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Analytic modeling of a high temperature thermoelectric module for wireless sensors

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Abstract. A novel high temperature thermoelectric module with thermoelectric materials never before combined in a module is currently researched. The module placement in the cooling channels of a jet engine where the cold side will be cooled by high flow cooling air (550°C) and the hot side will be at the wall (800°C). The aim of the project is to drastically reduce the length of the wires by replacing wired sensors with wireless sensors and power these (3-10mW) with thermoelectric harvesters. To optimize the design for the temperature range and the environment an analytic model was constructed. Using known models for this purpose was not possible for this project, as many of the models have too many assumptions, e.g. that the temperature gradient is relatively low, that thick electrodes with very low resistance can be used, that the heat transfer through the base plates are perfect or that the aim of the design is to maximize the efficiency. The analytical model in this paper is a combination of several known models with the aim to examine what materials to use in this specific environment to achieve the highest possible specific power (mW/g).

1. Introduction

Measuring pressure, temperature, stress and acceleration is essential for safe operation of jet engines. For test engines in development this means thousands of sensors and kilometers of wire connecting the sensors. The aim of this project is to place a thermoelectric module in the middle and the back of a test jet engine where it is complicated to place sensors due to both high temperature and the need of extensive cable wiring. Replacing the wired sensors with less wired or wireless sensors, coupled to an energy harvester as power source, can drastically reduce the cable wiring and the weight in total by not using cables. A high temperature thermoelectric module with thermoelectric materials never before combined in a module is currently researched specifically for this purpose [1].

A thermoelectric energy harvester is a device that converts a heat gradient into electricity. This is usually done by connecting alternating p-type and n-type semiconductors with high Seebeck coefficients in parallel thermally and in series electrically. The Seebeck coefficient (S) is the generated voltage difference per degree temperature difference of a material. It is material- and temperature dependent with negative values for the n-type and positive for p-type semiconductors. Electrical conductivity (σ) and thermal conductivity (κ) are also important when considering materials for thermoelectric energy harvesting to reduce Joule heating and maintaining a high temperature gradient. These properties are combined into the materials figure-of-merit, zT, value (zT=$\sigma S^2 T/\kappa$) that gives a measure of the efficiency of the thermoelectric material.

In the hot parts of a jet engine the walls are cooled down with air through cooling channels. Placing thermoelectric energy harvesters inside the cooling channels would give a hot side of 800-900°C, and with cooling air of 500-600°C on the cold side this means that a thermoelectric module may achieve a temperature gradient of roughly 200°C, if the heat transfer through the module is low enough.

To optimize the design for the temperature range and the environment an analytic model was constructed. Using known models for this purpose was not possible for this project, as many of the models have too many assumptions, e.g. that the temperature gradient is relatively low, that thick electrodes with very low resistance can be used, that the heat transfer through the base plates are perfect or that the aim of the design is to maximize the efficiency. In this project the aim of the design is to maximize the specific power output (mW/g).

2. Analytical Model

The thermally conductive parts of the device are the legs, contacts, base plates and the surrounding material. As a first analysis, the thermal conductance and electrical resistance in the thermoelectric legs are described. Each leg has a thermal conductance

$$K_i = \frac{\kappa_i A_i}{\ell_i} \tag{1}$$

Where κ_i is the average thermal conductivity in the temperature range, A_i the area of the leg and ℓ_i the length of the leg, giving a total thermal conductance of n couples of legs and surrounding thermally parasitic material

$$K = n(\frac{\kappa_N A_N}{\ell_N} + \frac{\kappa_P A_P}{\ell_P}) + \frac{\kappa_{Pa} A_{Pa}}{\ell_{Pa}} \tag{2}$$

where index i is N for n-type and P for p-type semiconductor and Pa the surrounding thermally parasitic material. For the electrical resistance the legs are in series and with similar derivation as for thermal conductance this gives the total resistance

$$R = n((\frac{\sigma_N A_N}{\ell_N})^{-1} + (\frac{\sigma_P A_P}{\ell_P})^{-1}) \tag{3}$$

with σ the average electrical resistivity in the temperature range. The thermal conductance and electrical resistance can then be used to formulate an energy transport diagram [2]. In Figure 1 the energy transport to the leg-electrode junctions can be seen. For the hot junction this gives following energy balance

$$Q_H = P_{TE} + Q_{Cond} - Q_{Joule} = nS_{avg}T_H I + K\Delta T - \frac{I^2 R}{2} \tag{4}$$

where Q_H is the heat input, $Q_{Cond} = K\Delta T$ the conduction away from the hot junction, $Q_{Joule} = I^2R/2$ the resistive heating and $P_{TE} = nS_{avg}T_H I$ the electrical energy from the thermoelectric effect, where T_H is the temperature and S_{avg} the average Seebeck value for n-type and p-type material in the temperature interval, a simplification that is known to introduce only minimal errors [3]. For one couple the Seebeck effect induces an open circuit voltage $V = S_{avg}\Delta T$ which from Ohm's law gives the short circuit current $I = V_{oc}/R$. For n couples this gives

$$I_{sc} = nV_{oc}/nR = n \cdot S_{avg} \cdot \Delta T/R \tag{5}$$

However, to extract power from the module there has to be a load R_L attached. For maximum power and efficiency this load should be resistance matched with the module resistance, $R_L = R$. By introducing $\mu = R_L/R$ the power output for an n-coupled module is

$$P = (n \cdot S_{avg} \cdot \Delta T)^2 \mu/R(\mu + 1)^2 \tag{6}$$

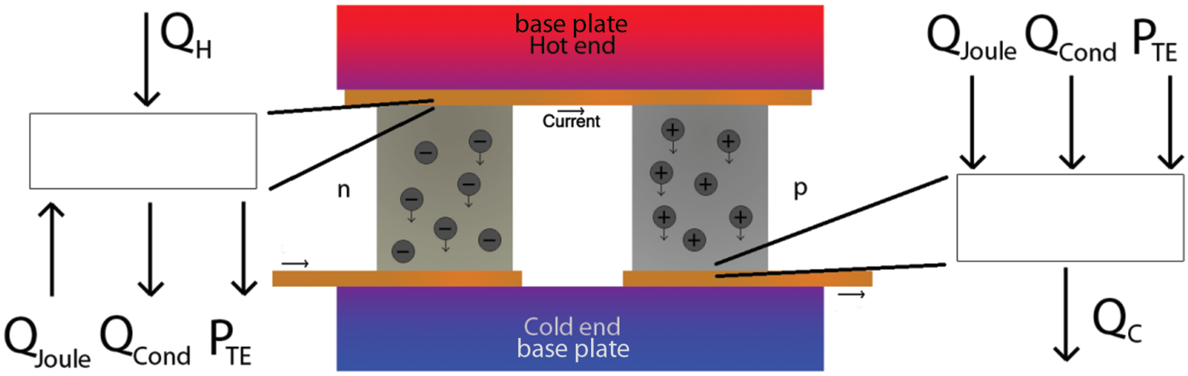

Figure 1. *Energy balance transport of thermoelectric module for hot junction (left) and cold junction (right).*

The simplification of perfect heat transfer through the base plates will now be corrected. Adding the two base plates to the calculations gives the total thermal resistance of the device.

$$R_{th} = \frac{1}{K} + \frac{2\ell_C}{\kappa_C A_C} \tag{7}$$

with the thermal conductivity of the plate material κ_C, the area A_C and the thickness of one base plate ℓ_C. From this the temperature on the legs can be calculated. This gives a new temperature difference, T_{diff}, between the hot- and cold side of the legs to be used in the calculations. One more aspect to consider are the electrodes and the contact resistance $R_{contact}$ [4]. Introducing $\delta = R_{contact}/R$ that we can add to the resistance in Equation 5 gives the device output power approximation

$$P = (nS_{avg}T_{diff})^2 \mu / R(\mu + (1 + \delta))^2 \tag{8}$$

Resistance of cables and the voltage amplification to 3.3V with a DC-DC step up booster [5] was also implemented in the model to match the requirements of the wireless sensors.

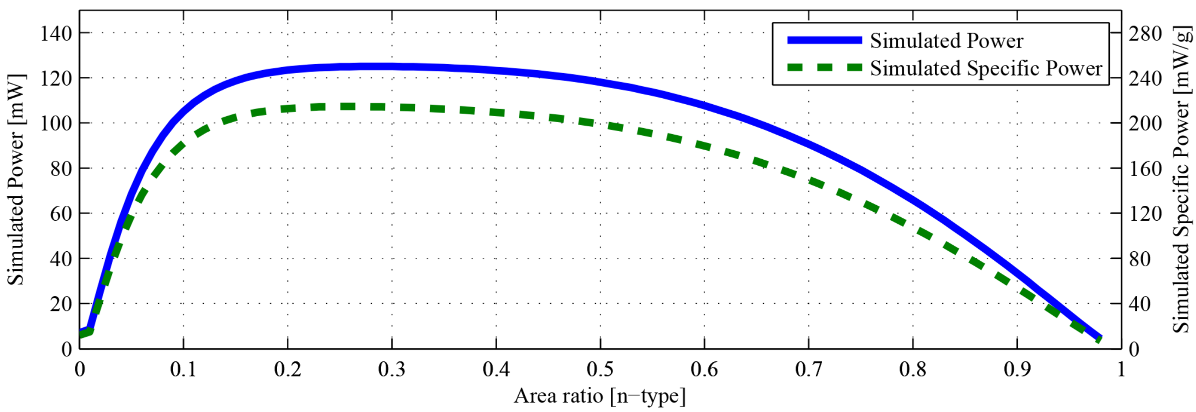

Figure 2. Estimated power output (blue, solid line) and specific power output (green, dashed line) of a 17-couple module as a function of the area ratio of the n-type:p-type material with a temperature gradient of 200°C. A DC-DC converter circuit with an efficiency of approximately 30% and 2m long wires with a resistance of 0.16Ω/m was included to the model.

3. Results

Some of the important variables examined by the model were the number of couples, area of legs, temperature gradient of environment, thermal conductance of base plates, area ratio between n-type and p-type material, thickness of electrodes, load resistance, parasitic heat conductance and several different materials for base plates, thermoelectric legs and electrodes, with the temperature dependence of all material properties included in the model. The simulation was done in temperature intervals set to 0.1°C and integrated over the whole temperature range (600-800°C). The fixed values was the module size of 1cm^2 with the leg height set to 1mm, as this is the minimum height that we could handle with the current fabrication techniques.

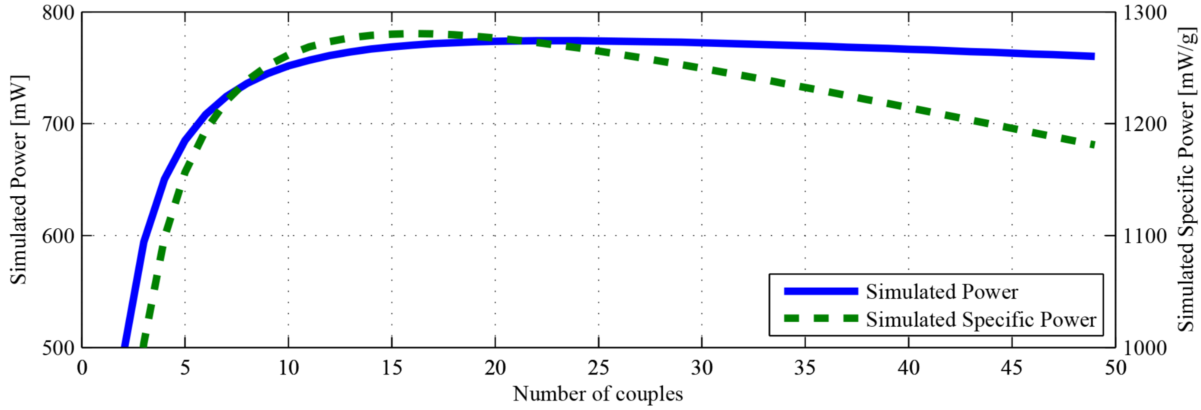

Figure 3. Simulated power output (blue, solid line) and specific power output (green, dashed line) of a thermoelectric module as a function of the number of couples with a temperature gradient of 200°C. No DC-DC converter circuit was included in this simulation and the load resistance was matching the module.

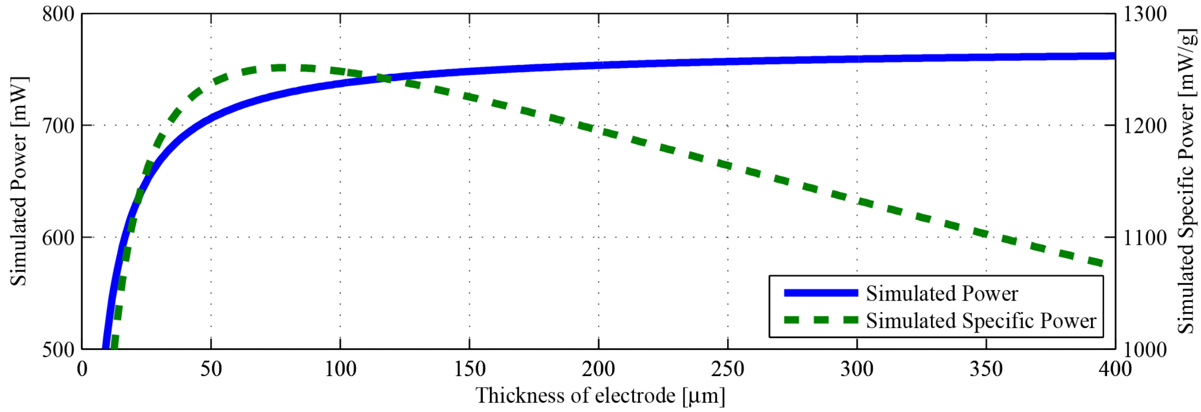

Figure 4. Estimated power output (blue, solid line) and specific power output (green, dashed line) of a 17-couple module as a function of the thickness of the Mo electrode with a temperature gradient of 200°C. No DC-DC converter circuit was included in this simulation and the load resistance was matching the module.

The highest specific power output after DC-DC conversion and cable losses was given with an n-type:p-type area ratio of 1:3.7 (Figure 2), 17 couples (Figure 3), 65m thick Mo electrodes

(Figure 4) with thermoelectric materials n-type $Ba_8Ga_{16}Ge_{30}$ and p-type La-doped $Yb_{14}MnSb_{11}$, alumina base plates (0.25mm thick) and the structure material (stability and sublimation repression) Cotronics Thermeez 7020. This gives, with an environmental temperature gradient of 200°C, a simulated specific power output of 215mW/g or 125mW/cm^2. When the load resistance is matched for a case without DC-DC conversion it gives a corresponding 1275mW/g or 771mW/cm^2.

A test module with one couple was fabricated and measured giving an open circuit voltage approximately 70% of simulated value, see Figure 5. The low voltage could be explained by the fact that the module, to reduce stress, was not attached to the heater or cold sink with any conductive paste.

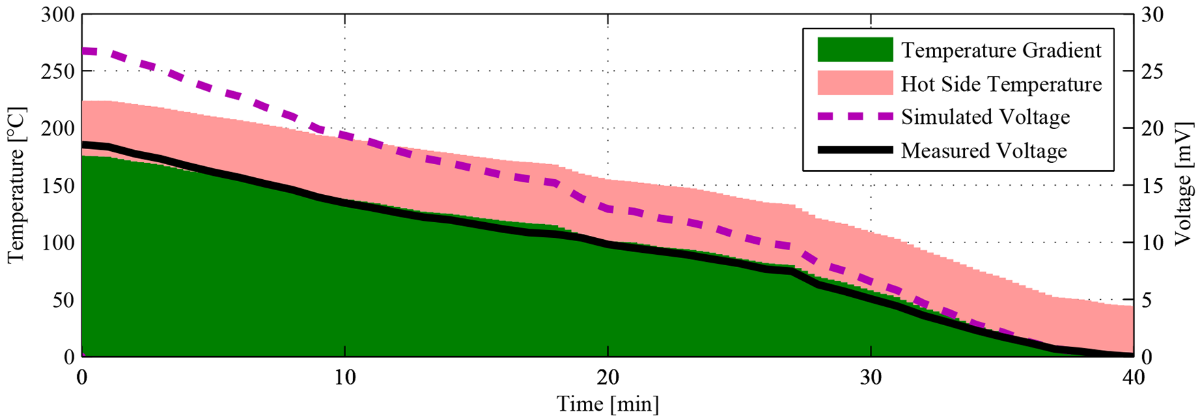

Figure 5. To verify the model, a 1-couple module was realized and measured. The figure shows the measurement and the simulated value with the measured value approximately 70% of the simulated value. Conductive paste was not used during the measurement which could explain the lower voltage.

4. Conclusion

The analytical model in this paper is a combination of several known models with the addition of DC-DC conversion and cable losses directly in the model with the aim to find the highest specific power instead of highest efficiency. For applications similar to the jet engine application mentioned in this paper where highest power-to-weight is wanted, this analytical model is very useful and give more suitable results than other known models.

5. Acknowledgement

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