Design, Modeling & Simulation of A Thermoelectric Cooling System (TEC)

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ABSTRACT: Thermoelectric Devices are solid state devices which directly convert thermal energy to electrical energy and vice versa. In the recent past, a lot of effort has been made to improve the performance and also the power generated by a thermoelectric device. This is done by attaching heat sinks on either sides of the device. Optimizing heat sinks improves the overall efficiency of it but on the other hand the device also has to be optimized. TEC are mostly used for electronic cooling where the heated electronic devices serves as target that needs to be cooled while air acts as a heat sink with natural convection. In this paper, maximizing the cooling power of a TEC system has been studied and its effect with respect to variations in the TEC geometry has been discussed. 1D analytical model has been developed using Mathcad and a 3D model of the same has been numerically simulated using ANSYS whose setup used has been explained in detail. At low leg length of the TEC, the cooling power can be improved but a lot of other parameters have to be taken into account to accurately model the system. The contact materials used to electrically connect the device and the resistance of the conductor play a very important role while calculating the cooling power at low leg lengths and hence cannot be neglected. Results show that cooling power of the TEC can be dramaticallyimproved at low leg lengths and with better heat sink material.

Key words: Design, Modelling, Simulation, TEC, ANSYS, Analytical Model

I. INTRODUCTION

Thermoelectrics is defined as the generation of electricity from a given temperature difference or vice versa. Solid state devices capable of producing power, these devices are environment friendly that come with low maintenance and reliability. They use a very simple concept of running on a temperature difference and as long as this criteria is being fulfilled, energy is produced. The concept of thermoelectricity can be classified into 2 parts. Thermoelectric Coolers (TEC) and Thermoelectric Generators (TEG). In order to run a TEC, a certain amount of current has to be input along with maintaining a temperature difference which gives a cooling power and the coefficient of performance of the device can then be measured. However, in a TEG, a load resistance is input along with maintaining a temperature difference and electricity is thus generated from these conditions. There have been quite a few number of applications in the recent past and the number of applications are increasing with time. Thermoelectrics has found its way into air conditioning systems, automobile applications, solar energy applications and many others.

History & Derivation of Thermo-Electrics

In 1821, Thomas Seebeck discovered that an electromotive force could be generated when a circuit was made out of two dissimilar materials and when the junction was heated. The electromotive force that was generated was named the Seebeck Effect. A few years later, Jean Peltier discovered that this same process could be reversed to produce heat when voltage was applied across the junction of two dissimilar materials [1]. In short, when current is passed through a circuit, one junction increases in temperature while the other junction cools down. A thermoelectric module is formed when a number of dissimilar materials are connected thermally in series and electrically parallel to each other [2]. At the end of the 19th century, electrons were discovered. And that was when the concept of thermoelectricity came to be clearer to the people working on it. We now understand that electrons can be liberated from any source even at temperatures as low as the room temperature. This is the reason we have electrostatics everywhere [1]. When a temperature difference is applied across a conductor, the hot region liberates more electrons and diffusion takes place from the hot side to the cold side. This distribution of electrons provoke the generation of an electric field which helps the electrons move from the hot side to the cold side due to Coulomb force. Therefore an electromotive force (emf) is generated which causes the current to move in the direction opposite to the flow of temperature. The same can be said about the opposite criteria as well. The movement of electrons due to the

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application of a current results in the generation of temperature difference.

Thermo-electric cooling & it's Background

Thermoelectric devices are devices of the future. The applications of thermo electric cooling devices have so far been employed in a lot of devices where the size of the device is small. In applications where the temperature needs to be stabilized, a cooling effect needs to be produced or heat up the device using a reverse current, thermoelectric cooling modules have been used. Peltier models have also been used in many everyday life situations like cool storage boxes for medicine or for coolingboxes for picnic storage [3].Some of the most recent applications in the concept of thermoelectric cooling is in vehicle air conditioning. Almost 10% of the annual consumption of fuel can be directed to the use of air conditioning [8]. Most of these use refrigerants like R- 134a which has adverse effects on the environment being a major greenhouse gas. There is a lot of debate in the current day about banning all the environment depleting compounds and R-134a is definitely one of them. [9]. The U.S. Department of Energy (DOE) and the California Energy Commission funded a project to research an application involving thermoelectric heat ventilating and air conditioning system (TE HVAC) that promised to replace the traditional air conditioning systems in vehicles [9] [10]. Use of a thermoelectric air conditioning system (TEAC) in place of the traditional air conditioning system has been proven to have benefits such as being able to produce a cooling effect without the use of environment depleting substance like the R-134 and also having a scope to select the areas needing heating or cooling instead of randomly cooling the whole area which in turn reduces the amount of fuel consumed considerably hence also reducing the exhaust [11].

II. LITERATURE REVIEW

Thermoelectric Cooling (TEC)

The literature showed a number of studies on TEC. The study started off early and in the most recent studies, Terry [17] summarized the phenomena of thermoelectrics, their materials and their applications. Sootsman [18] also briefed thermoelectric concepts in the early ages and the modern developments in thermoelectricity that gives an idea of all the concepts that have already been covered. A lot of work was done with respect to the element size of a thermoelectric system. Semenyuk.V [13] in an international conference mentioned the working of a miniature thermoelectric device at low temperatures. He also referenced to the improvement in the power density when the ceramic material is changed. The same author in a different work [13] discussed the increase in cooling power of a miniature thermoelectric cooling device. There has been a good amount of work on the optimization of a thermoelectric model. Zhang [14] in his work discussed about a generalized method of optimizing a thermoelectric cooler. Lee [11] in his work also detailed the readers about a more accurate optimal design method of thermoelectric modules that is used in this work.

Heat Sink Optimization & it's Heat Transfer Coefficient

A typical thermoelectric system consists of a thermoelectric module and two heat exchangers (or heat sinks) attached to both the hot and cold side of the module. It can be seen that the researchers make an effort to combine theoretical thermoelectric equations and heat sinks equations, and then optimize the geometric parameters of the heat sinks [13]. Optimization of the heat sinks and heat exchangers are very well established in the literature and Lee [12] summarizes a comprehensive study on the optimization procedures. As for the accuracy of the Nusselt number, analytical correlation can be used but it would be more reliable to have an experimental validation especially for more complicated shapes. Therefore, Teertstra et al [19]. developed an analytical correlation to calculate the Nusselt number based on flow in a parallel plate channel and a combination of developing and fully developed flow. After modifying the Nusselt number correlation to consider the fin effects, they compared the new correlation with experimental values which showed good agreement. Furthermore, Zhimin and Fah [16]used two correlations to calculate the Nusselt number for microchannel heat sinks for both laminar and turbulent flow. The results of the thermal resistances were then validated against other work. These studies of the heat sink optimization and Nusselt number correlation can be adopted on the current work on thermoelectric system.

Optimum Design of Thermoelectric System

The recent developments in thermoelectrics needs to be addressed in order to investigate their optimum design. Literature shows several methods on how to optimize thermoelectric parameters. Analyzing parameters like the number of thermocouples, the element geometric ratio, and the thermal conductivity, which is defined as the thermal conductance of elements, is a very practical way to study the optimum design of the thermoelectric parameters [17]. The literature also showed some techniques that can help analyze the optimum design of thermoelectric parameters.

Dimensionless parameters for a thermoelectric cooler system were introduced by Yamanashi [22] in order to optimize thermoelectric parameters. The paper studied the effect of different dimensionless parameters on the TEC performance as a function of dimensionless electrical current. One of the highlights of this paper is to show that the thermal resistance of the hot side of the TEC has a greater impact on the performance than the cold side thermal resistance. Furthermore, this technique gives the ability to obtain the maximum COP when the heat exchanger of the TEC system is provided. Even though

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Yamanashi technique is not very adoptable due to the difficulties in obtaining the optimum parameters for the cooling power, some researchers applied it and provide useful results. In fact, Xuan [21] was able to use Yamanashi method to optimize the length of the element while Pan et al [22]. Studied the optimum design of cooling power for a thermoelectric cooler.

Objective

After studying all the literature and understanding the basic concepts of thermoelectrics and the concepts that drive a thermoelectric system, it has been found that a practical approach to this problem, though is quiet accurate, is very expensive. A lot of analytical study has been done on the cooling system of a thermoelectric module. In order to prove and validate the theoretical module, experimental work has also been done. In order to understand the physics better, a simulation has been done in order to validate the theoretical model in this work. The objective of the current work can be defined as "Design and modeling of a thermoelectric cooling system using theoretical modeling and numerical simulation."

A Huge amount of theoretical & analytical work has been done on a thermoelectric cooling system. All the work can be segregated into the following parts.

- Modeling a thermoelectric couple and extending the same to a module. Validating the accuracy of the said model using analytical solution and a numerical simulation.
- Optimizing the module with respect to input parameters and geometry of the module to calculate the maximum output parameters.
- Studying the optimized unit and understanding the same for a system.

The work that has been done in this paper includes a simulation using ANSYS 16.0 while validating the theoretical data to prove that the formulae used in theory are self-sufficient to be applied in real life applications. Validation has been done for a single module at leg lengths varying from 0.1mm to 0.5mm with leg area at 0.41mm*0.41mm and a comparison has been done for the same at higher leg lengths varying from 1mm to 1.5mm and leg area at 1mm*1mm.

III. RESULTS & DISCUSSIONS

All information in this chapter is with respect to the methodologies explained in Ref. [10], [20], [21], and [22] with the author's contribution. Here, validation of existing thermoelectric module is done to prove the authenticity of the ideal equations. A comparison is done between the analytical modeling and ANSYS simulation of the modules under various conditions. Initially, a comparison is done between the results of MathCad and ANSYS when contact resistance is included and excluded and to understand its importance at low leg lengths. Once its importance has been established, the focus is then shifted to electrical contact resistance of copper. Then, a validation is done of the thermoelectric ideal equations using MathCad and ANSYS. The discussion is then extended to the module when heat sinks are introduced. All discussions are made at low leg lengths (0.1mm- 0.5mm), also called miniature devices and bigger leg lengths (1mm-1.5mm) also called macro devices or rather commercial modules. Following dimensions and material properties have been used for all the results.

Geometry	**Value**	**Units**
P type-miniature Thermal Cross Section Area Length	0.41mm*0.41mm 0.1mm-0.5mm	mm^2 mm
P type-macro Thermal Cross Section Area Length Seebeck Coefficient (α_p) Thermal Conductivity (k_p) Electrrical Resistivity (ρ_p)	1mm*1mm 1mm-1.5mm 210 1.6 1*10^5	mm^2 mm µV/K W/m*K Ω*m
N type-miniature Thermal Cross Section Area Length	0.41mm*0.41mm 0.1mm-0.5mm	mm^2 mm
N type-macro Thermal Cross Section Area Length Seebeck Coefficient (α_p) Thermal Conductivity (k_p) Electrrical Resistivity (ρ_p)	1mm*1mm 1mm-1.5mm 210 1.6 1*10^5	mm^2 mm µV/K W/m*K Ω*m

Table 1 Module Specifications used in the study

Contact Resistance

Contact resistance is a parameter in studying the behavior of thermoelectric materials that defines the total output of a given module. In the following discussion, we understand the importance of contact resistance as a function of leg length of the module.

The following graphs show the change in power output when contact resistance is included at a constant input power. The current input in this set up is constant. We can see that there is a maximum power at a certain leg length

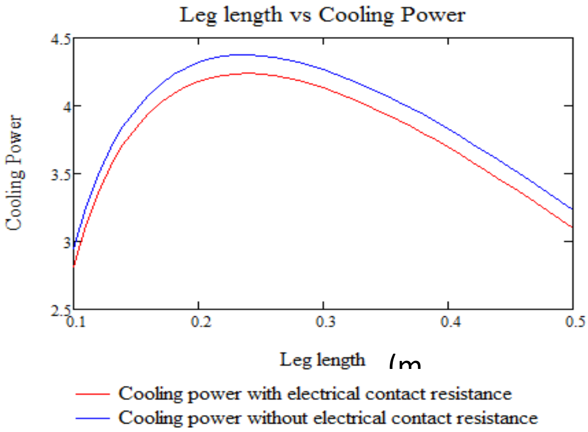

Figure 1 The Cooling poer of a miniature module as a function of leg length

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The above figure is at a constant current with leg length varying from 0.1mm to 0.5mm and current 2A.

Copper Resistance

We know that copper is an electric conductor. This material also has an electric resistance and though the value is very low, it has a significant importance under certain conditions. The plots below show the difference in cooling power when the resistance of copper is not included. ANSYS considers a default value of electrical resistance of copper while MathCad requires manual input.

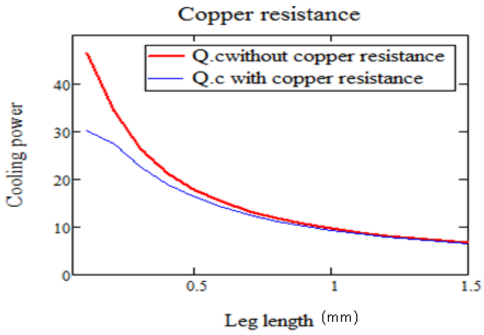
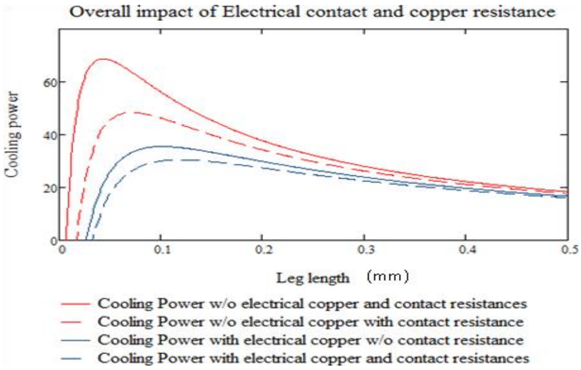


Figure 2 Impact of electrical copper resistance

In the figure above, when we look at lower leg lengths, i.e. leg lengths lesser than 0.3mm, the deviation from the actual cooling power is very high. The difference is almost 20W. This means that the mathematical definition given to copper resistance is extremely important and it has to be included. Without the copper resistance, the cooling power obtained mathematically is over predicted. One of the main reasons for this effect for copper electrical resistance is its geometry. A thickness of 0.1mm is considered and at leg lengths of 0.1mm in the thermoelectric module, the copper electrical resistance starts dominating the effects of thermoelectrics. This impacts the cooling power majorly and hence the overall cooling power reduces at this geometry. If the geometry of copper is considerably reduced with a reduction in the leg length, its impact will also significantly reduce hence giving a considerable cooling power. Since the impact of electrical contact resistance and electrical copper resistance has been established, we can conclude that its effects are rather significant and hence these resistances have been included in all our discussions irrespective of the leg lengths.

Overall Impact of Electrical Contact Resistance & Electrical Copper Resistance

The impacts of these electrical resistances have been discussed in detail in previous sections. In this section, we will discuss about the overall impact of electrical copper and contact resistances together. Their impact as a function of leg length will be discussed in this section.



The above figure is at current 2A and hot side temperature 310K and cold side temperature 288K.

In the figure above, the red colored solid lines show the cooling power at varying leg lengths when copper electrical resistance is neglected in theoretical calculations while the blue line show the value of cooling power when copper electrical resistance is included. We can see that under the same conditions, the difference in the calculated cooling power is very significant when electrical resistances of copper and contact are included.

Especially at low leg lengths, the difference in the power is almost 30W. This power difference corresponds to a percentage error of almost 53%. Such high errors are caused especially when the leg length is around 0.2mm. At these values of leg lengths, the power predicted using analytical modeling is over predicted. This is a huge difference and hence it can be concluded that both electrical contact resistance and copper electrical resistance play an important role in calculating the cooling power of a given module. As mentioned in the previous section, since it has been established that the effect is higher in few cases while it is not much in others, these resistances have been included in all the equations for calculating the cooling power of the module in question.

Comparison of Real Values to Ideal Equations

Ideal equations are theoretical equations that are modeled in order to predict the performance of a thermoelectric module under ideal conditions. These equations neglect all kinds of contact resistances. These resistances include the electrical contact resistance, the copper electrical resistance and the thermal contact resistance. In this section, we will discuss about the difference in the prediction of performance theoretical calculations are made using ideal equations and real equations.

The figure below shows the performance prediction of a thermoelectric cooler when calculated using ideal equations and real equations. In the curve obtained by the ideal equations, we can see that, as leg length reduces, there is an exponential increase in the power output. This situation however, is not practical. There is an optimum value of leg length in the real case beyond which the cooling power is reduced due to the dominance of contact resistances. Hence, at these leg lengths, the cooling power is

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realistically defined by including the thermal contact resistances, electrical contact resistances and the copper electrical resistances.

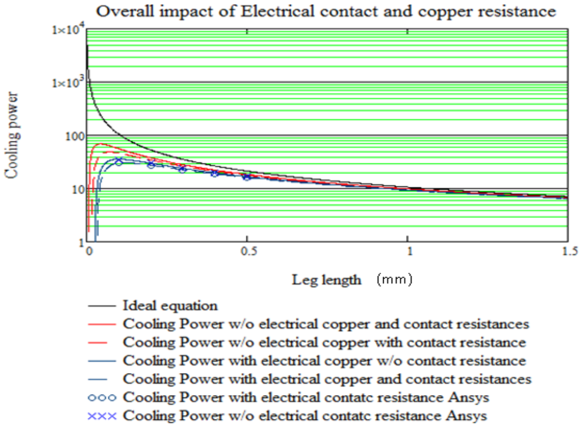

Figure 4 Prediction of cooling power using ideal equations vs real equations

Effect of Heat Sink

Set up and result

In order to study the effect of heat sink in a TE system, the developed Mathcad equations were verified with an ANSYS setup that integrated fluent flow with thermoelectric module. Using Lee's [2] optimum design technique, an optimum heat sink was designed along with thermoelectric module. The module consisted of 127 couples. The leg length used in this setup is 1mm. the thickness of copper is 0.1mm and the length of copper is 2.90mm. The ceramic designed for this set up is 30mm*30mm and the thickness of ceramic is 0.50mm. An air duct is designed in order to analyze forced convection, with a given velocity and a given mass flow rate.

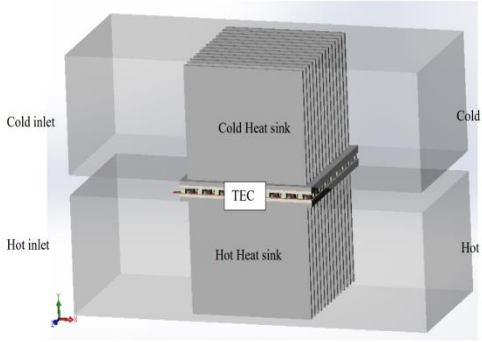

Figure 5 Thermoelectric system setup for fluent analysis

As discussed in earlier sections, ANSYS simulation for this setup needs an integration of CFD model and thermoelectric model.

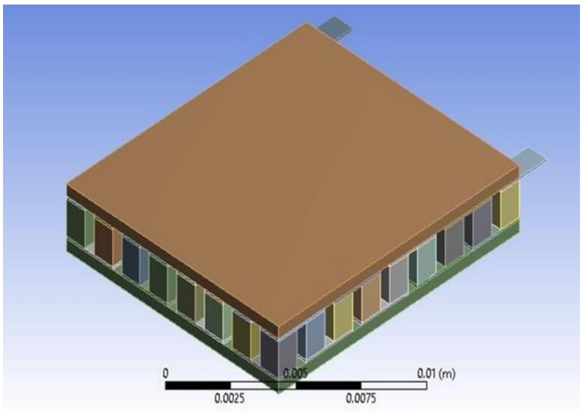

Figure 6 Module with 39 couples, copper & ceramic

This figure shows the geometry of the module in ANSYS. This software defines different bodies in different colors by default.in this system, we have 127 couples, copper and ceramic in the dimensions mentioned. Copper acts as an electric conductor while ceramic helps in electric insulation of the system

In order to come to this solution, using CFD, temperature inputs and mass flow rates on the cold side and hot side of the heat sink must be given as shown. Once these inputs are given and all the boundary conditions are setup, the CFD is run. And the result is shown. Once the results have been calculated using CFD, it is integrated in the thermoelectric module as shown. Once the integration is done and once the results of the CFD have been imported into the thermoelectric module, the module is then solved in order to calculate the cooling power on the cold side of the module.

IV. CONCLUSION

This work was mainly aimed at validating analytical equations using numerical simulation. A lot of discussion has also been made on the importance of electrical contact resistance and electrical copper resistance. It has been found that integrating CFD into thermal electric module during the ANSYS simulation helps in deriving reliable results to validate the accuracy of the ideal equations. The discussion started off with explaining about the impact on a single module and then the same discussion was implemented on a complete module containing 36 modules.

Miniature modules and macro modules were discussed and each of the parameters that impacted the overall cooling power of module was focused. The value of copper resistance and contact resistance is as such very low. But when the leg length is very low, the resistance values come in comparison with the value of the leg length. Hence, it starts impacting the cooling power and performance of the system. In higher leg lengths, however, the value of resistance is very low when compared to the value of the leg length.

Hence, even though there is an impact on the cooling power, it is so insignificant that it can be neglected. Both

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kinds of modules have their respective applications, hence from the discussion, we can conclude that depending on the application, we can choose to select the type of module we would like to use. Also, we can safely say that numerical simulation is close to experimental validation. Since the work done concentrates on optimized modules, it is difficult to manufacture these modules according to customized dimensions. Each application needs to be optimized in a certain way and hence most of the times, no two modules have similar dimensions. While optimizing, the modules for its input conditions end up with different optimized parameters depending on its input conditions.

Modules ending up with very low leg length is very difficult to manufacture and sometimes need a new technology to build it. It is very difficult and also expensive to manufacture these kinds of modules. Hence the ANSYS simulation acts as a supplement to an experimental analysis.

V. REFERENCES

[1] H. Lee, Thermoelectrics- Design and Materials, John Wiley and Sons, 2016.

[2] H. Lee, Thermal Design: Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat Exchangers, and Solar Cells, Hobooken: John Wiley & Sons, Inc., 2010.

[3] A. Attar, "Studying the Optimum Design of Automotive Thermoelectric Air Conditioning," Kalamazoo, 2015.

[4] S. S. J. G. P.K.S. Nain, "Non-Dimensional Multi-Objective Performance OPtimization of Single Stage Themoelectric Cooler," Springer, pp. 404-413, 2010.

[5] C. Vinning, "An inconvenient truth about thermoelectrics," Nature Materials, vol. 8, no.2, pp.83-85, 2009.

[6] J. L. T. a. J. H. C.W. Maranville, Improvinf efficiency of a vehicle HVAC system with comfor modeling, zonal design, and thermoelectric devices, 2012.

[7] H. Lee, "The Thomson Effect and the ideal equation on Thermoelectric Coolers," Energy, vol. 56, pp. 61-69, 2013.

[8] H. Lee, Thermal Design: Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat Exchangers, and Solar Cells, Hoboken: John Wiley & Sons, Inc., 2010.

[9] H. Lee, A. Attar and S. Weera, "Performance Prediction of Commercial Thermoelectric Cooler Modules using the Effective Material Properties," Journal of Electronic Materials, vol. 44, no. 6, pp. 2157-2165, 2015.

[10] D. C. a. M. K. J.R. Sootsman, New and old concepts in thermoelectric materials, 2009.

[11] H. Lee, "Optimal design of thermoelectric devices with dimensional analysis," Applied Energy, vol. 106, pp. 79-88, 2013.

[12] V. Semenyuk, Thermoelectric Micro Modules for Spot Cooling of High Density Heat, 2001.

[13] V. Semenyuk, Miniature Thermoelectric modules with increased cooling power, 2006.

[14] H. Zhang, A general approach in evaluating and optimizing thermoelectric coolers, 2010.

[15] H. Lee, Optimimal design of thermoelectric devices with dimensional analysis, 2013.

[16] C. Zhimin, The optimum design of microchannel heat sinks, 1997.

[17] M. R. a. D. Walke, "Thermoeelctric Air Cooling for Cars," International Journal of Engineering Science and Technology, vol. 4, no. 5, pp. 2381-2394, 2012.

[18] A. Attar, H. Lee and S. Weera, "Experimental Validation of the Optimum Design of an Automotive Air-to-Air Thermoelectric Air Conditioner (TEAC)," Journal of Electronic Materials, vol. 44, no. 6, pp. 2177-2185, 2015.

[19] A. Attar and H. Lee, "Designing and testing the optimum design of automotive air-to-air thermoelectric air conditioner (TEAC) system," Journal of Electronic Materials, no.Manuscript sumbitted for publication, 2015.

[20] K.-i. Uemura, "history of thermoelectricity development in japan," Journal of Thermoelectricity, no. 3, 2002.

[21] N. C. S. N. C. L. J. K. C. S. Junior, "Modeling a Thermoelectric HVAC System for Automobiles," Journal of Electronic Materials, vol. 38, no. 7, pp. 1093-1097, 2009.

[22] D. C. D. a. L. J. Wang, "Design and Analysis of a Thermoelectric HVAC System for Passenger Vehicles," SAE International, Vols. 2010-01-0807, 2010.

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