Temperature Field Modeling Technique of a Thermoelectric Generator, Taking into Account Parasitic Internal Sources

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The thermoelectric electricity generation is the conversion of thermal energy into electrical energy using thermoelectric generators (TEGs). TEG include the heat source, heat sink and located between them thermoelectric modules (TEMs). The principle of TEM operation in electricity generation mode is based on the Seebeck effect, which consists in the fact that when creating a temperature difference between the sides of TEM the electric energy appears at the ends of the thermoelectric circuit.

One of the main object of study in TEGs is the inner temperature field. Due to the fact that the physics of thermoelectric processes is well studied the numerical simulation is actively used in the study of thermoelectric devices.
For the accurate modeling of temperature distribution in TEG it’s important taking into account the influence of TEM design features and the physical processes that occur in the TEM when it works.

TEM include hundreds of thermocouples, and at real work they are under their own temperature conditions and have internal parasitic heat sources with their own values of power. So if we want to take into account the influence of every parasitic heat source on the temperature distribution we should use the direct mathematical modeling.

But because of thermocouples size is smaller than TEG by several orders of magnitude the calculation grid would have complicate configuration with a huge number of cells and big difference of cell sizes which negatively affects the convergence of calculation. As a result, to realize the calculation a great computational powers are required.

This work, presents a technique in which the process of calculation is splitting on several stages, that allows avoid using a complex grid with cells that can differ by orders of magnitude.
It should be noted that the small-scale elements are located only in the TEM area. So, instead of modeling TEG with detailed geometry and complex grid, a calculation in regions where required a small-scale grid can be performed separately from the calculation of the whole TEG.

To realize this, the following steps should be performed:

1) Mathematical model of TEG
2) Mathematical model of the TEM
3) Describing of the calculation scheme which provide thermal balance between the temperature fields of both models.
In this work we would consider liquid type of TEG. In TEG model TEM has simple “layer” geometry. The thermocouples replaced by homogeneous layer which have equal thermal resistance that created by thermocouples. The layer has effective thermal conductivity coefficient calculated by:

$$\lambda_e^0 = \lambda_{n,p} \frac{S_{br} \cdot n}{S_m}$$

Heat transfer in solid elements:

$$\text{div}\{\lambda \cdot \text{grad}[T(x,y,z)]\} = 0$$

hydrodynamic and heat transfer in a heat carrier liquid:

For laminar flow:

$$\text{div}(\vec{v}) = 0$$  \hspace{1cm} \text{– Continuity equation}

$$\text{div}(\rho \vec{v} \cdot v_i - \rho v_x \nabla \vec{v}) = -\frac{\partial P}{\partial x_i}$$  \hspace{1cm} \text{– Momentum equation}

$$\text{div}\left(\rho C_p \vec{v} \cdot T - \frac{\rho v_x}{Pr} \nabla T\right) = 0$$  \hspace{1cm} \text{– Energy equation}

For turbulent flow:

$$\text{div}\left[\rho \vec{v} \cdot K - \left(\frac{\rho v_T}{Pr_K}\right) \nabla K\right] = \rho (P_K - \varepsilon)$$  \hspace{1cm} \text{– Equation for the energy of turbulent pulsations}

$$\text{div}\left[\rho \vec{v} \cdot \varepsilon - \left(\frac{\rho v_T}{Pr_\varepsilon}\right) \nabla \varepsilon\right] = \frac{\rho \varepsilon}{K} (C_1 P_K - C_2 \varepsilon)$$  \hspace{1cm} \text{– The equation for the dissipation rate}
The TEM consists of individual thermocouples connected in a circuit: branches of an n- and p-type semiconductor and copper conductors connecting them. The circuit is located between two ceramic plates. In TEM elements, heat transfer is described by three-dimensional stationary heat equation for solid objects:

$$\text{div}\{\lambda \cdot \text{grad}\left[ T(x, y, z) \right]\} + q_v = 0$$

Surface heat sources act on the junctions of the thermocouples, due to the Peltier effect. They are set as boundary conditions for S-surfaces located at the junctions:

$$q_{c_j} - q_{c_{j+1}} = \frac{s \cdot T_{c_j} \cdot I}{a^2}$$

$$q_{h_j} - q_{h_{j+1}} = -\frac{s \cdot T_{h_j} \cdot I}{a^2}$$

On the hot and cold sides of the module, boundary conditions of the third kind are set for modeling heat exchange with hot and cold heat carrier fluid:

$$q = \alpha_h (T_{hw} - T_{hl})$$

$$q = \alpha_c (T_{hw} - T_{cw})$$
The calculation process has following steps:

1) TEG model:
   calculation of temperature field and hydrodynamic in TEG and determining the local heat transfer coefficients for each TEM by equation:
   \[ \alpha = \frac{q}{(T_w - T_i)} \]

2) TEM model:
   calculation of temperature field for every TEM in TEG, using the detailed TEM model the local heat transfer coefficients calculated for it. Calculation of effective thermal conductivity coefficient for each TEM:
   \[ \lambda_e = \frac{q \cdot l_{br}}{\Delta T_{av}} \]

3) Goes to the step 1) and begin the next iteration
   with obtained values of the effective coefficient of thermal conductivity for layer geometry TEM in TEG model. Calculation is completed when the temperature distribution in the TEG at the previous and subsequent iterations does not differ from the accepted value.
Results of test calculation

The calculations were carried out for a TEG consisting of 4 TEM with overall dimensions of 160mm * 40mm * 83mm. The cross section of the heat exchanger channel has dimensions 38mm * 38mm.

Temperature distribution in the TEG volume. Calculated with PHOENICS

Temperature distribution in the volume of the detailed TEM model. Calculated with PHOENICS
Conclusion

- The paper presents a method for calculating the temperature field in a TEG. This method allows to take into account the features of the geometry and the influence of thermal processes in the TEM, due to the partition of the model into two levels that are different in scale: the TEG model, and a detailed TEM model. Descriptions of these models were given, as well as the methodology for exchanging data between them.

- The technique also allows avoid using a complex grid with cells that can differ by orders of magnitude and simplifies the description of the TEG geometry. Also, this technique allows you to change the model and design of the TEM without making changes to the grid of the full design.
Thank you for attention!

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