AC 2010-1777: DESIGN OF A FLEXIBLE THERMOELECTRIC ELEMENT

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Design of a Flexible Thermoelectric Element

Abstract

Most thermoelectric devices (TEDs) are rigid. Their rigid nature makes them undesirable for adaption to existing structures with confined areas; locations that may experience severe mechanical vibrations; operate in extremely high temperatures; and where rapid temperature drop exists. The TEDs become a constraint when incorporating them in designs with varying contours. A flexible TED design is therefore desired to enable adaption of the devices in more applications. One approach towards the development of a flexible energy harvesting device such as the TED is to develop a flexible thermoelement. Developing a flexible thermoelement is a multi-stage design process. The design has to account for efficiency, structural integrity, and flexibility. This paper addresses the flexibility aspect while future work will include structural integrity by addressing thermal and mechanical loading; and efficiency by addressing materials selection and segmentation to achieve the highest possible power. The paper presents a Finite Element Analysis (FEA) based approach for thermoelement design studying correlation between element length of the cells and heat flux generation within a thermoelectric unit cell. Varying length sizes contribute towards flexibility of the TED. In conclusion, the paper points out how undergraduate students could benefit from exposure and participation in such a design process even though students were not involved in this study originally.

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Introduction

Thermoelectric devices are used in a wide variety of applications for portable or remote power generation, cooling (refrigeration), temperature measurement, and heat pumping. Thermoelectric generators (TEG) provide quiet, solid state, and reliable power that is not adversely affected by harsh conditions such as major changes in temperatures or vibrations. Due to lack of moving parts, TEGs require virtually no maintenance becoming suitable power sources for remote areas such as space and human body. A challenge facing TEGs is their low efficiency due to obtaining their energy from low energy sources such as waste heat and a low figure of merit (ZT) that enable conversion of heat into electricity[1]. $ZT = \frac{s^2}{k}\sigma$, where T is the absolute temperature, s is Seebeck coefficient, σ is electrical conductivity, and k is thermal conductivity. In power generation, the Seebeck effect enables the direct conversion between heat and electric energy streams. Heating one end of the unit cell while holding the other end cooler induces electromotive force within the material and may be harnessed for electrical power[2]. In Figure 1, two dissimilar semiconductors A and B are connected electrically in series but thermally in parallel with two junctions maintained at different temperatures[3]. The effect is that a voltage is created in the presence of a temperature differential between two different semiconductors. The governing equation is such that:

$$V = \int_{T1}^{T2} (\alpha_b(T) - \alpha_a(T))dT \quad (1)$$

where V is the induced voltage, T_2 is the higher temperature, T_1 is the sink temperature, α is the thermopower also known as Seebeck coefficient with V/K units, a and b are the thermoelements with varying properties. If the thermopower for both materials are constant for the measured temperature range, equation 1 can be approximated as equation 2.

$$V = \alpha_{ab}(T_2 - T_1) \quad (2)$$

where α_{ab} is the Seebeck coefficient for the junction, meaning, the difference between the absolute Seebeck coefficients α_a and α_b for each of the materials the junction is composed[4].

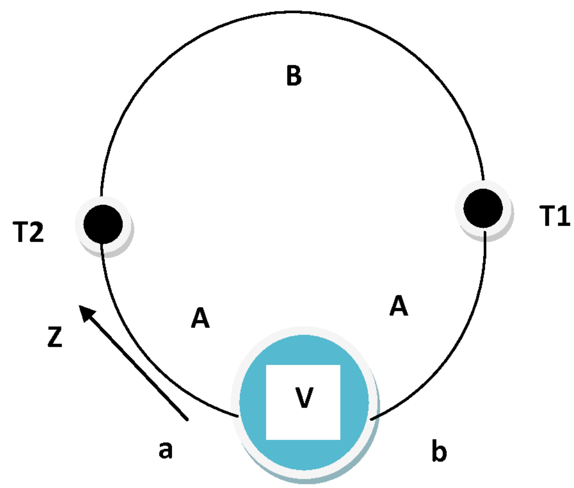

Figure 1: Seebeck Effect with materials A and B, and junctions of T_1 and T_2

Rowe suggested that wire-like (long and thin) thermoelements would be the ideal geometry for power generation while the squat (short and fat) would be ideal for refrigeration[5]. This project focused on power generation with thermoelectric configurations.

Method

A two step approach was employed to study the heat flow phenomenon. First, 1D heat flow pattern was determined using the computational software, MATLAB as shown in code (see Appendix). Results included heat flux values and the temperature distribution along the model. The second step was set up to determine the heat flow in 2D. Algor, an FEA software, was used to determine the results for the 2D environment under steady-state conditions. This method was chosen because it could simulate temperature distribution and provide directions and values for the heat flux analysis which is essential for power generation.

Two models of varying theremoelement (TE) leg length sizes were created and studied. The TE leg length of one model was 11 mm while the second model was 22 mm. All other geometric variables were left unchanged. Before the models were developed, the geometry and material properties were determined [4] as indicated in Table 1 with corresponding unit cell components. Table 1 and figure 2 identify components of the TE. The hot and cold ends are made of metalized ceramics; copper thermal and electrical conductors are placed between the metalized ceramic ends and the TE legs; and N- and P-type semiconductor legs of Bismuth Telluride. Table 1 also presents the conditions for the surrounding air and the mechanisms of heat transfer for the components of the 2D models.

Table1: Boundary Conditions and Material Properties

Material/ Component	Temp. (C)	Thermal Conductivity (W/m.K)	Density (Kg/ m^3)	Specific Heat (J/kg.K)	Size (mm)	Heat Transfer Process
Metalized Ceramic (Hot- left side of unit cell. Fig. 2) 1	230	200 (Aluminum Nitride ceramic)	3260	740	0.7x0.7.x3.4	Conduction
Thermal Conductor (between hot side and TE legs) 2		386 (Copper)	8940	385	0.3x0.7x2.4	Conduction
N-type leg (bottom leg) 3		127.8 (Bismuth Telluride)	9780	.12	0.7x0.7x11	Conduction/ Convection
P-type leg (top leg) 4		99.2 (Bismuth Telluride)	9780	.12	0.7x0.7x11	Conduction/ Convection
Electrical Conductor (2) 5		386 (Copper)	8940	385	0.3x0.7x1.2	Conduction
Metalized Ceramic (Cold –right side of unit cell) 6	50	200	3260	740	0.7x0.7x3.4	Convection

The air surrounding the legs had a convectional heat transfer with a temperature of 25^{o}C and a heat transfer coefficient of 50 W/ m^2.K.

Model Generation:

Finite element analysis in Algor involves four steps. The first step is to build the model or import one from an existing CAD STEP files (*.stp, *.ste, or *.step). This step requires for one to provide a file name, geometry, and orientation. The second step involves defining the Element Type and Material Data. The element type has several options to choose from including truss, beam, brick, 2D and many more. A 2-D Element type must be drawn in the YZ plane. The orientation option allows mesh creation which can be selected in quadrilateral, triangular, or mixed format. Global element size has a default mesh density of 400 and mesh size of 0.3. Material Data offers a window to select or input material properties such as modulus of elasticity and thermal conductivity. The third step requires placing loads and constraints. Loads and constraints are added to vertices or surfaces. Loads such as force, pressure, heat, and temperature can be applied based on the type of analysis to be conducted. Constraints are also referred to as Boundary Conditions (B.C s) in Algor. B. C s include defining geometry indicating whether fixed or free, while thermal B.C s offer several choices including heat flux or temperature. The fourth step involves running the analysis and getting results. A pull down menu is given and a selection of "Perform Analysis" is required to run the model data. Also on the pull down menu is an option for "Results" which is used to retrieve numerous values.

Initial study with the 2D models required adjustment of mesh sizes. Two different mesh densities (400 and 600) and two different refinement values (0.2 and 0.3) were employed. The changes in mesh settings enabled geometric model to be divided into smaller elements for a better analysis that matched MATLAB results. The meshed model shown below is the 11 mm long 2D model.

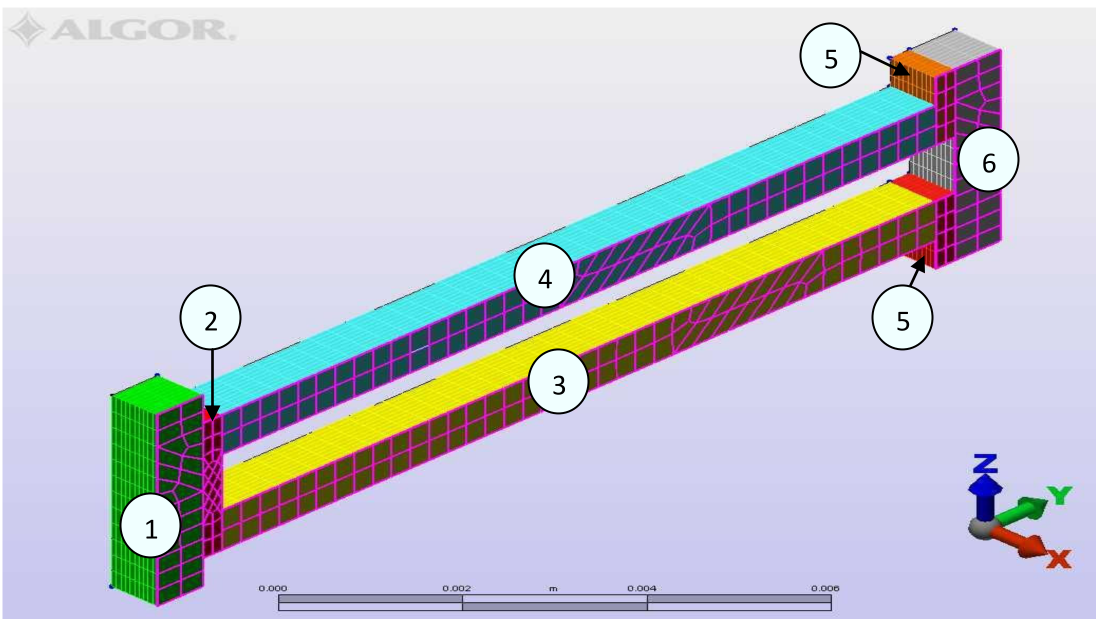

Figure 2: Meshed 2D model

After meshing was done successfully, element definitions and material properties were applied to the models. Their details are shown in Table 1 above. Components of the thermoelement and heat flow can be followed in Figure 3 beginning from the left end that indicates an applied temperature constraint of 230 ºC, followed by a thermal conductor, followed by a N-type TE leg at the bottom, and a P-type TE leg at the top. To the right of each TE leg is an electrical conductor that is attached to the heat sink with a constant temperature of 50 °C. The ambient air was applied on top and bottom of each TE leg as depicted by the yellow color. Algor assumes insulated surfaces if no boundary conditions are assigned. Once the boundary conditions were added to the model, the models were tested.

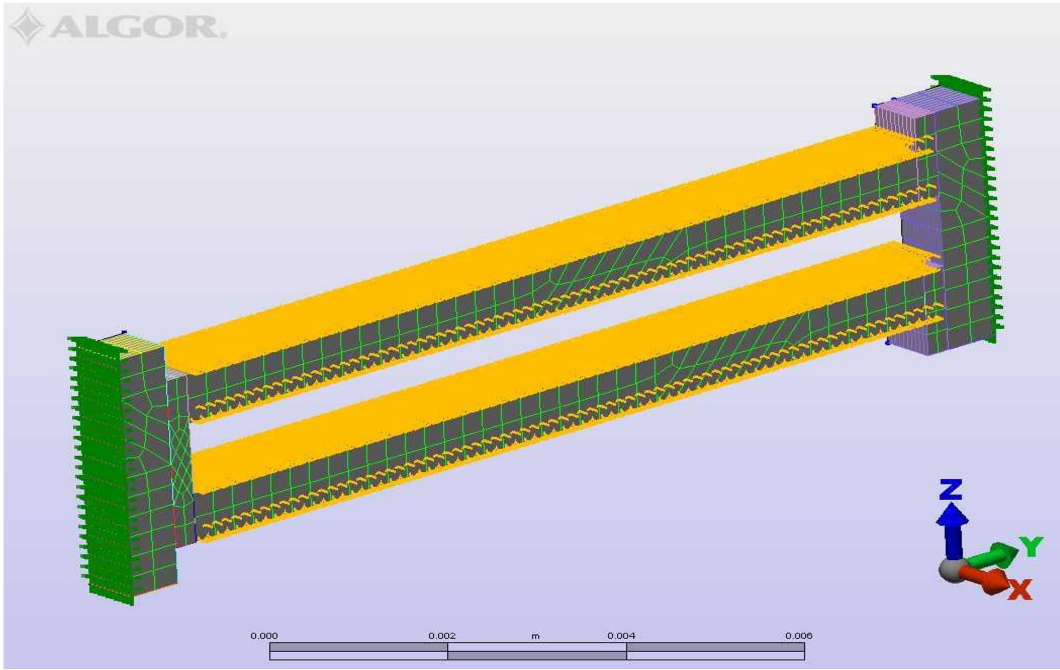

Figure 3: Boundary Conditions employed

Two assumptions were made for both 2D models. First, the materials used in the study were isotropic and second the interfaces between the elements were perfectly smooth without any imperfections.

Results

The temperature distribution for either the 11 mm or 22 mm TE legs did not differ much from each other nor from the 1D MATLAB model showing the flow from hot to cool as indicated in Table 2. An example temperature distribution is also given in Figure 4 depicting the 22 mm TE model.

Table 2: Comparison of temperature distribution between MATLAB 1D and Algor FEMPRO results

MATLAB 1D results (ºC)	Algor FEMPRO results (°C)
230	230
215	212
177	194
169	176
154	159
145	140
108	122
50	50

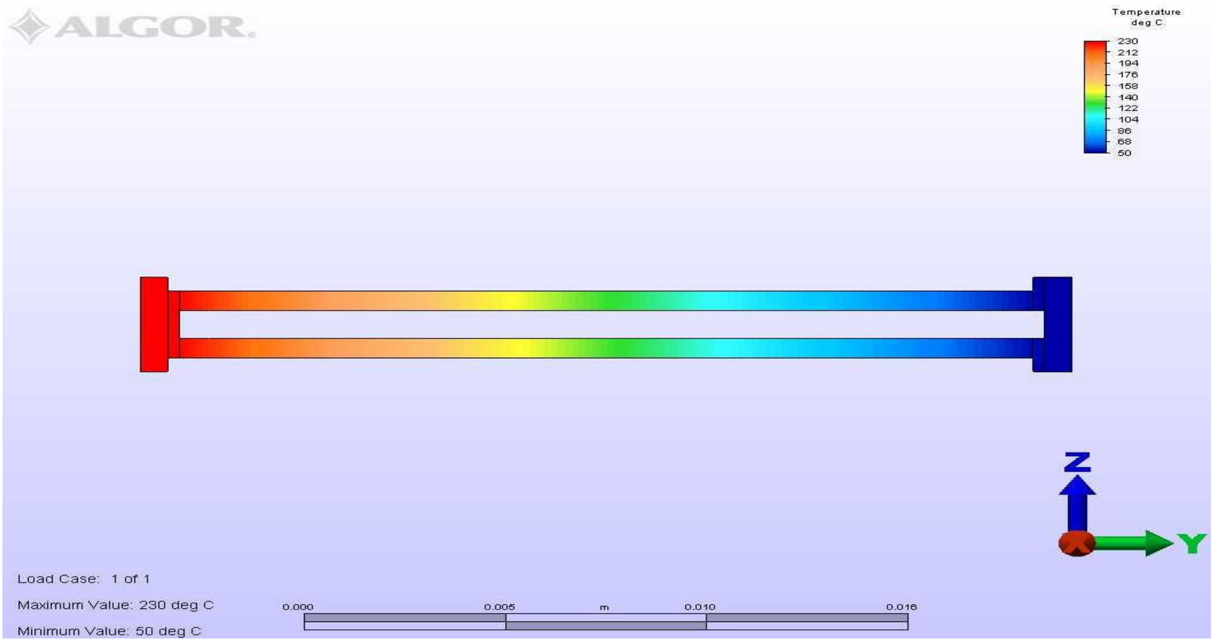

Figure 4: Temperature distribution for the 22 mm TE leg

Results of the heat flux portrayed the effects of the difference in thermal conductivities of N-type leg and P-type leg. The N-type indicated a higher heat flux concentration than the P-type. Figures 5 and 6 show the differences in heat flux concentration for both models. The differences between the heat flux values are presented in Table 3.

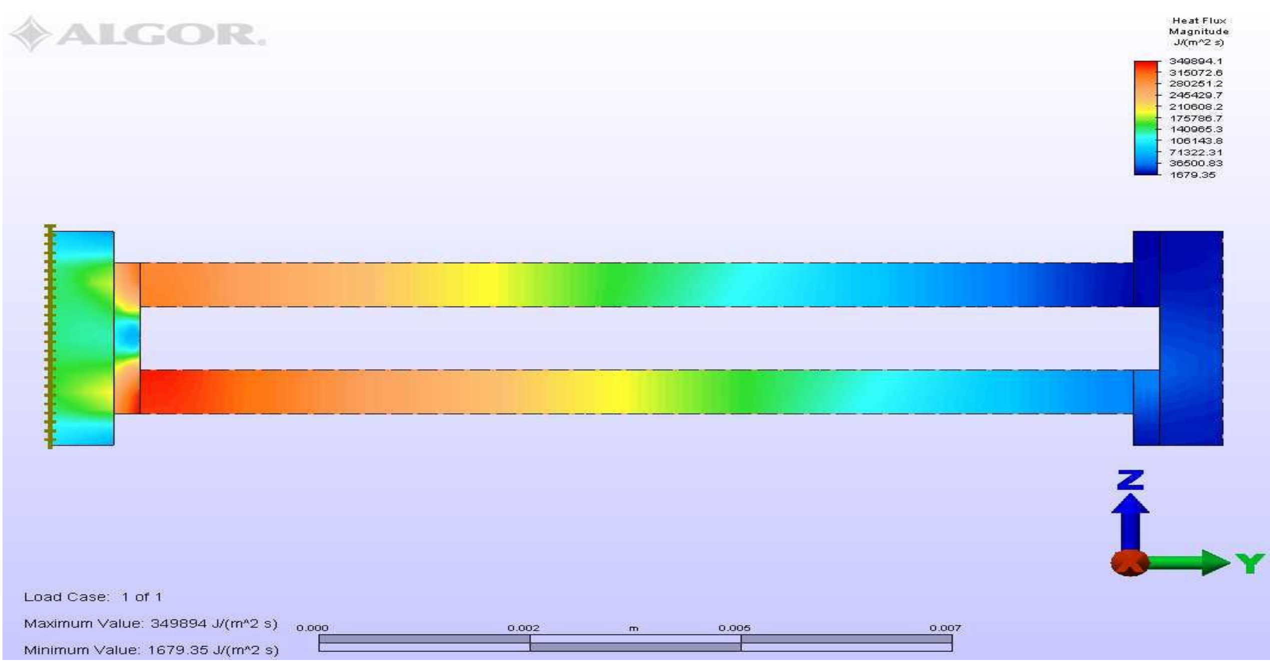

Figure 5: 11 mm thermoelement heat flux distribution

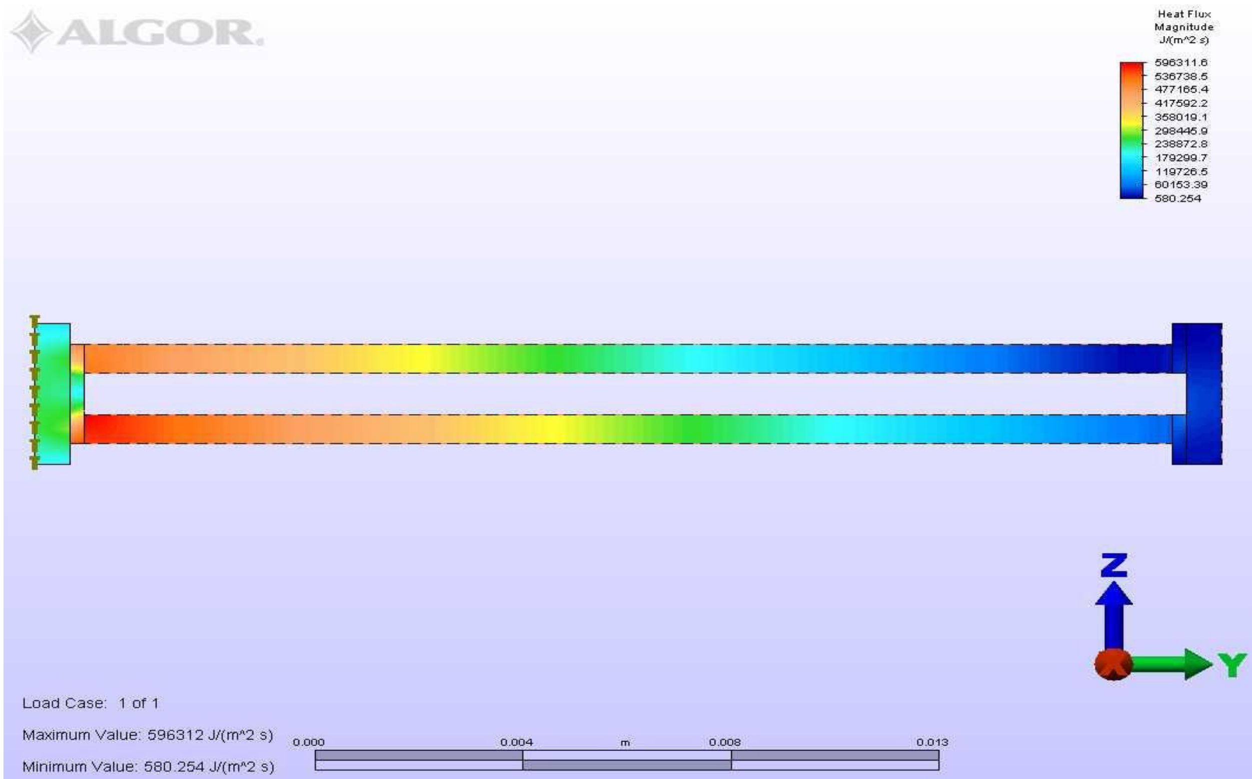

Figure 6: 22 mm thermoelement heat flux distribution

Table 3: Summary of heat flux of two models

Model	Maximum heat flux (W/m^2)	Minimum heat flux (W/m^2)	Difference of heat flux (W/m^2)
22 mm leg	596312	580.254	595732.0
11 mm leg	349894.1	1679.35	349894.0
Overall difference			245838.0

Discussion

Recent advances in thermoelectric elements have been largely on materials in seeking to enhance the figure of merit ZT[5,6]. The mechanical design done on this project provides a high potential towards higher enhanced TEs. As seen from the results, the TE leg size in particular makes a difference in heat flux distribution. Upon excitation by heat, the N-type material produced an abundance of "carrier" electrons in the material which are depicted by the flux in this project and as in equations 3 and 4 below. When energy balance is made between the two TE legs, overall gain is clearly shown in Figures 5 and 6. This is also supported by equation 5.

$$q_n = -k_n \frac{\Delta T}{L} \qquad (3)$$

$$q_p = -k_p \frac{\Delta T}{L} \qquad (4)$$

$$q_t = q_n - q_p \qquad (5)$$

where q_t is total heat flux, q_n is heat flux at N-type TE leg, and q_p is heat flux at P-type TE leg.

Results from the two models show that the longer the TE leg (while holding all other factors the same) the more flux generation occurs. By doubling the length size of the TE leg, the heat flux almost doubled. The results seem to agree with Rowe who advocates for wire-like TE legs for power generation purposes[4]. It becomes apparent that the difference in thermal conductivity between the two type semiconductors coupled by the length of the element is making a difference in terms of the heat flow. This partnership would control the electric (voltage) output of each unit. A question then arises, why aren't there wire-like thermoelements for power production purposes? The easy response is that the TE legs also are structural support for the TE devices. A very thin wire-like structure would not support the physical load that these devices experience. The next phase, not covered in this paper, is to develop a structural support for the unit cell.

Educational Impact

This analysis project did not include any undergraduate student contributions. However, the ability to demonstrate state-of-the-art elements like TEG is critical for the undergraduate engineering education at this critical point in the U.S. history where our leads in science and engineering have been seriously threatened. Therefore, engaging students in a learning atmosphere where computational analysis and simulation is conducted will equip them with the tools they need to predict outcomes which they can verify with experimentation as well as better prepare them for future challenges. Various ways can be employed in incorporating modeling into undergraduate curriculum early and often:

- Simple models like these conducted in MATLAB or ALGOR can be done in Introduction to Engineering or Technology courses giving students a head start and a taste of engineering research early in their education.
- Materials or Energy courses can include detailed studies (within the Energy Harvesting area) enriched with experimentation and at higher theoretical levels. A Design of Experiments course can lead to development of effective TEGs.
- Combinations of analytical, numerical (with MATLAB and/or FEA) coupled with experimentation can allow better understanding of the place of numerical methods in engineering design and analysis.

Conclusion

Thermoelectric element unit cell design and simulation of heat transfer and heat flux process indicates that more efficient and flexible TEDs for power generation can be developed. The authors will further explore the flexible physical unit cell that supports structural loads. The next step of the design and the development process will involve student help in the forms mentioned in the educational impact section as well as experimental directions and improved numerical models.

References

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[6] Synder, G. J. and Caillat, T. Materials Research Society: Symposium Proceeding. Vol. 793 P. 37-42. 2004.

Appendix

MATLAB code 1D Heat Transfer

```
%Heat conduction (5 layers) with convective B.C. on both sides

% local matrix (Direct FEA formulation)

clear

% Divide into 7 thermoelements (2 convective and 5 conductive layer elements) and 8 nodes =>
8 by 8 [K} matrix

el_no = 7;

% geometric and material properties (the area is equivalent to 1.5mm^2)

area=1.6e-5;

% U-factors

U1=5.88; U2=2.27;U3=10.0;U4=5.81;U5=10.0;U6=2.27; U7=1.47;

U=zeros(el_no,1)

% convective U-factors

U(1)=U1; U(el_no)=U7;

%conductive U-factors

U(2)=U2;U(3)=U3;U(4)=U4;U(5)=U5;U(6)=U6;

% Assembly of Local conductance matrices into global matrix (upper diagonal of k1g matrix)

A=zeros(el_no+1,el_no+1);

for i = 1:el_no

  AA=zeros(el_no+1,el_no+1);

  AA(i,i)=U(i); AA(i,i+1)=-U(i); AA(i+1,i+1)=U(i);

  A=A+AA;

end

%Populate lower half of matrix

AA

KK=A+A'-diag(diag(A))
```

```
KK=KK.*area
% apply boundary conditions for temperature T1=100 and T7=680
K=KK;
K(1,1)=1; K(1,2)=0;K(el_no+1,el_no)=0;K(el_no+1,el_no+1)=1;
%apply nodal heat loads
heatload=zeros(el_no+1,1);
heatload(1,1)=230; heatload(el_no+1,1)=50;
%Solve for unknown nodal temperatures (t)
t=inv(K)*heatload
%find nodal heat
q=zeros(el_no,1);
for i = 1:el_no
  q(i)=area.*U(i).*(t(i+1)-t(i));
end
%
q
```