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# Thermoelectric Generators on Systems —an Approach for Waste Heat Recovery and to Save Energy

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***Abstract—As waste heat recovering techniques, especially thermoelectric generator (TEG) technologies, develop during recent years， its utilization in automotive industry is attempted from many aspects and it is a promising approach for energy harvesting. TEG as a waste heat harvesting method is feasible, even though efficiencies for TEGs are as low as 3-5% with existing technology; useful electricity generation is possible due to the great amount of waste heat emitted from the internal combustion engine operation, because of their solid state characteristics. As they do not have any moving parts, they do not cause any vibrations in the system. Environmental radiation in space (from the Sun, etc.), operational thermal loads which result in heat flows inside the structure of satellites, Combustion Engines, Furnaces in factories, Firewood stoves in many villages across the country can be trapped for harvesting Energy. Today these heat flows remain unused and are collected, fed back to the system for higher efficiency. For example the radiation istransported to a radiator and emitted to space to prevent the satellite, from overheating, but they hold a huge potential to generate electrical power independently of solar panels. They are said to be maintenance-free and highly reliable. Energyharvesting on space systems is a new approach for increasing the efficiency and reliability. In this paper, different systems are studied and applications are discussed.***

***Index Terms— thermoelectric generator; power systems; energy harvesting***

## I. INTRODUCTION

In recent years, energy harvesting has become a popular term in both academic and industrial world, as traditional power generation resources, such as fossil fuels and nuclear fission, are either facing global shortage crisis or simply being quite costly. In contrast, the resources for energy harvesters are usually naturally present, for instance, the temperature gradient from the combustion engine, electromagnetic energy from communication and broadcast, motion from human movement, just to name a few. Currently, areas of research interests mainly consists of piezoelectric energy harvesting, pyroelectric energy harvesting, waste heat recovery, electromagnetic energy harvesting, ambient-radiation energy harvesting, etc. However, current technologies of energy harvesting are capable of producing only enough power to drive relatively low-power electronics. Also, high volume applications of these technologies depend on further enhancement of the energy harvesting efficiencies.

Among all research directions, waste heat recovery (WHR) is most concerned, due to the widespread existence and high accessibility of suitable resources. According to India Bureau of Energy Efficiency [1], the benefits of WHR includes reduction in the process consumption and costs, reduction in pollution and equipment sizes, and also reduction in auxiliary energy consumption.

### 1. Examples of Waste Heat Sources and End Uses

| Waste Heat Sources | Use of Waste Heat |
|---|---|
| ▪ Combustion Exhausts:<br>Glass melting furnace<br>Cement Kiln<br>Fume incinerator<br>Aluminium reverberatory furnace<br>Boiler | • Combustion air preheating<br>• Boiler feed water preheating<br>• Load preheating<br>• Power generation<br>• Steam generation for use in power generation, mechanical power |

| | |
|---|---|
| ▪ Process off-gases: Steel electric arc furnace Aluminium reverberatory furnace<br>▪ Cooling water from Furnaces Air compressors Internal combustion engines<br>▪ Conductive, convective and radiative losses from heated products | • **Space heating**<br>• Water preheating<br>• Transfer to liquid or gaseous process streams. |

While there are a number [2]of devices to fulfil WHR, thermoelectric generator (TEG) has been utilized in most automotive applications, which are the targets of this thesis.

TEGs are devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" (or "thermoelectric effect"). Their typical efficiencies are around 5-10%. TEGs are solid-state devices which have no moving parts. Sub-branches of TEG have been developed to cater the needs of specific target applications, such as radioisotope TEG for spacecraft and automotive TEG (ATEG) for automobiles [3]. Moreover, some house-hold applications based on bio-fuel have been realized, as well as power supply for wearable electronics. Recently, TEG is often mentioned together with photovoltaic as promising energy harvesting device in the near future. Photovoltaic has a longer history of application. But when it comes to the effective applicable time, TEG is in fact advantageous in that it has no dependence on factors such as daylight hours and changes of seasons.

## 2. Thermoelectric Devices

The most common design of a thermoelectric generator is shown in Figure 1. Metal interconnections are printed on an alumina oxide substrate. On top of every one of these (copper) interconnections are both: a p- and an n-doped leg. Here a combination of a p- and an n-doped leg is called a thermocouple. Inside a thermoelectric generator a lot of thermocouples are connected electrically in series and thermally in parallel. On the top side of the generator a further substrate is connected.

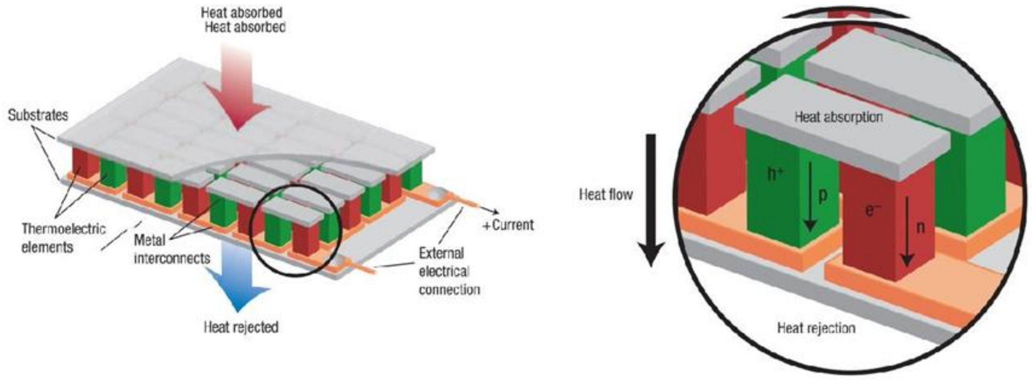

**Figure 1: Schematic Diagram of a thermoelectric generator**.

Both substrates have to be parallel because they establish the thermal interface of the generator. The heat flow crosses the substrate; therefore this design is called ***cross plane***. Generators commercially available nowadays are mostly part of this class. They can be manufactured in various dimensions. The smallest device have a cross section of around 3 mm × 3 mm with a height of 1 mm, the functional material has a height of 19 µm. These devices are made by a thin-film process inspired by processes from the chip industry. Because these small devices are very sensitive against mechanical stress bigger devices (so called bulk-device) are preferred for most applications. Bulk-TEGs are made of differential parts that are soldered in semi-automatic processes.

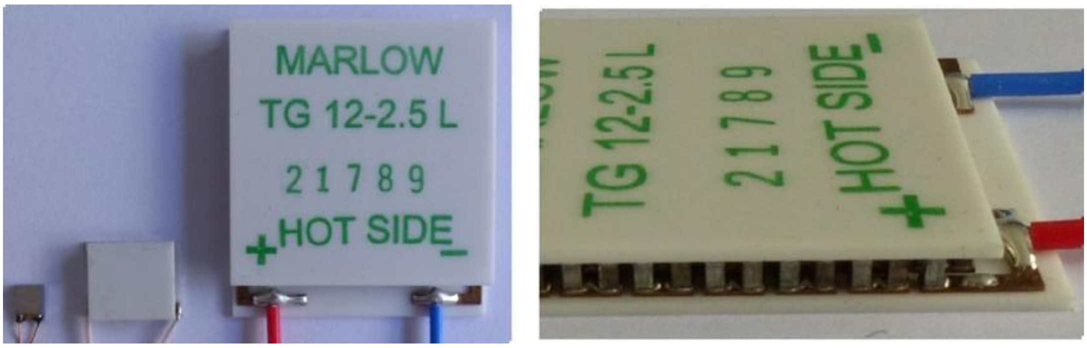

**Figure 2: Three TEGs of different surface area 3mmx3mm, 10mmx10mm, 30mmx30mm**

Another basic design of TEGs is the so called ***in-plane device***. Inside these devices the heat flow is parallel to the substrate which is commonly a flexible film or foil like kapton. The main advantage of such devices is their flexibility. Thus, gaps can be bridged without inserting a new mechanical connection, which is important for an easy integration, but the efficiency of such a design is lower than that of cross plane devices, because only a part of the available heat flows through the functional material, the remaining heat passes the device through the substrate that cannot be used for power generation [5]. Also the manufacturing process differs strongly from that of cross plane devices. It is dominated by cost-effective printing processes like screen- or inkjet-printing.

### 3. Efficiency of Thermoelectric Materials:

Figure of Merit (ZT) of Good TE materials should have the following characteristics:

- high electrical conductivity to minimize Joule heating (rise in temperature from resistance to electric current flowing through it);
- large Seebeck coefficient for maximum conversion of heat to electrical power or electrical power to cooling performance; and
- low thermal conductivity to prevent thermal conduction through the material.

These three properties are commonly combined into a single metric that measures the overall performance of a thermoelectric device: the “figure-of-merit” or Z. The figure-of-merit of a thermoelectric material is defined as:

$Z = \alpha^2 \sigma / \lambda$

Where α is the Seebeck coefficient of the material (volt·kelvin$^{-1}$),

σ is the electrical conductivity of the material (ampere·volt$^{-1}$·meter$^{-1}$), and

λ is the thermal conductivity of the material (watt·meter$^{-1}$·kelvin$^{-1}$)

Since *Z* has a unit of per degree of temperature, a more useful dimensionless figure-of-merit can be defined as *Z·T*, where *T* is the average operating temperature. This important parameter dictates the magnitude of the maximum power conversion efficiency TE devices.

### 4. Current and Voltage:

The voltage-current-characteristics of a generator include different aspects like the open-circuit-voltage, the generated power and the internal resistance. TheV-I-characteristic of TEGs is nearly linear and is shifted parallel by changing the heat flow or rather the temperature gradient. This behaviour is shown by the example of a small Bulk-TEG in Figure 3. The tested TEG has a cross-area of 10 mmˆ10 mm and a high of ca. 2 mm [10]. A major challenge for using the generated power is given by the low voltage. The expected temperature gradients are mainly lower than 30 K, therefore the current will also decrease. Due to the required constant higher voltage for supply of consumers, the voltage has to be converted. It is assumed, that the conversion efficiency is ca. 30% [11, 12]. One approach to increase the output voltage of the generator is given by thin-film-device due to the high amount of thermocouples. A characteristic under similar conditions is shown in Figure6. Sincealotof small thermocouples are realised in a small area the internal resistance increases strongly. This can be seen in the lower generated current. For this reason we need to consider between lower conversion losses but lower generated current (thin-film device) and higher losses at higher current.

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A characteristic under similar conditions is shown in Figure 6. Since a lot of small thermocouples are realised in a small area the internal resistance increases strongly. This can be seen in the lower generated current. For this reason we need to consider between lower conversion losses but lower generated current (thin-film device) and higher losses at higher current.

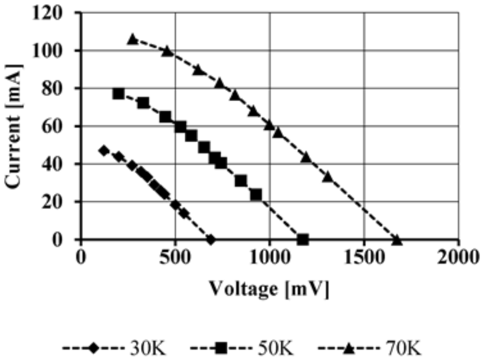

**Figure 3: *V-I*-characteristic of Small bulk TEGat different gradients and a constant cold side at $0^0$C**

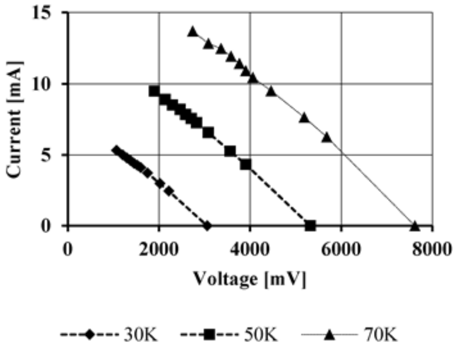

**Figure 4: *V-I*-characteristic of a thin-film TEG at different gradients and a constant cold side at $0^0$C**

### 5. Specific Power and Efficiency of TEG in space heating:

Particularly for space application light weight technologies are mandatory, so the specific power (W/kg) of generating devices and specific electrical energy of storing devices have to be increased. Therefore, the electrical power is divided by the weight of the device.For the calculation the mass of the device without cables or other infrastructure was taken. The mass is 0.03 g for the thin-film device, 0.61 g for the small bulk device and 10.69 g for the big bulk device. There are big differences between the two classes of TEGs: the thin film device achieves a specific power of 700 mW/g, the Bulk-TEGs start at 52 mW/g. But it could be possible, that the bulk devices generate benefits at higher heat flows due to the higher electrical current. In these cases the lower internal resistance of the TEGs could decrease losses. Nevertheless, the later discussed applications work only in low power conditions, therefore the thin-film devices are superior in terms of the specific power. In energy harvesting the efficiency is not crucial since the heat is available anyway. Even at low efficiencies TEGs will generate benefits if their power can be used. This efficiency is lower than 2% under the conditions mentioned in the figure.

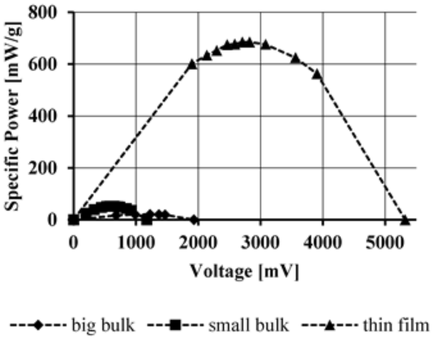

Figure 5: Specific power of three different TEGs at a temperature gradient of 50K and a temperature level of $0^0$C.

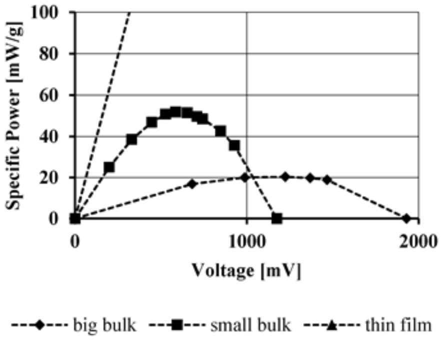

Figure 6: Details of the lower curves shown in figure 5 under same conditions.

### 6. Power Saving in Small Satellites:

Considering the available electrical power of satellites, Cubesats seem to be satellites on which TEGs could provide the main electrical power system. Cubesats have an installed power lower than 5 W. Therefore also some mill watts of additional power have a high impact on the efficiency of the satellite. This examination is based on the Cubesat of the Institute of Aerospace Engineering at TU Dresden was used same thing written three different ways in two sentences—pick a style and use it consistently. This is a double unit Cubesat (100 mm 100 mm 200 mm) that has solar cells on four surfaces.

Characteristic are the two PCB stacks that have a different orientation. In this configuration two different designs were taken into account. The thermal model were built up in ESATAN-TMS and includes 86 knots. Different conductors between the outer surfaces and PCBs are implemented; the view factors were determined by the Monte-Carlo-Method. On the PCBs different configurations of heat loads according to power consumption of the satellite were foreseen. Next to the mechanical configuration different operation modes were investigated. The orbit is a high inclined circular orbit (600 km, i = 70″) that is typical for such scientific missions. Also a rotation around the flight axis of 0.5″/s was considered. A verification of the model was not executed due to the greatly simplified internal design. This is mandatory because the optical and geometrical properties are very complex (e.g., cables) and therefore the calculation is both, very time-consuming and unreliable. But the representation accuracy is adequate for general results.

Although different locations of integration were considered, the potential for an energy harvesting on small satellites is quite low with today's technologies. The temperature gradient that occurs at the integrated TEG is in all cases lower than 3 K. The highest thermal potential with up to 3.5 K arises if two facing solar cells are connected directly by a TEG. Due to the integration effort and specific power this is only a theoretical approach.

In contrast to big satellites the whole internal space of small satellites is filled by PCBs and cables. Consequently the heat flow is very diffuse. A great effort would be necessary to concentrate the heat flows and guide it through a TEG. Since in reality there are much more thermal contacts between PCBs and the outer surfaces like connectors or cables, the heat flows will be more diffuse.

In summary, an application of TEGs in small satellites is not promising today due to the diffuse heat flows. Nevertheless, a technology demonstrator will be launched in 2017 on a small satellite built by TU Dresden. The demonstrator is located under a solar cell that is adapted to this application. The assumed temperature gradient of 3 K is not high enough to feed in the generated electrical power into the main power system. But test results show that it is high enough to characterize the thermoelectric generator under real space conditions. After that mission the results will be used for further experimental setups and are therefore the next step to bring TEGs into space in an energy harvesting application.

## 8. Conclusions:

Inside the structure of satellites heat flows occur that are driven by environmental (sun radiation, etc.) and operational loads (electronics, etc.). These heat flows are unused so far, although there is a potential for generating electrical power in general. Thereby the generated electrical power can be used for an increase of the satellites efficiency by a feed-in to the main electrical power system. Because of the low efficiency of available TEG technology this is not sufficient today. Also inside small satellites with a very low power demand the generated power is relatively low due to the diffuse heat flows.

Another approach is to use the generated power to increase the reliability of the satellite by implementing new systems. These systems should have a low power demand and no electrical interfacetothesatellite. Tasksofsuchsystemscouldbeanautonomousthermalcontrol ora redundant communication system as discussed above. In general it is feasible to use low power thermoelectric generators that are manufactured for terrestrial applications in space. Examinations of the device behaviour under thermal cycling and vibration loads show thatthey canwithstand them if they areexposed tomedium loads. The diffusion barrier between the copper contacts and the functional material was identified as a main weakness.

Besides the generator a power-management and an electrical storage system is required. The power management converts the transient and low voltage into a constant usable voltage. At such low voltages the efficiency of this process is in the range of 30%. Storage is used for balancing the power mismatch because the time of available and required power is not synchronised.

A promising storage is presented by super capacitors due to their insensitivity to temperature and loading cycles. It can be expected that generators with better electrical performance will appear on the market. But according to the physical basics their efficiency will also be limited in future. Another approach is to develop the manufacturing process towards printing. Consequently large area devices are feasible; therefore the heat does not to be concentrated. New knowledge about the behaviour and thermal potential of space applications for an energy harvesting is expected.

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