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Design of a Thermoelectric Generator for Electrically Active Implants

Electrically active implants for regenerative therapies (e.g. regeneration of bone tissue or deep brain stimulation for the treatment of motion disorders) are gaining on importance within an aging population. The implants must be replaced during the course of the therapy. To improve an implant's lifetime, it is a reasonable endeavor to satisfy a significant share of its energy demand by means of harvesting mechanical or thermal ambient energy [1]. In this work, we present a multiphysical model of a miniaturized thermoelectric generator (TEG) for electrically active implants, which uses temperature gradients in human tissue. Based on this model, we analyze the influence of the geometry and material parameters on the thermal and electrical properties and aim for an optimal transducer design.

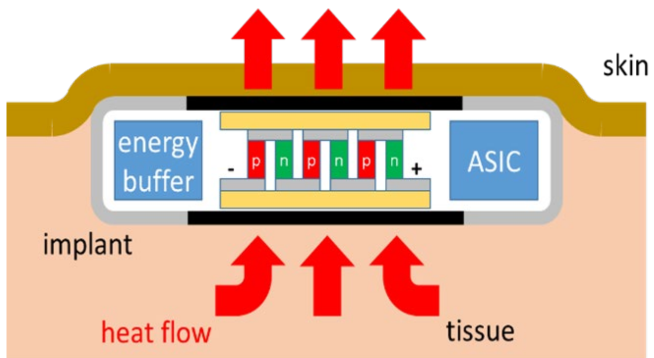

Fig. 1. Implant with thermoelectric energy conversion powered by flow of body heat

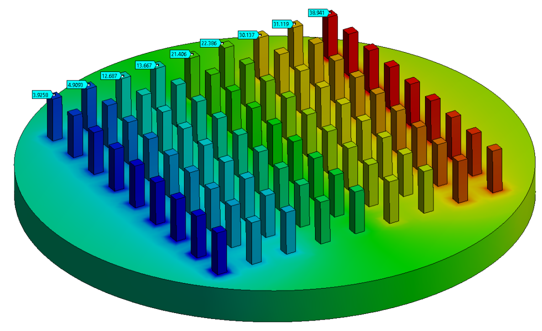

Fig. 2. Electric potential across 81 thermocouple legs of bismuth telluride.

MODEL DESCRIPTION AND DESIGN OPTIMIZATION

We use a simplified tissue model consisting of muscle, fat and skin layers [2]. The stationary heat conduction in the tissue is described by the bioheat equation of Pennes, which considers the perfusion (blood circulation) as an additional heat source:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla(\kappa \nabla T) = Q_b + Q_m \quad (1)$$

with $Q_b = \rho_b c_b \omega_b (T_a - T)$ and Q_m as metabolic heat generation rate. Where ρ, c, κ are the density, specific heat capacity and thermal conductivity of the tissue types, ρ_b, c_b describe the thermal properties of blood, and ω_b is a measure of perfusion. T is the resulting temperature distribution and T_a is the temperature of the arterial blood, which is assumed constant with $T_a = 37$ °C. Furthermore, a constant body core temperature of 37 °C is assumed. The heat is dissipated by convection at the skin surface with a heat transfer coefficient of $h = 20$ W/(m²K) whereas the environmental temperature is set to 14.85 °C. Fig. 3 shows the resulting steady-state temperature profile through the tissue. The temperature gradient is the highest within the fat layer, due to its low thermal conductivity.

The Seebeck voltage generated by this TEG is given by:

$$V_{out} = n \cdot \Delta T \cdot (\alpha_1 - \alpha_2) \quad (2)$$

where ΔT is the temperature difference, n is the number of thermocouples, α1,2 are the Seebeck coefficients of the thermocouple legs. Choosing the right geometry for thermoelectric generator poses an optimization problem. We analyze the impact of the leg's cross section on thermal properties and electrical performance of TEG (see Fig. 4). The open circuit voltage of TEG decreases with the increasing cross-section of the leg. The electrical power delivered in a matched load resistor reaches a maximum of 94,5 µW at a cross-section of 275 × 275 µm².

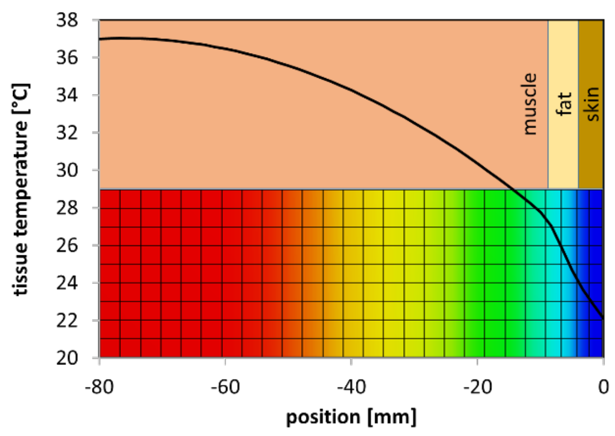

Fig. 3. Temperature profile across human body tissue

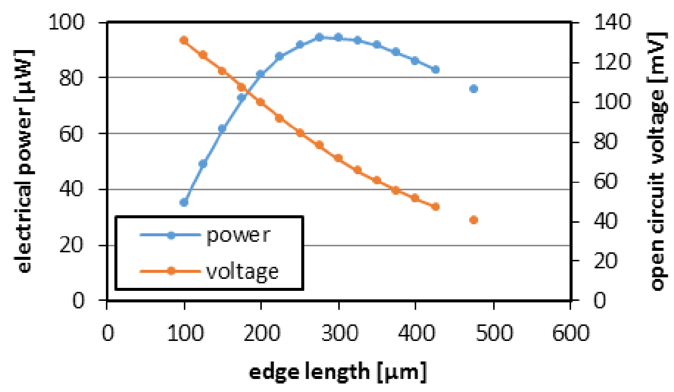

Fig. 4. Influence of the leg edge length on electrical power output and temperature difference in TEG

MODEL ORDER REDUCTION AND SYSTEM-LEVEL SIMULATION

After spatial discretization with the finite element method (FEM), the model (1) is turned into an ordinary differential equation (ODE) system of the form:

$$\Sigma_n \begin{cases} E \cdot \dot{T}(t) = A \cdot T(t) + B \cdot u \\ y(t) = C \cdot T(t) \end{cases} \quad (3)$$

where, $A, E \in R^{n \times n}$ are the global heat conductivity and heat capacity matrices, $B \in R^{n \times m}$ is the input matrix and $C \in R^{n \times p}$ is the output matrix. $T(t) \in R^n$ is the unknown temperature state vector and $y(t)$ is the user defined output vector. Transient thermal simulation was performed to evaluate the effect of a change in the convection boundary condition. In this case we apply a homogenous heat generation rate across the muscle tissue as input.

The large-scale model (3) can not be used for the co-simulation with a power management circuitry. An accurate but compact model can be constructed by using mathematical methods of model order reduction (MOR), which has been proven to work well for linear thermal models [3].

Fig. 5. Workflow for the model order reduction of the TEG model

The reduced model reads:

$$\Sigma_r \begin{cases} E_r \cdot \dot{z}(t) = A_r \cdot z(t) + B_r \cdot u \\ y(t) = C_r \cdot z(t) \end{cases} \quad (4)$$

where $E_r = V^T E V, A_r = V^T A V, B_r = V^T B, C_r = CV$ and the projection matrix $V \in R^{n \times r}$ with $r \ll n$ is constructed by using the Block-Arnoldi algorithm from [4].

Fig. 6 shows an excellent match between the temperature distribution of the full scale model of order 106.467 DOF and the reduced order model of order 30 DOF.

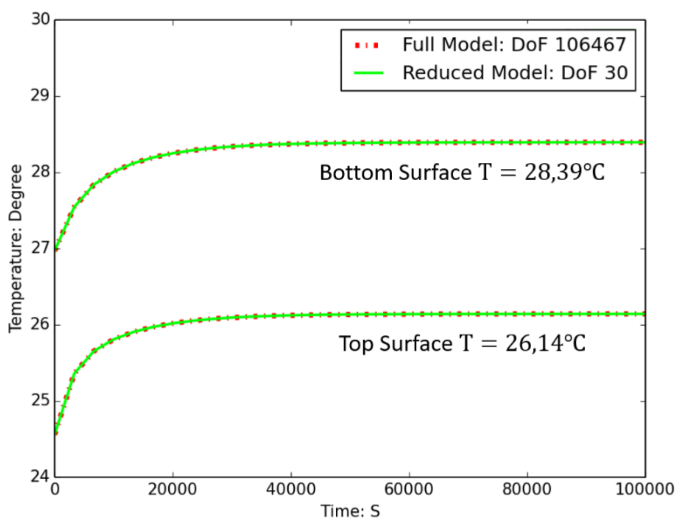

Fig. 6. Temperature comparison between full and reduced models at top and bottom surface of the center thermocouple leg in TEG model.

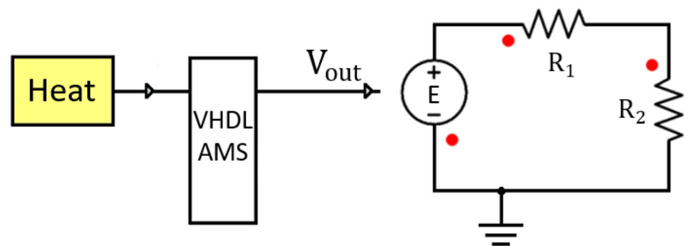

Fig. 7. Co-simulation setup with VHDL-model for transient thermal analysis of power output

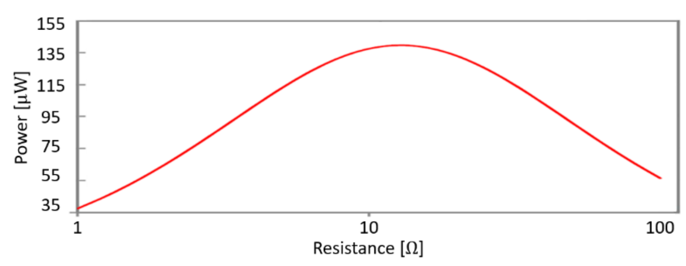

Fig. 8. Power dissipated in load resistor for different load resistance values.

The temperature difference of $\Delta T = 2{,}25$ °C is obtained and the voltage output is calculated as 72,9 mV according to the Seebeck effect (2). A simplified co-simulation setup is displayed in Fig. 7. Reduced order TEG model is described in VHDL format, R_1 models the internal resistance of TEG and R_2 is the load resistor. Fig. 8 shows the power dissipation for different values of the load resistor between 1 Ω and 100 Ω.

CONCLUSIONS

- We employed a thermo-electrical model to study the impact of the thermocouple leg's cross section on electrical power output of a TEG.
- Transient thermal simulation was performed to evaluate the effect of a change in the convection boundary condition.
- Mathematical model order reduction was successfully applied to enable the device-circuit co-simulation.

LITERATURE

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