Conceptual Study of a Micro Energy Converter Using Thermoelectric Materials

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Abstract

This contribution aims at the development of a PowerMems device that converts liquid bounded chemical energy by combustion to electrical power avoiding any moving parts. The concept relies on the Seebeck effect converting heat to electrical power by using appropriate thermoelectric materials.

A major step of this work is to couple a micro combustion chamber with a micro evaporator. The present work comprises a CFD simulation of the combustion chamber, the thermoelectric material and the integrated evaporator giving insight into the interaction of these components. Variation of the geometry and the boundary conditions reveals starting points for improvement, which were adopted easily in the CFD simulation for certification.

The goal of the CFD simulation is to optimize the interplay of heat sources and heat transfer to the thermoelectric material for best thermodynamic efficiency. Challenges are the integration of the evaporator avoiding dry-out, combustion temperatures near walls compatible with the critical thermal loads of the corresponding materials and high heat fluxes through the thermoelectric material.

Keywords: PowerMEMS, Thermoelectric Material, Numerical Investigation

1 - INTRODUCTION

Recent developments in the field of micro mechanical and electronic devices such as mobile phones, laptops, or micro robotics call for increasing energy densities of the power supply. Today various types of secondary-batteries are predominantly in use but their limits are almost achieved.

In search for new power storage technology for micro devices, hydrocarbon fuels have the potential to replace conventional batteries. The reason is the huge energy density of hydrocarbon fuels: compared to batteries it is up to 50 times larger. Thus even a poor efficiency of a hydrocarbon fuel based micro electrical power generator can achieve a higher power density than a battery today. The development of such PowerMems devices already started.

On the one hand, developments of PowerMems devices exist scaling down conventional macroscopic devices such as gas turbines, or engines [1, 2, 3, 4, 5]. On the other hand, approaches were made avoiding any moving parts such as fuel cells, photovoltaic materials, or thermoelectric materials [6, 7, 8, 9, 10, 11]. At this initial stage so far all prototypes struggle with several specific issues.

The present numerical study is focused on the principal lay-out of a micro electrical power generator using liquid methanol as fuel. The thermoelectric effect is used to convert the combustion heat to electrical energy, thereby avoiding any moving parts. The study investigates mutual interactions of fuel evaporation, combustion, heat transfer, thermoelectric conversion and geometrical constraints.

2 - PHYSICAL BASICS

2.1 - Figure of Merit

The thermoelectric effect, also known as Seebeck effect, describes the direct conversion of thermal to electrical power. This effect is based on the capability of isolated conducting materials to generate electrical voltage when they are subjected to a temperature gradient. The efficiency of a thermoelectric material depends on its Figure of Merit Z.

$$Z = \frac{S^2 \sigma}{\lambda} \quad ; \quad \left[\frac{1}{K} \right] \quad\quad (1)$$

S is the Seebeck coefficient, σ is electric conductivity, and λ is the thermal conductivity. Multiplied with temperature T these parameters define the dimensionless Figure of Merit ZT. ZT is a measure of the potential of thermoelectric material to generate electrical power. A high ZT promises a high efficiency.

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2.2 - Efficiency of a thermoelectric generator

The efficiency of a thermoelectric generator depends on ZT and temperatures on the hot T_h as well as cold T_c side of the junction [*12, 13*].

$$\eta = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_c}{T_h}} \qquad (2)$$

The theoretical maximum efficiency is reached for ZT approaching infinity. In this case the efficiency of the Carnot process is reached. The Carnot process efficiency serves in this study as a measure to evaluate the performance of different system designs.

3 - REFERENCE CONFIGURATION

The basic idea is to design a PowerMems device that converts chemically bounded energy to electrical power using the thermoelectric effect and avoiding moving parts. Liquid methanol is used as fuel. The methanol is evaporated in a micro evaporator and the vapor is then supplied to the cylindrical micro combustion chamber together with preheated air. Mixing and combustion of the air and methanol vapor are taking place in the combustion chamber (non-premixed combustor). After combustion hot exhaust gas passes the thermoelectric material for energy conversion before exiting. To avoid flame extinction due to excess heat losses within the reaction zone the exhaust duct encloses the combustion chamber.

Figure 1 shows the two dimensional axis-symmetric geometry, that is meshed by 130000 cells for numerical simulation. To model the non-premixed combustion a standard k-ε model in connection with a "mixed is burned" assumption and an enhanced wall treatment model for near wall zones are used. Fluent 6.2.16 was used for CFD calculations.
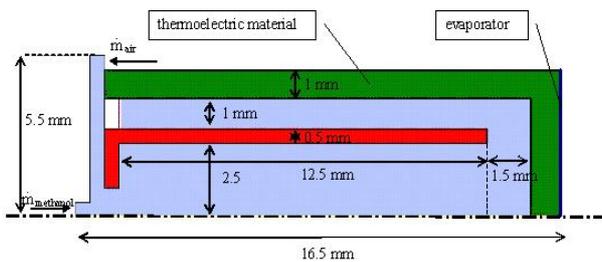

Figure 1: Reference geometry of the micro energy converter

The geometry contains the methanol and air supply channels, the combustion chamber, the exhaust duct and thermoelectric material. The micro evaporator is located at the front side of the device (right hand side in Figure 1).

The basic geometry (reference geometry for subsequent parametric variations) has a length of 16.5 mm and the radius is 5.5 mm. The dimension of the combustion chamber is r x l = 2.5 mm x 12.5 mm. For the thermal boundary condition at

the cylinder barrel natural convection in connection with cooling fins is assumed.

$$Nu = 0.24(Gr\,\Pr\frac{b}{d})^{(\frac{1}{3})} \qquad (3)$$

Equation 3 shows the Nusselt-number equation for a finned tube. Gr is the Grasshof-number, Pr the Prandtl-number, b the intermediate space of the fins and d is the diameter of the tube. A constant heat flux of $\dot{q}$ = - 90 000 W/m^2 is assumed as boundary condition at the evaporator side. The thermal conductivity of the thermoelectric material is set to 5 W/(mK). The thermal power released by combustion was set to approximately 100 W corresponding to a methanol mass flow of $5 \cdot 10^{-6}$ kg/s and an air mass flow of $4 \cdot 10^{-5}$ kg/s.

4 - PARAMETRIC STUDY

In order to design an efficient PowerMems device in a first step a parametric study has been conducted to identify parametric sensitivities. Relative to the reference geometry thermal power, thickness of thermoelectric material, thermal conductivity and heat transfer coefficients were varied. Heat flux and Carnot-efficiency on the cylinder barrel are used to quantify the effects of these parameters on the system efficiency. The most important results are summarized in the following sections.

As mentioned starting point of all investigated calculations is the described reference geometry / configuration. At these reference conditions 32% of the thermal power is leaving the system through the cylinder barrel and is available for energy conversion by the Seebeck effect. Multiplying this fraction with the respective Carnot-efficiency, which is ~3.4% in this case, results in a maximum theoretical system efficiency of only 1.1%. Raising the system efficiency by different measures is the goal of this parametric investigation.
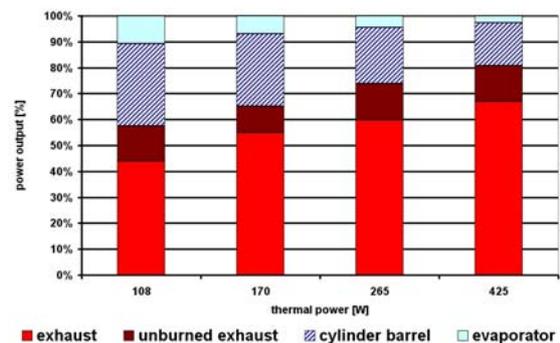

Figure 2: Power output distribution for different thermal power

Increasing the thermal power without adjusting the basic geometry leads to an even more inefficient use of chemical energy. Figure 2 shows, that a poorly adjusted power scaling decreases the fraction of thermal power available for energy conversion but increases the losses mainly through the

exhaust channel: Increasing the thermal power up to 420 W, about 80% of the energy leaves the system through exhausts. Independent on the power scaling, the main reasons for the bad system efficiency are the wall temperatures at the "cold" and "hot" sides of the thermoelectric material. Due to high internal temperatures and a low temperature difference the Carnot-efficiency of the thermoelectric material is very poor (Figure 3).
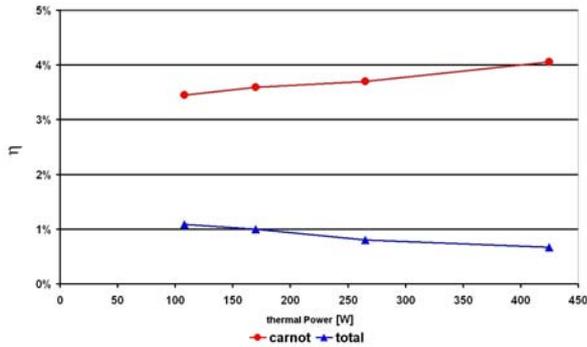

Figure 3: Efficiencies for different thermal power

There are a number of measures to increase the temperature difference between the hot and cold sides. The simplest is increasing the thickness of the thermoelectric material.

Figure 4 shows the Carnot-efficiency for different thicknesses of the thermoelectric material. The Carnot-efficiency scales linearly with the wall thickness but the total efficiency does not. The reason is a decreasing fraction of thermal power that is transferred through the cylinder barrel.
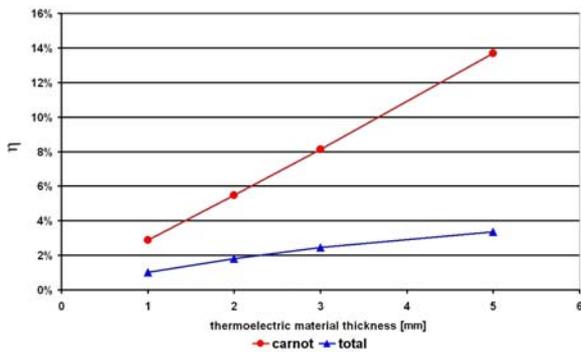

Figure 4: Efficiencies for different thicknesses of thermoelectric material

A second way to influence the temperature difference at the cylinder barrel is using a thermoelectric material with smaller thermal conductivity. Figure 5 shows the influence of the thermal conductivity on the Carnot- and system efficiency.

Figure 6 shows that a variation of λ does not change the fraction of energy available for conversion significantly. This indicates that the overall thermal resistance is dominated by the convective heat transport inside and outside of the

cylinder barrel rather than by heat conduction in the thermoelectric material.
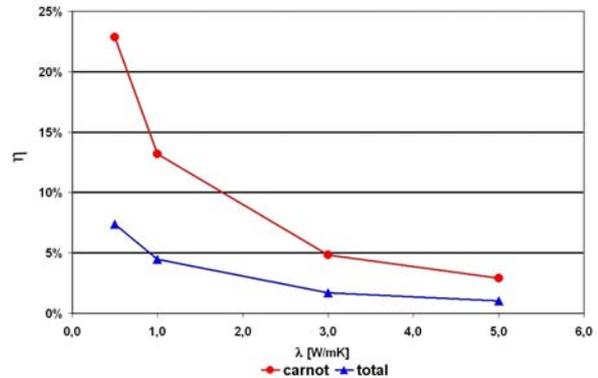

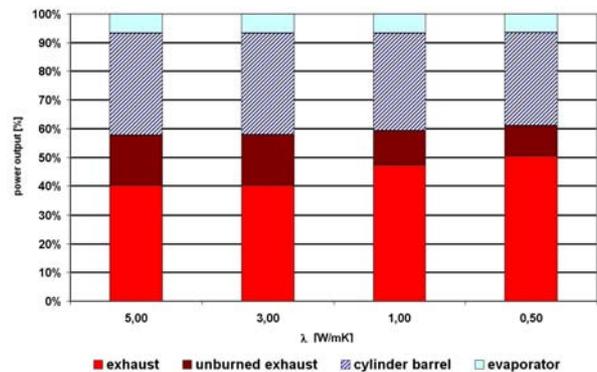**Figure 5**: Efficiencies for different thermal conductivity

Figure 6: Power output for different thermal conductivity

Based on this finding increased convective heat transport inside and outside of the cylinder barrel improves the performance of the device. Manipulating the thermal boundary condition on the cylinder barrel is the easiest way to investigate the influence of the convective heat transport.

Figure 7 shows the effect of the heat transfer coefficient on the efficiencies. Enlarging the heat transfer coefficient influences both the temperature differences and heat transfer through the thermoelectric material positively (Figure 8).
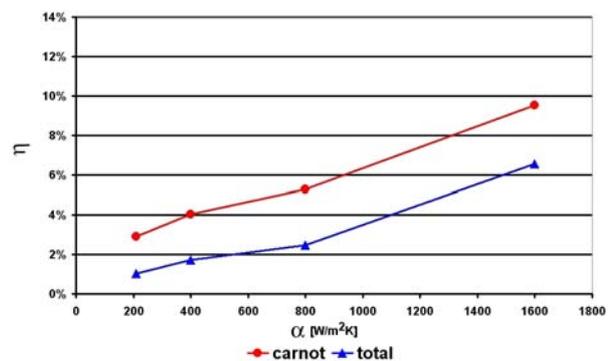

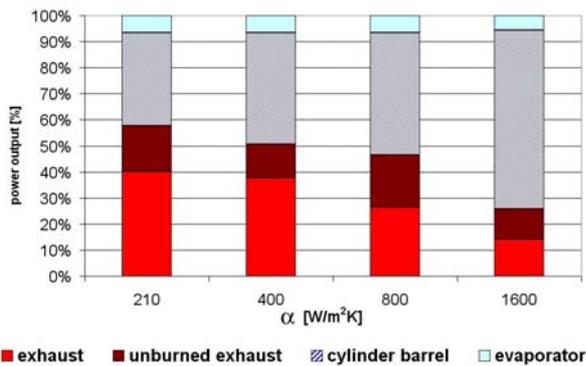**Figure 7**: Efficiencies for different heat transfer coefficients

Figure 8: Power output distribution for different heat transfer coefficients

5 - CONCLUSIONS

The present numerical simulation shows the behavior of a thermoelectric PowerMems device by variation of different system parameters. Based on these results the following guidelines can be deduced:

- Thermal resistance of the thermoelectric material needs to be high. (Constructive solution for high resistance are for instance heat spreading [*14*])

- Wall thickness of the thermoelectric material should be as large as possible but is in practice limited by the materials.

- Convective heat transfer inside and outside of the thermoelectric material should be as high as possible.

- Wall temperatures at the hot side need to be decreased for higher efficiency. This favors catalytic combustion.

Considering these guidelines an exemplarily calculation was accomplished. Starting from a reference configuration, the thermal conductivity of the thermoelectric material was lowered to 1.5 W/(mK), and its thickness was enlarged up 2.5 mm. Such a low thermal conductivity can be achieved for instance by using appropriate thermoelectric material as Bi_2Te_3- Bi_2Se_3 (λ= 1,3 W/(mK)) or constructively using heat spreading [*9, 14, 15*].

The convective heat transfer coefficient on the cylinder barrel was set to 600 W/(m^2K) and the constant heat flux of the evaporator was adjusted to $\dot{q} = -$ 82.000 W/m^2. These changes compared to the reference configuration led to a significant improvement of the thermal performance of the device. 38% of the generated thermal power left the system through the thermoelectric material on the cylinder barrel. Because of increasing thermal resistance of the thermoelectric material and high convective heat transport on the cylinder barrel the Carnot-efficiency rises up to 29%. Hence, the theoretical maximum efficiency of the cylinder barrel rises to almost 11%. The thermoelectric material on

the evaporator side has also to be considered. This will increase the total efficiency additionally.

REFERENCES

[1] I. A. Waitz, G. Gauda, Y.-S. Tzeng, "Combusters for Micro-Gans Turbine", Journal of Fluids engineering, 109-117, 1998.
[2] C. M. Spadaccini, "Combustion systems for power-MEMS applications",2004
[3] K. Isomura *et al.*, "Experimental verification of the feasibility of a 100W class micro-scale gas turbine at an impeller diameter of 10 mm", Journal of Micromechanics and Microengineering, 254-261, 2006.
[4] M. Wu, J. Hua, K. Kumar, "An improved micro-combustor design for micro gas turbine engine and numerical analysis", Journal of Micromechanics and Microengineering, 1817-1823, 2005.
[5] A. H. Epstein, "Millimeter-Scale, MEMS Gas Turbine Engines", Proceedings of ASME turbo Expo 2003, 2003.
[6] K. Maruta *et al.*, "Catalytic Combustion in Microchannel for MEMS Power Generation", 1-4, 2001.
[7] L. Sitzki, K. Borer, E. Schuster, P. D. Ronney, "Combustion in Microscale Heat-Recirculating Burners", 1-4, 2001.
[8] T. Okamasa, G.-G. Lee, Y. Suzuki, N. Kasagi, "Development of Micro Catalytic Combustor Using Ceramic Tape Casting", PowerMems 2005, 206-209, 2005.
[9] K. Yoshida, S. Tanaka, S. Tomonari, D. Satoh, M. Esashi, "High-Energy Density Miniature Thermoelectric Generator Using Catalytic Combustion", Journal of Microelectromechanical Systems, 195-2003, 2006.
[10] M. K. Drost, C. Call, J. Cuta, R. Wegeng, "Microchannel Combustor-Evaporator Thermal Processes", Microscale Thermophysical Engineering, 321-332, 1997.
[11] F. J. W. a. M. Rowe, G. Min, "Novel high performance small-scalethermoelectric power generationemploying regenerative combustionsystems", Journal of Physics D: Applied Physics, L61-L63, 2002.
[12] D. M. Rowe, "CRC The Handbook of Thermoelectrics", 1995
[13] J. Schilz, L. Helmers, W. E. Müller, M. Niino, "A local selection criterion for the composition of graded thermoelectric generators", J. Appl. Phys., 1150-1152, 1997.
[14] P. M. M. a. R.J.Ram, "Optimization of Heat Sink-Limited Thermoelectric Generators", Nanoscale an Microscale Thermophysical Engineering, 10, 143-155, 2006.
[15] B. Wölfing, "A New Thermoelectric Material with Record Efficiencies",2001