Chapter 26
Modeling and Design of Tubular Thermoelectric Generator Used for Waste Heat Recovery

H. Tjoa, B. Plochmann, and G. Fischerauer

Abstract In many energy conversion processes, thermal energy is released to the environment; that is, it remains unused. With the aid of thermoelectric generators (TEGs), a part of this energy can be converted into electrical energy. The efficiency of the process can be increased and the CO_2 emissions are therefore reduced. In this contribution, the simulation and the design of a new concept of thermoelectric generator are discussed. The TEG is built ribbonlike and is wrapped around an electrically insulated tube, which is heated by waste heat from the inside and cooled by water from the outside. A numerical model is developed to theoretically study this concept. The goal is to understand the characteristics of the TEG and with it achieve a performance-optimized TEG design. In order to achieve the optimal design, parameter studies were carried out with the numerical model, which should help to determine the performance of the TEG. Geometrical dimensions, thermal resistance, and electrical resistance in the components are taken into account to accurately model the modules. The convective heat transport was taken into consideration in the study of the heat transfer as it plays a major role in the later application. Furthermore, the temperatures and the heat flows are also studied as small changes of these can often have a direct impact on the system.

Keywords Thermoelectric generator • Simulation • Finite element method • Design • Modeling • Waste heat recovery

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Introduction

Thermal energy is produced as a by-product in many energy-conversion processes. This energy is often unused and released directly to the environment. With a thermoelectric generator (TEG), a portion of this energy can be converted into electrical energy.

There are different ways to integrate a TEG in a system. As a promising concept for a TEG system we propose a design in which a ribbonlike flexible TEG is wrapped around an electrically insulated tube (the TEG materials can, for example, be an n-type and a p-type semiconductor). The tube will be heated by waste heat and cooled by water. To analyze this concept, a combination of computational fluid dynamics (CFD) analysis and finite element method (FEM) was used. With this method, both the gas flow and the temperature distribution can be studied, and thus the electrical performance of the TEG can be predicted.

In the design of the planned TEG, different challenges need to be addressed. To ensure a high temperature difference over the TEG and a high usable output voltage, the heat transfer from the environment to the TEG surfaces must be as good as possible. Furthermore, the TEG should have a small internal resistance to reduce the electrical losses. These two parameters are directly influenced by the TEG geometry. In the following, we describe our attempt to find optimal design parameters by simulation. The goal of the simulation is a performance-optimized TEG system.

Model Setup

We have based our analysis on CFD and FEM simulations. The program platform used was Ansys as the suitability of this code to model conventional TEGs has already been demonstrated in various works [1–4]. The analysis process is depicted in Fig. 26.1. The solution of the CFD analysis yields the temperature distribution in the tube which will be used as boundary conditions in the thermoelectric analysis by FEM simulation. This two-step process takes the fluid flow and heat transfer into account, therefore providing realistic results for the TEG output.
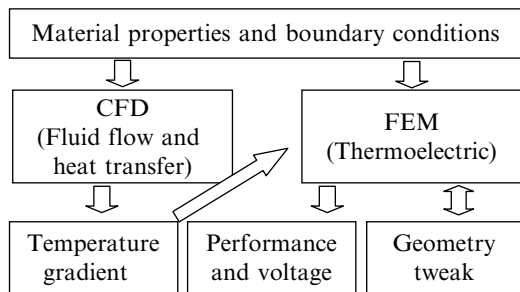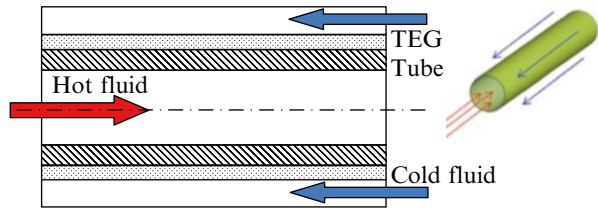

Fig. 26.1 Modeling approach
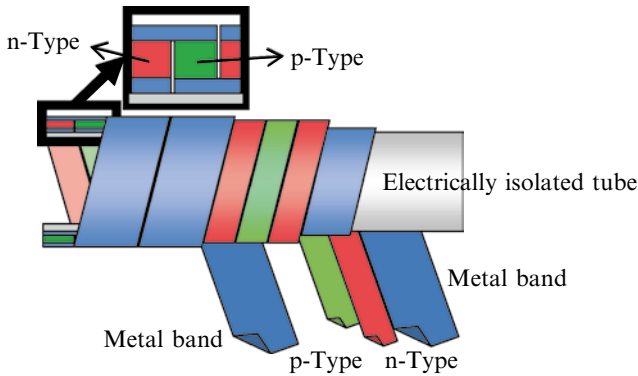
Fig. 26.2 Geometry of the proposed TEG

Fig. 26.3 Sectional view of model geometry with the TEG wrapped around a tube

The components and arrangement of the planned TEG are depicted in Fig. 26.2. It consists of flexible thermoelectric materials that are wrapped around an electrically insulated tube. The thermoelectric legs are contacted electrically by a flexible metal band. To isolate the thermocouple from one another a longitudinal cut along the surface is needed.

Figure 26.3 shows the sectional view of the model for the TEG in operating condition. It consists of two fluid flows that are separated by the TEG-wrapped tube wall. To determine the temperature difference between the two sides of the TEG, the heat transfer needs to be investigated. The convective heat transport was taken into account in the investigation since, in most cases, heat transfer in the fluid flows is influenced by convection, which is affected by properties of the flow (flow velocity, Reynolds number, Prandtl number, etc.). A 3-D model was created using Ansys Fluent to simulate the behavior of the TEG.

The equations used in the thermal-electric analysis in Ansys include all governing equations and also consider relevant effects such as Seebeck, Peltier, Joule heating, and Thompson. The model of the thermoelectric legs and the electrical contacts uses a free mesh with tetrahedral elements (Solid227), which are typically used for thermal-electric analysis [4]. To reduce the number of finite-element nodes and the calculation time, only one thermocouple is modeled as unit cell of the geometry under consideration (in other words, the geometry was considered to be infinitely periodic along the tube axis; Fig. 26.4). The result of the simulation of a single thermocouple can then be extrapolated analytically to the number of thermocouples in a module.
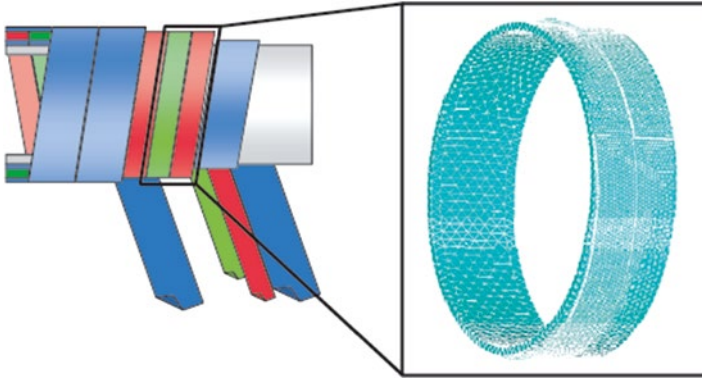
**Fig. 26.4** Modeling of one thermocouple in Ansys

The geometry was modeled with Ansys Designmodeler and then exported to Ansys apdl as an Ansys neutral file. The geometry was meshed and the boundary conditions were defined in Ansys apdl. Since only one thermocouple is modeled, the mean temperature in the tube wall was used as the boundary condition instead of the temperature distribution. Surface effects such as thermal radiation were neglected as the tube is surrounded by water. The temperature dependence of the material is also neglected because the simulation is intended for low temperatures (80 °C at most).

Parameter Studies

To discuss a first design test, we assume that the flexible TEG is made of materials with Seebeck coefficients of, respectively, 200 µV/K (p-type leg) and −200 µV/K (n-type leg), with a thermal conductivity of 2 W/m K, and an electrical conductivity of 10^5 S/m. The flexible thermoelectric legs are connected electrically by copper band, and the TEG module is assumed to be load matched. With these material parameters, we can determine the optimal design parameters. Of particular importance are the tube diameter and the TEG foil thickness, as they directly affect the temperature drop over the TEG and the internal resistance. Results of variations in these parameters are presented in the following. The simulation is carried out with a hot-side temperature of 80 °C and a cold-side temperature of 10 °C. We assume that both fluids have a good heat transfer coefficient.

The simulated relation between the temperature drop over the TEG and the TEG thickness on the one hand and that between the internal resistance and the TEG thickness on the other hand is plotted in Fig. 26.5. By increasing the thickness of the TEG foil, both the internal resistance and the temperature drop increase. The former is equivalent to the electric resistance of the foil material, and can be calculated analytically from the material resistivity, the foil thickness, and the cross-sectional area of the foil. The temperature difference was obtained through the CFD analysis.

Fig. 26.5 Temperature difference between the two TEG surfaces and internal resistance for different values of TEG foil thickness (leg length)
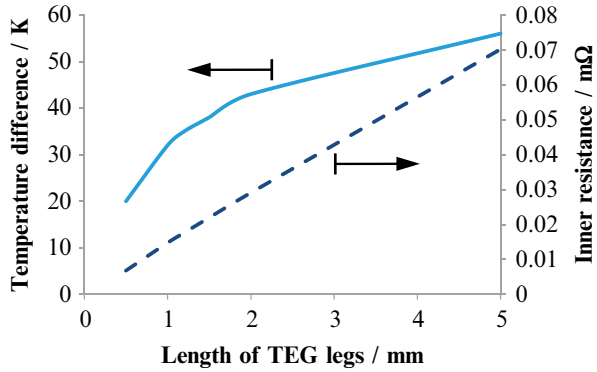
Fig. 26.6 Power output as a function of TEG foil thickness (leg length). Tube dimensions: Inner diameter 80 mm and wall thickness 2 mm
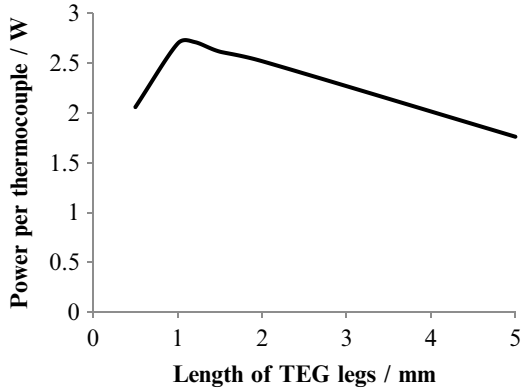

Figure 26.6 presents the theoretically achievable performance of the TEG in load-matching condition as a function of the foil thickness. The maximum power occurs at around 1 mm. A close look at the curve indicates that the maximum power reduces significantly with increasing foil thickness. At 10 mm thickness, the power reduces to around one-third of the maximum power as the internal resistance increases. The high output power of the single thermocouple is due to the small internal resistance and the large values of the electrical conductivity and the Seebeck coefficient assumed for the TEG material, which results in a high electric current.

In addition to the TEG thickness, the tube diameter is also studied. The size of the tube diameter determines the length of the TEG foil wrapped around the tube as well as the flow characteristics in the tube (laminar or turbulent). In our parameter study, we only considered standard DIN size tubes. It is assumed that the flow rate is constant. The results are plotted in Figs. 26.7 and 26.8. It is evident that both the internal resistance and the temperature difference decrease as a result of the reduction in flow velocity as the tube gets bigger. The looked-for optimum occurs at around 25 mm tube diameter.

Fig. 26.7 Temperature difference between the two TEG surfaces and inner resistance for different tube diameters
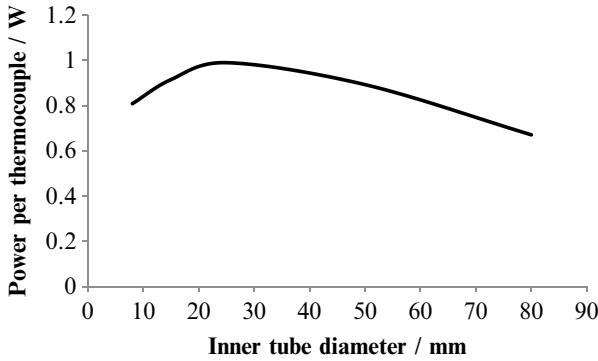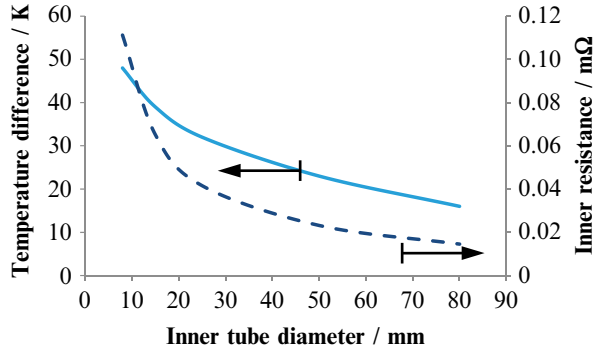
Fig. 26.8 Investigation of optimal tube diameter. TEG foil dimensions: Thickness 1 mm, width 5 mm

## Comparison with Analytical Model

To corroborate the numerical results, they were compared with the results of an analytical model based on known basic equations. For this calculation, the geometry parameters of the proposed TEG will be converted to those of an equivalent standard TEG as the known equations are intended for standard TEGs.

The model for the TEG circuit is depicted in Fig. 26.9. The TEG is represented as a simple voltage source with an inner resistance (equivalent Helmholtz/Thévénin source) and is connected to a load resistance to get output power. Hence, the inner resistance and the output power of the circuit at load-matching conditions are determined by
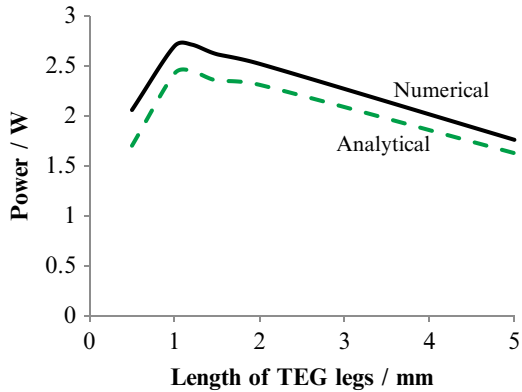
$$R_i = \frac{\rho \ell}{A}, \tag{26.1}$$

$$P_{out} = \frac{\left(\left(k_p - k_n\right)\Delta T\right)^2}{4R_i}. \tag{26.2}$$

Fig. 26.9 Equivalent electric circuit of the TEG module
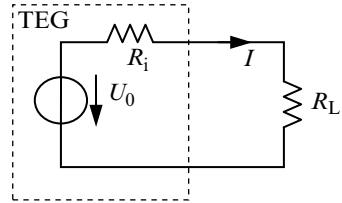
Fig. 26.10 Comparison numerical vs. analytical calculation

Here, ρ, ℓ, and A are the electric resistivity, the length, and the cross-sectional area of the thermocouple legs, respectively. k_p and k_n denote the Seebeck coefficients of the p-type and the n-type thermoelectric, and ΔT is the temperature drop over the TEG.

The results of the numerical simulation are compared with those from the analytical calculation in Fig. 26.10. The two curves are in good agreement as far as the functional dependence is concerned. As to the absolute power level, a constant offset is observed. This may be an indication of the fact that the model assumptions and the approximations involved in both the simple analytical model and the numerical model are consistent with each other. The constant difference between the two curves visible in Fig. 26.10 is thought to be mainly due to the Thomson effect and the Peltier effect which are taken into account in the numerical model, but not in the simplified analytical model.

Conclusion

The proposed concept of TEG with a novel geometry was analyzed and modeled. We developed a CFD model for the fluid flow system and a steady-state FEM model for the TEG. The models solved the temperature and electric potential equations and accounted for all thermoelectric effects. The models were used to investigate

the characteristics of the novel TEG and to determine the optimal design parameters through parameter studies.

The design optimum can be determined by the aid of the numerical models. The output power is quite sensitive to the foil thickness and the inner tube diameter, as these change both the inner resistance and the temperature difference between the two TEG surfaces. The output power of the example TEG presented reaches a maximum at 1 mm foil thickness and 25 mm inner tube diameter.

References

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