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Optimized thermal coupling of micro thermoelectric generators for improved output performance

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ABSTRACT

There is a significant push to increase the output power of thermoelectric generators (TEGs) in order to make them more competitive energy harvesters. The thermal coupling of TEGs has a major impact on the effective temperature gradient across the generator and therefore the power output achieved. The application of micro fluidic heat transfer systems (μHTS) can significantly reduce the thermal contact resistance and thus enhance the TEG's performance. This paper reports on the characterization and optimization of a μTEG integrated with a two layer μHTS. The main advantage of the presented system is the combination of very low heat transfer resistances with small pumping powers in a compact volume. The influence of the most relevant system parameters, i.e. microchannel width, applied flow rate and the μTEG thickness on the system's net output performance are investigated. The dimensions of the μHTS/μTEG system can be optimized for specific temperature application ranges, and the maximum net power can be tracked by adjusting the heat transfer resistance during operation. A system net output power of 126 mW/cm^2 was achieved with a module *ZT* of 0.1 at a fluid flow rate of 0.07 l/min and an applied temperature difference of 95K.

It was concluded that for systems with good thermal coupling, the thermoelectric material optimization should focus more on the power factor than on the figure of merit *ZT* itself, since the influence of the thermal resistance of the TE material is negligible.

1. Introduction

Due to the simultaneous rise in energy consumption and environmental awareness, the worldwide demand for more efficient and clean energy systems is growing. One promising approach to improve a system's efficiency is to recover the produced waste heat by means of the thermoelectric effect. Thermoelectric power generation can potentially be applied for waste heat recovery in energy conversion systems [1], industrial processes [2] or automotive applications [2,3]. So far, however, the commercial applications of thermoelectric generators (TEGs) have been limited to niche markets, such as space [4,5] and remote or hazardous places [6,7]. The main reasons for this are (1) the relatively low thermoelectric conversion efficiency, (2) high fabrication costs of thermoelectric modules, and (3) suboptimal exploitation of the available temperature gradients. While much effort is spent to improve the thermoelectric figure of merit (*ZT*) by quantum confinement or phonon scattering [8–10] as well as to develop low-cost fabrication technologies [11], less attention has been paid to the optimization of the overall system's performance so far. This includes thermal coupling of the thermoelectric device to the heat source and heat sink, as well as an optimal matching of the thermal contact and TEG resistances [12]. By decreasing the thermal contact resistance to the cold and hot side reservoir, a significant enhancement of the generator's output power can be achieved [13]. The major impact of the thermal contact resistance on the output performance of a thermoelectric generator is illustrated in Fig. 1 and compared to the effect of *ZT*. While the influence of *ZT* on the output power has a close to linear dependency, the thermal contact resistance exhibits a power dependency proportional to $1/R_{\mathrm{Con}}^2$.

The most straight-forward approach to achieve small thermal contact resistances is to apply fluidic heat exchanger systems for the heat supply and dissipation. This is also the most effective method for waste heat recovery. Several large scale fluidic systems using liquid as active media have been tested for use in industrial applications. Tsuyoshi et al. [14] reported experimental results on a

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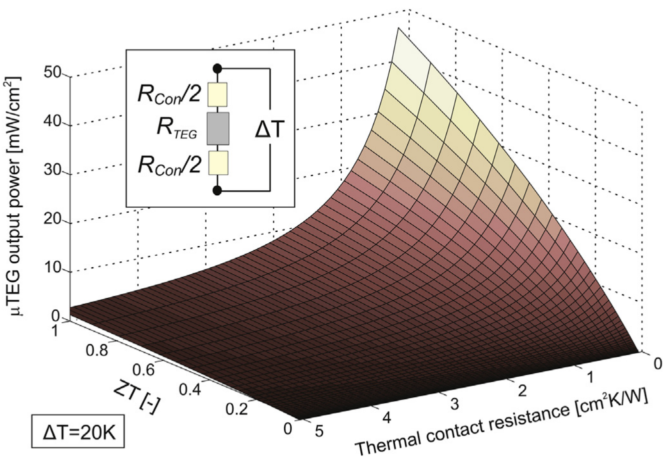

Fig. 1. Simulated output power of a 215 μm thick Bi_2Te_3 μTEG ($R_{TEG} = 2.8$ cm^{2}K/W) in dependence of the *ZT*-value and the thermal contact resistance R_{Con} at an applied temperature difference of 20K. The simulations were performed applying a thermoelectric model under matched electrical load [17].

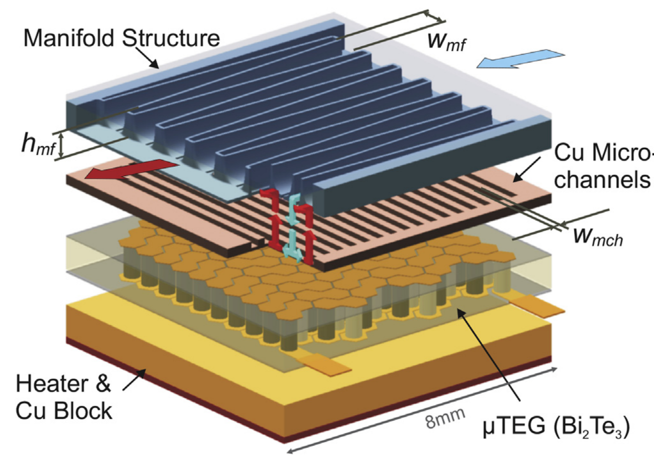

Fig. 2. Exploded view of the μHTS/μTEG system.

thermoelectric engine made out of TEGs stacked between a parallel plate heat exchanger using oil and water as active media. At an applied temperature gradient of 130K, an output power of 170 W could be reached. Niu et al. [15] built a similar parallel plate heat exchanger with commercially available Bi_2Te_3 modules reaching, 140 W at an inlet temperature difference of 120K. Crane et al. [2] constructed a TEG-heat exchange assembly with a stack of 6 TEG modules producing 500 W at an inlet temperature difference of 205K. Due to the growing interest in thermoelectric waste heat recovery for automotive applications, several gas/liquid heat exchange systems have been studied and tested [3]. First functional prototypes have already been installed in test engines and values as high as 507 W at a ΔT of 553K could be reached [16].

Although the achieved output power values from the experimental studies are remarkable, the systems are generally very large and heavy resulting in rather low output powers per volume. Often, standard large scale heat exchangers are applied, where high amounts of the working fluid are pumped through the system and the consumed pumping power is neglected. Furthermore, the reported systems usually work without optimized thermal contact resistance and overall system performance. In contrast, scaling down the heat exchangers to the micrometer range brings several advantages. Micro heat transfer systems (μHTS) can achieve high heat fluxes due to an increase of the convective heat transfer coefficient as well as of the surface area [17]. Even though μHTS generally exhibit larger hydrodynamic resistances, the effect on the pumping power can be compensated by smart design and smaller flow rates needed. With the reduced heat transfer resistances, thinner generators can be applied for thermal resistance matching. This makes the system compatible for waste heat recovery in industrial applications, where high heat fluxes are often necessary. Additionally, more compact systems with reduced size and weight can be built, resulting in increased applicability and modularity of the system. The performance characteristic of different micro heat sinks for chip or LED cooling applications have been investigated in several theoretical and experimental studies [17,18]. Rezania et al. [19] evaluated the theoretical performance of a thermoelectric generator using a rectangular microchannel heat sink. The simulation results showed no net TEG power improvements of the micro heat sink system compared to macro scale heat sinks, mainly due to the large pressure drops inside the microchannels. To avoid such large pressure losses and to still benefit from the improved thermal performance of microchannels, multiple layer manifold systems can be applied [20–22].

Therefore, a novel approach of minimizing thermal resistances by integrating two layer μHTS with μTEGs is proposed. This paper presents an experimental study on the performance of such an integrated system as shown in Fig. 2. The μHTS consists of a copper microchannel layer for efficient heat removal and a polymeric manifold channel layer responsible for the fluid distribution [13]. Besides a small pressure loss and a low heat transfer resistance, the proposed system also benefits from uniform cooling properties. Many different sets of parameters influence the performance of the described μHTS/μTEG system; namely the dimensions of the μHTS itself, the properties and dimensions of the thermoelectric generator and the applied boundary or working conditions. The paper focuses on the analysis and characterization of the most important μHTS/μTEG system parameters with the aim of optimizing the overall system's net output performance. In the first part, the μHTS is characterized in regards to the system's dimensions, flow rates and applied temperature gradients. In the second part, the output power of the μHTS/μTEG systems is investigated with respect to the μHTS dimensions, boundary conditions and μTEG thermal properties. The advantages of variable thermal resistances are discussed, and practical aspects of the thermal resistance matching are evaluated.

2. Experimental

The μHTSs were designed based on system and fabrication constraints in combination with performed simulations results. The parameter with the largest impact on the thermal and hydrodynamic performance of the μHTS was identified to be the microchannel dimensions. Therefore, μHTSs with different channel widths were fabricated and analyzed. The relevant parameters of the μHTSs used are summarized the Table 1.

The investigated μHTSs were fabricated using standard photolithography and electrochemical deposition. The detailed working principle and the fabrication process of the μHTS are reported in Ref. [13]. The μTEGs used were provided by greenTEG GmbH and are based on the electrodeposition of Bi_2Te_3 thermoelectric material into flexible polymer molds. A detailed fabrication process is

Table 1
μHTS design parameters.

Microchannel width − w_{mch} [μm]	Microchannel height − h_{mch} [μm]	Fin/channel ratio [−]	Manifold channels width − w_{mf} [μm]	Manifold channels height − h_{mf} [μm]	Total area [mm]
35, 50, 60, 80	190	1	150–300 (tapered)	1000	8 × 8