bai, H. Lu, T. Wu, X. Yin, X. Shi and L. Chen, "Numerical and experimental analysis for exhaust heat exchangers in automobile thermoelectric generators," Case Studies in Thermal Engineering, vol. 4, pp. 99-114, 2014.

[4] X. F. Zheng, C. X. Liu, R. Boukhanouf, Y. Y. Yan and W. Z. Li, "Experimental study of a domestic thermoelectric cogeneration system," Applied Thermal Engineering, vol. 62, pp. 66-80, 1 10 2014.

[5] X. F. Zheng, C. X. Liu, R. Boukhanouf, Y. Y. Yan and W. Z. Li, "Experimental study of a domestic thermoelectric cogeneration system," Applied Thermal Engineering, vol. 62, pp. 66-80, 1 10 2014.

[6] R. E. Simons and R. C. Chu, "Application of Thermoelectric Cooling to Electronic Equipment: A Review and Analysis," 16th SEMI-THERM Symposium, pp. 1-9, 2000.

[7] A. Altun, "Understanding hypertext in the context of reading on the web: Language learners' experience," Current Issues in Education, vol. 6, no. 12, July 2003. [Online]. Available: http://cie.ed.asu.edu/volume6/number12/. [Accessed Dec. 2, 2004] (Example for an e-journal article extracted from the internet)

[8] S. B. Riffat and X. Ma, "A review of present and potential applications," Applied Thermal Engineering, vol. 23, pp. 913-936, 2003.

[9] G. Meisner, "Advance Thermoelectric Materials and Generator Technology for Automotive Waste Heat," Thermoelectric Application Workshop, 2011.

[10] A. Cengel, "Thermodynamics: An Engineering Approach," 2008.

[11] J. Haidar and J. Ghojel, "Waste heat recovery from the exhaust of low-power diesel engine using thermoelectric generators," in 20th International Conference on Thermoelectrics (ICT), 2001.

[12] L. I. Anatychuk, R. V. Kuz and Y. Y. Rozver, "Efficiency of thermoelectric recuperators of the exhaust gas energy of internal combustion engines," in 9th European Conference on Thermoelectric (ECT), 2011.

[13] D. Crane, J. LaGrandeur, V. Jovovic, M. Ranalli, M. Adldinger, E. Poliquin, J. Dean, D. Kossakovski, B. Mazar and C. Maranville, "TEG On-Vehicle Performance and Model Validation and What It Means for Further TEG Development," Journal of Electronic Materials, November 2012.

[14] G. Mishra and S. Sharma, "A review of automotive thermoelectric generator," International Research Journal of Engineering and Technology (IRJET), pp. 2787-2788, 2017.

[15] Harun, M. H. (2016). Peltier and seebeck efficacy of hot and cold air system for portable O-REF. Proceedings of Mechanical Engineering Research Day 2016, 81-82.