Optimal Installation Configuration of Thermoelectric Generators

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Abstract: This study presents a multiphysics model to the convective, conductive and radiative heat transfer for the thermoelectric modules (TEMs), which are used to convert heat flux into electrical current. The model basically consists of heat transfer in solids, heat transfer in thin shells, surface-to-surface radiation and non-isothermal turbulent flow. The developed model has a good agreement with the experimental measurements. The model is used to estimate the optimal configuration for TEM installation so that the maximal temperatures do not exceed allowable values and at the same time maximum heat flux through the TEM is obtained.

Keywords: heat transfer, radiation, convection, conduction, non-isothermal flow.

1. Introduction

It is possible to convert the wasted heat energy into the electrical current by means of a thermoelectric generator (TEG). Figure 1 shows a typical TEG and its possible configuration with respect to heat flux and electrical current.

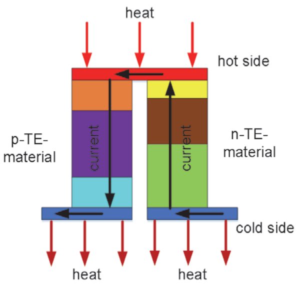

Figure 1. TEG, a typical element of TEM

The generated electric current purely relies on the heat flux through the TEG which is a typical element of TEM. Since there is no mechanically moving parts, TEGs are very reliable and robust. The TEGs have long being used by the aerospace industry and recently introduced also in automobile industry as an alternative to the classical accumulators.

Energy efficiency and reduction of CO_2 emissions in the iron-making and steel industry is an important research topic which is funded nationally and internationally. As an alternative way of recovering the wasted heat energy, the possibility of using TEMs is researched. In the frame of this research project, the optimal installation configurations of the TEMs are investigated by some numerical simulations using COMSOL Multiphysics® and several laboratory experiments.

2. Numerical Model by Using COMSOL Multiphysics® Software

The COMSOL Multiphysics® model for the heat transfer in the experimental setup of the TEMs basically consist of the heat transfer in solids, heat transfer in thin shells, surface-to-surface radiation as well as non-isothermal turbulent flow of the air. The TEM itself as shown in Figure 2 has a very complex geometry. Therefore, a series of simplifications have been performed in the numerical model. Moreover, the symmetries are utilized to reduce the required computational resources.

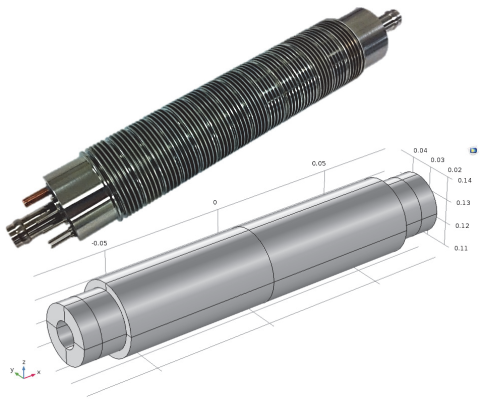

Figure 2. Photo of the TEM and its simplified model geometry for numerical simulations

In the laboratory experiments, the TEMs shown in Figure 2 have been used. The target of this project is to use TEMs for the recovery of the radiative waste heat (e.g., from hot slabs), although, the original design is to recover the heat from waste exhaust gases. Therefore, the surface of TEMs is covered by heat conducting rips to enhance the heat convection in the hot gas environments. In the simplified COMSOL Multiphysics® model, these rips are replaced with an auxiliary material, whose thermal material properties (i.e., the heat conduction tensor and the density) are modified accordingly.

The model geometry is shown in Figure 3. The heat source is a hot steel plate (~800°C) placed at the bottom of the setup. The TEMs are cooled by water through their centers, which generates a heat flux through the TEG elements. Additionally, the insulation box top can be opened or closed to control the surrounding air flow or to increase the radiative heat flux into the TEMs reflectors can be placed above the TEMs (see Figure 4). Some model parameters are shown in Table 1. Some of these parameters set the boundary conditions like the hot plate temperature, cooling water temperature or room temperatures as well as the surface emissivity values by using the laboratory measurements.

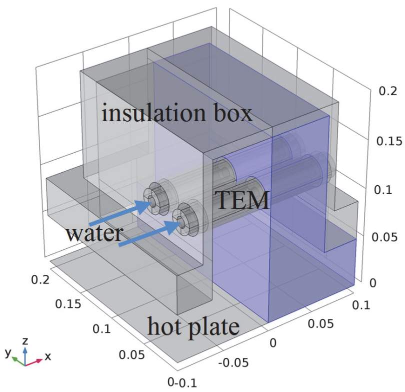

Figure 3. Model geometry for the setup

Table 1: The parameters used in the numerical model

Th	823[degC]	1096.2 K	heater temp.
Tw	11[degC]	284.15 K	cooling water temp.
Ta	20[degC]	293.15 K	room temperature
Tb	108[degC]	381.15 K	box temp.
em_htr	0.95	0.95	heater surf.
em_teg	0.50	0.5	TEG surf.
em_mir	0.95	0.95	diffuse mirror surf.
em_ff	0.95	0.95	ff surf.
rhoRef	(((1[atm])[1/Pa])*0.02897/8.314/((20[...	1.2044 kg/m³	ref. density
hhtr	30[W/(m*m*K)]	30 W/(m²·K)	Convective HTC from HTR
Dhtr	125[mm]	0.125 m	Distance to HTR
Tteg0	0.7*Ta+0.3*Th	534.05 K	initial teg temp
Tff0	0.5*Tb+0.5*Th	738.65 K	initial ff temp
Tmir0	0.3*Ta+0.7*Th	855.25 K	initial mir temp

2.1 heat transfer in solid TEMs and box

The insulating box and several components of TEMs are modelled as solid domains. The temperature of the solid domains is described by the field variable Ts in the model. Moreover, the thermal material properties are scaled in order to represent the geometrical simplifications of the rips on the surface of TEMs, or TEG material itself between the surface rips and internal cooling water pipe. The heat flux boundary conditions are coupled to those of the non-isothermal flow and surface-to-surface radiation physics. Hence, the convective heat fluxes as well as the radiation are explicitly modeled on the surfaces. The thin layers which belong to the solid domains (e.g., the thin steel cooling water pipe through TEM center, the steel plate covers on the insulating box, etc.) are modeled by the thin layer feature in heat transfer in solids.

2.2 heat transfer in thin shell reflectors

The reflectors cannot be modeled as thin layer feature since they are not surface of any solid domains. Therefore, they are modelled using the heat transfer in thin shells physics interface. The temperature field variable is also named as Ts in order to couple the temperature along solid to shell connection edge. The heat exchange with the surrounding air is defined by the coupled heat flux boundary condition as in described section 2.1. That is the convective heat fluxes as well as the radiation are explicitly modeled on the thin surfaces.

2.3 surface-to-surface radiation

The radiation mode of the heat transfer is dominated at high temperatures and, therefore, it is essentially included in the numerical model. The radiation directions of the solid surfaces are explicitly defined considering the opacities. The thin shell reflectors radiate to both directions. Radiation models have dense system matrices. Hence, their memory requirement is quite high. Thanks to the symmetry plane feature, the model size can be halved. The emissivity of each surface is defined as a model parameter which can be calibrated to the experimental results. The temperature input for surface-to-surface radiation model is directly defined as Ts.

2.4 non-isothermal turbulent flow of the air

The available TEMs have surface rips to enhance the convective heat transfer. Therefore, an explicit non-isothermal L-VEL turbulent flow model has been adopted in order to estimate this heat convection contribution. Thanks to the symmetries, only a quarter of the flow domain is computed. The fluid temperature field variable is named as Tf. The thermal coupling on the walls is defined by the wall temperature as nojac(Ts). Here nojac operator enables placing unknown field variables Ts and Tf into separate segregated groups in the segregated solver.

2.5 results of the numerical model

The influences of several experimental setup configurations and the behavior of TEMs are investigated by the help of developed COMSOL Multiphysics® model. It is used to estimate the optimal experimental setup configuration (e.g., opening/closing box top, placing reflectors, TEM spacing, etc.). The objective of the optimization is to maximize the heat flux through TEGs without exceeding the allowable temperatures.

The list of some adjustable configuration parameters is given in Table 2. Main simulation results are given in Table 3. Solid temperatures as well as stream lines are visually compared for Sim1 and Sim4 in Figure 4. It is clear that closing the top of insulation box produces higher heat fluxes through TEGs, which can be explained by the heat accumulation in the insulation box cavity. Furthermore, increased surface emissivity (e.g., by coating) also enhance the heat flux through TEGs significantly.

Table 2: The simulation configurations

	Sim1	Sim2	Sim3	Sim4	Sim5
reflector	yes	yes	yes	**no**	**no**
closed top	**no**	yes	yes	yes	yes
box height (mm)	178	178	178	**140**	**140**
TEG spacing (mm)	33	33	33	33	**10**
epsTEG1	0.2	0.2	0.2	0.2	0.2
epsTEG2	0.2	0.2	**0.9**	**0.9**	**0.9**

Table 3: Computed temperatures and heat fluxes

	Sim1	Sim2	Sim3	Sim4	Sim5
Tmir1 (°C)	221.2	269.7	278.3	-	-
Tmir2 (°C)	246.0	300.9	319.9	-	-
Tteg1 (°C)	143.6	165.6	168.0	199.5	167.8
Tteg2 (°C)	148.3	172.7	271.4	316.3	297.0
Tair (°C)	200.9	313.2	319.2	455.5	455.2
Qw TEG1 (W)	**-257**	**-300**	**-305**	**-367**	**-346**
Qw TEG2 (W)	**-268**	**-316**	**-485**	**-571**	**-585**
Qw_conv1 (W)	25	38	41	41	41
Qw_conv2 (W)	20	31	13	7	14
Qhtr_conv (W)	-1016	-1022	-1028	-976	-1045
Qhtr_rad (W)	5239	5239	5239	5239	5239

The main simulation results (variable names) in Table 3 have the following meanings:

- Tmir1, Tmir2: average temperatures of the reflector over inner and outer TEMs, respectively
- Tteg1, Tteg2: average surface temperatures of the inner and outer TEMs surfaces where rips located
- Tair: average air temperature at the top of TEM opening in insulation box
- Qw TEM1, Qw TEM2: total heat fluxes through TEM1 and TEM2, respectively
- Qw_conv1, Qw_conv2: total convective heat fluxes through TEM1 and TEM2, respectively
- Qhtr_conv: total heat flux (convection) from heated plate to the air
- Qhtr_rad: total radiation of the heated plate

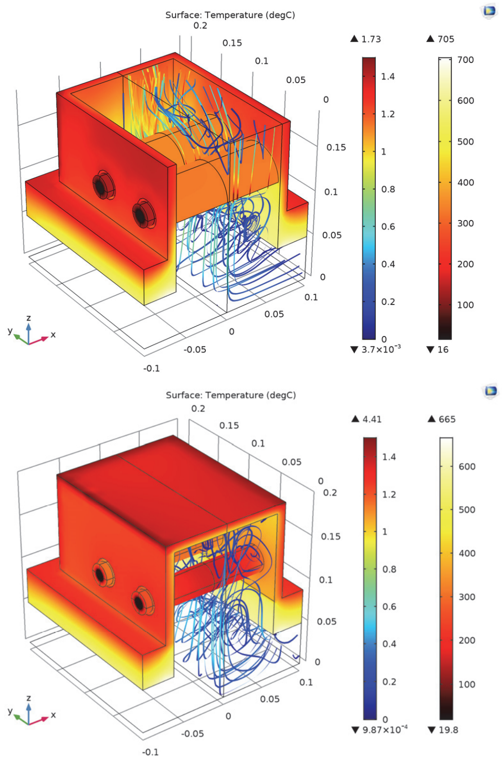

Figure 4. Results of Sim1 (top) and Sim4 (bottom)

3. Experimental Results

Laboratory experiments are performed to test the performance TEMs to recover radiative heat loses from hot steel slabs. The photo of the experimental setup and measurement positions are show in Figure 5. The insulation box is just to protect the cables and equipment for the measurements. The labels in Figure 5 and some other details are explained as follows:

- T1 – T4: cooling water inlet temperatures
- T5 – T8: cooling water outlet temperatures
- T9 – T12: TEMs down side temperatures (between rips)
- T13: TEMs upper side temperatures (between rips)
- T14, T15: TEMs temperature at the end-caps
- T16, T17: side wall temperatures
- T18: box wall temperature below cables
- T19: reflector temperature (not shown in photo)
- T20: air temperature in the box
- T23, T24: surface temperature of heated plate (not shown in photo)
- T25: air outlet temperature above TEMs
- Cooling water (CW)-inlet and outlets
- N2-inlet and outlets

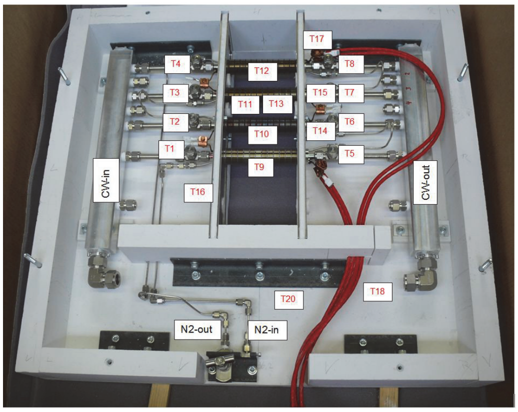

Figure 5. Thermocouple positions in the setup

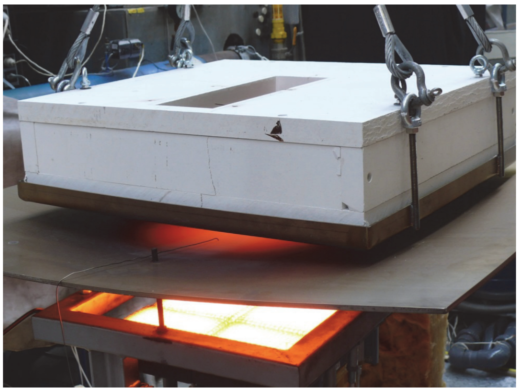

Figure 6. A photo taken during an experiment.

The experimental setup is placed over a steel plate which is heated using a gas burner up to approximately 800°C as seen in the photo taken during an experiment (Figure 6). Temperature evolutions are observed to get a steady state after a while as shown in Figure 7. The numerical model results fit to those average steady state temperatures for reflectors (Tmir), inner and outer TEM pairs (Tteg1 and Tteg2), and air (Tair), which are given in Table 4. As computed by the numerical model, closing the box top contributes more than placing reflectors.

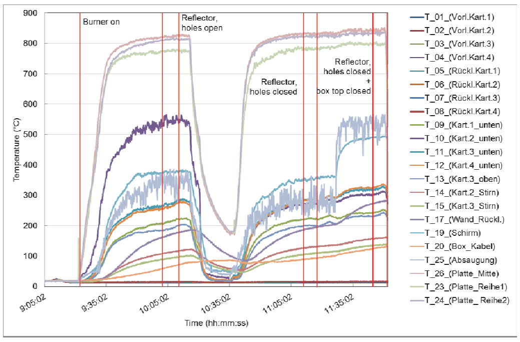

Figure 7. Measured temperatures during a typical experiment.

Table 4: The simulation configurations

	Tmir (°C)	Tteg1 (°C)	Tteg2 (°C)	Tair (°C)
M2: with reflector, box open	353.8	278.3	283.2	283.6
M3: with reflector, box closed	485.3	309.3	324.3	526.5
M4: with reflector, box closed	448.1	264.7	265.6	506.9
M5: with reflector, box closed	428.4	293.1	281.3	499.0
M6:with reflector, box closed	484.2	314.8	305.1	569.3
M7: no reflector, box closed	-	310.0	299.2	490.6

4. Conclusions

Once the box top is closed, the reflectors have negligible contribution. Additionally, TEMs should be coated to increase the emissivity and the distance to the hot plate should be optimized. Convection ribs on the TEMs have negligible contribution in the close vicinity of 800°C hot steel slab where the heat radiation dominates over the free convection.

5. Acknowledgements

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