Performance parameters and numerical model of thermoelectric generator dedicated for energy harvesting from flue gases

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Abstract. The paper presents results of preliminary studies of thermoelectric generator (TEG) dedicated for waste heat harvesting from flue gases. Investigation includes numerical analysis for estimating power losses due to pressure drop in the installation with the TEG and experimental tests for obtaining electrical parameters and operation conditions, such as casing temperatures and the temperature difference between the inlet and the outlet. Proposed prototype has been equipped with the pin fins for increase the heat transfer. Results indicates that power losses are negligible in comparison with generated electrical power. The heat exchanger’s interior demands to be modified to enhance the efficiency by increasing temperatures on the external surfaces of the hot-side heat exchanger (HHX). Further research will focus on numerical analysis of the influence of geometry modifications on the thermal and flow parameters of the TEG resulting in the increase of generated power and efficiency.

1. Introduction
The increase of energy usage and waste heat generation requires solutions for the improvement of energy efficiency in the industry and transportation. In last years, the cost of renewable energy is becoming competitive with others sources of energy [1]. Among a wide range of Renewables, thermoelectric technology is interesting, especially due to continuous progress in energy conversion efficiency improvements. TEG is a device used for heat-into-electricity conversion. As a result of Seebeck phenomenon, due to temperature difference between hot and cold sides of thermoelectric module, heat flux is converted into electrical energy with the defined efficiency. The efficiency of a TEG as a whole device depends on both, the efficiency of the thermoelectric modules and the effectiveness of the heat exchangers (HXS) on the cold and on the hot sides (figure 1).

The performance of thermoelectric module depends on its ZT, which is determined by $\sigma$, $\kappa$ and $\alpha$. Researchers present materials with ZT reaching even 2.4 [2], so it will be possible to design efficient thermoelectric modules in the future. Commercially available modules allow to design and manufacture TEGs with the efficiency about 5% [3]. TEG contains three main parts: HHX, thermoelectric modules and cold-side HX (CHX). Due to temperature difference between hot and cold sides, electrical energy is generated as a result of Seebeck effect.
Big effort has been put in development of TEGs and HXs dedicated for TEGs. A hybrid thermoelectric waste-heat-recovery system for Portland cement production rotary kiln could generate 211 kW of electrical power [4]. The kiln with the system can utilize more than 32% of wasted energy. Device is designed to supply both thermal energy and electricity. The new solar thermoelectric cogeneration system consisting of an evacuated tubular solar collector and thermoelectric modules has been proposed [5]. The solar to thermal efficiency is 69% and solar to electrical conversion efficiency can reach 3.87% in presented system. The performance of a thermoelectric-based solar conversion has been investigated computationally [6]. The electrical output of the system has been evaluated, demonstrating maximum power output of 33.7 W. Automotive applications are one of the most interesting in view of thermoelectric technology utilization. Experimental and computational study of exhaust gas waste heat recovery system for vehicles, using thermoelectric modules and HXs has been presented [7]. As the conclusion, methods of simulation modeling and experimental verification need to be combined with heat transfer theory and materials science to optimize the overall exhaust heat utilization and enhance power generation. One of the most important things in designing of the TEG is pressure drop, in some cases the energy consumption of the supply pump in the installation with the TEG could be equal of even greater than generated energy [8]. Numerical model and experimental analysis of TEG with finned HX was presented in [9]. Some research has also been done in application of the TEG into flue gas installation of gas boiler [10]. Different heights and thicknesses of fins were analyzed. Another attempts to improve the performance of TEG were presented in [11, 12]. Researches try to find an optimal module area, which is dependent on medium flow rate and put some insertions to disperse the stream of hot gas for achieving better performance of the TEG.

Designing an efficient TEG to convert waste heat from flue gases is a complex problem including designing of HHX, placement of thermoelectric modules and choosing or designing a proper cooler. In this article, a new prototype of TEG is presented. Due to the small size, it could be applied in the installation with gas boiler or other similar appliances. Casing covered with 24 thermoelectric modules is cooled by 2 rectangular coolers. Modules are placed on two casing walls, while the others two are thermally insulated. Results from numerical modeling and measurements of thermal and electrical parameters are presented. HHX (figure 2) has rectangular cross-sectional shape, is fitted with 15 cm duct and equipped with pin fins to extend heat exchange surface area.

2. Numerical model
2.1 Boundary conditions and settings
Numerical steady state analysis was carried out to obtain the relationship between pressure drop and gas mass flow rate. Model was prepared and solved using Ansys CFX solver. Spatially averaged governing equations for mass, momentum and energy have been solved on control volumes to obtain pressure drop for two different inlet temperatures in air domain. Turbulence modeling was performed with SST model, which combines the advantages of both k-ε (in free stream) and k-µ (near the wall) models. This model is widely used in similar problems solutions. Table 1 presents mesh statistics and the quality of the model.
Table 1. Mesh statistics.

| Parameter       | Value  |
|-----------------|--------|
| Volumes         | 1011119|
| Nodes           | 5567074|
| Orthogonal quality | 0.86   |

Figure 2. 3D scheme of the HHX.

Figure 3. Generated mesh of the HHX.

Calculations were done using mesh presented on figure 3 for two air-inlet temperatures (400°C and 250°C) and five mass flow rates for both cases. Adiabatic conditions were set, which means there is no heat transfer between air and surroundings.

2.2 Results

Power losses generated by the TEG could be calculated using equation (1).

\[ P_{\text{loss}} = \Delta P \cdot \dot{V} \]  

(1)

Figure 4. Pressure drop in the HHX.

Figure 5. Power losses due to pressure drop in the HHX.
The results presented on figure 4 and figure 5 show the influence of mass flow rate on pressure and power losses. In the range of TEG operating flow rates: 0.01 – 0.02 kg·s\(^{-1}\) their magnitude is small and impact on performance of TEG is nearly negligible. The increase of losses is visible in higher flow rates, so potential application of TEG with proposed geometry could be limited.

3. Experimental results

The test stand for analyzing TEGs operating conditions allows to produce hot gas (air) in volumetric flow rate range between 50 to 140 m\(^3\)·h\(^{-1}\) and 16 kW heater is able to rise temperature from 20°C to 550°C.

![Figure 6. Experimental stand scheme.](image)

| Parameter | Value |
|-----------|-------|
| \(U_{\text{load}}\) | 23.7 V |
| \(I_{\text{load}}\) | 1.43 A |
| \(P_{\text{el}}\) | 34 W |
| \(R_{\text{load}}\) | 16.5 Ω |

### Table 2. Water and air temperatures for different volumetric flow rates.

| Parameter | 70 m\(^3\)·h\(^{-1}\) | 100 m\(^3\)·h\(^{-1}\) | 140 m\(^3\)·h\(^{-1}\) |
|-----------|----------------|----------------|----------------|
| \(T_{\text{in, air}}[^{\circ}\text{C}]\) | 410 | 335 | 275 |
| \(T_{\text{out, air}}[^{\circ}\text{C}]\) | 372 | 313 | 260 |
| \(T_{\text{in, water}}[^{\circ}\text{C}]\) | 13 | 13 | 13 |
| \(T_{\text{out, water}}[^{\circ}\text{C}]\) | 19 | 18 | 17 |

![Figure 7. TEG with indicated main parts.](image)

![Figure 8. Voltage distribution [V] at thermoelectric modules on the left side and on the right side of the TEG.](image)
Measurement done in volumetric flow rate 70 m$^3$·h$^{-1}$ and inlet temperature 410°C presents non-uniform voltage distribution (figure 8) of the thermoelectric modules. Highest result was obtained at the inlet of the TEG, which was caused by the highest temperature difference between hot and a cold side of the module. Irregularity of the other voltages could be caused by design of the CHX (simple rectangular module without any filling), which led to improper cooling of the modules at the edges and smaller temperature differences. This problem will be trying to be solved in further investigation.

![Figure 9](image9.png)

**Figure 9.** Calculated Seebeck coefficient for selected modules.

![Figure 10](image10.png)

**Figure 10.** Hot-side temperature for selected modules.

Obtained temperature values are the highest directly above the flue gas inlet, which was foreseeable. There is no significant dependency between flow rate and calculated Seebeck coefficient, so it proves, that thermoelectric modules operate similar in different conditions. Measurements with higher flow rates were performed with lower inlet temperatures. Electrical power of each module can be calculated using equation (2).

$$ P_{el} = \frac{(0.5 \cdot V_{oc})^2}{R_{load}} $$

(2)

Load resistance was estimated as internal resistance to obtain maximal power at the modules.

![Figure 11](image11.png)

**Figure 11.** Temperature distribution for $\dot{V} = 70$ m$^3$·h$^{-1}$ and $T = 400^\circ$C on thermally insulated wall.

![Figure 12](image12.png)

**Figure 12.** Power generated by thermoelectric modules [W].
Figure 11 presents temperature distribution at the outer surface of the insulated wall. HHX has been properly insulated, thus small amount of supplied heat was dissipated to the ambient air. Relatively high temperature difference between inlet and outlet parts of the casing (136.6°C) causes irregularity in generated electrical power (figure 12). It is directly connected with the voltage distribution (figure 8). Further development of the prototype will focus on unification of the heat distribution inside the HHX and the CHX, which will result in uniformly generated power and on maximizing the overall efficiency of the device.

\[
\varepsilon_{AP} = \frac{P_{el}}{P_{loss}} > 99\%
\]

\[
\eta_{el} = \frac{P_{el}}{m \cdot c_p \cdot \Delta T} \approx 1\%
\]

Ratio between heat converted into electrical energy and power losses due to pressure drop in the device could be estimated using equation (3). Result is promising, but big effort must be put in optimizing the construction. The energy conversion efficiency of the TEG, calculated by equation (4) reaches 1%, but after modifications and the improvement of the heat exchangers it is possible to obtain 3-4%. In the case when waste heat source is available, this value becomes economically profitable. For gas boilers and similar appliances applications, energy contained in flue gases is directly a waste heat, so this condition is satisfied.

4. Conclusions
Thermoelectric generators since a couple of years have been introduced as a waste heat harvesting devices. Taking into account their advantages like compact size, lightweight, no moving parts and high power density they are great candidates to be utilized in heat recovery systems. Presented in this paper prototypical thermoelectric generator was designed to be implemented with boilers and fireplaces. Finned HHX and rectangle CHX operated with thermoelectric modules based on BiTe alloys generate 34 W for air at temperature 410°C flowing with 70 m³·h⁻¹. The numerical model has been prepared to obtain the dependency between pressure drop and flue gases flow rate.

First prototype will be improved by redesigning heat exchanger to be able to extract more heat from flue gases. In the future more complex numerical models will be developed and modeling of CHX and thermoelectric modules will be included, so higher performance of a whole device will be able to obtain.

Nomenclature

| Symbol | Description |
|--------|-------------|
| ZT     | Figure of merit [-] |
| \( \sigma \) | Electrical conductivity [Sm⁻¹] |
| \( \kappa \) | Thermal conductivity [Wm⁻¹K⁻¹] |
| \( \alpha \) | Seebeck coefficient [VK⁻¹] |
| \( \varepsilon_{AP} \) | Coefficient of losses [-] |
| \( \eta_{el} \) | Efficiency of TEG [-] |
| \( \dot{m} \) | Mass flow rate [kg s⁻¹] |
| \( \dot{V} \) | Volumetric flow rate [m³·h⁻¹] |
| \( c_p \) | Specific heat of air [J kg⁻¹ K⁻¹] |
| \( P_{el} \) | Electrical power generated by TEG [W] |
| \( V_{oc} \) | Open circuit voltage of TEG [V] |
| \( U_{load} \) | Voltage on the load [V] |
| \( I_{load} \) | Current on the load [A] |
\( R_{\text{load}} \) Load resistance [\( \Omega \)]

\( T_{\text{in}_{-}\text{air}} \) Air inlet temperature [\( ^\circ \text{C} \)]

\( T_{\text{out}_{-}\text{air}} \) Air outlet temperature [\( ^\circ \text{C} \)]

\( T_{\text{in}_{-}\text{water}} \) Water inlet temperature [\( ^\circ \text{C} \)]

\( T_{\text{out}_{-}\text{water}} \) Water outlet temperature [\( ^\circ \text{C} \)]

\( P_{\text{loss}} \) Power losses due to pressure drop [W]

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