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Review

Thermoelectric generators: A review of applications

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ABSTRACT

In past centuries, men have mainly looked to increase their production of energy in order to develop their industry, means of transport and quality of life. Since the recent energy crisis, researchers and industrials have looked mainly to manage energy in a better way, especially by increasing energy system efficiency. This context explains the growing interest for thermoelectric generators.

Today, thermoelectric generators allow lost thermal energy to be recovered, energy to be produced in extreme environments, electric power to be generated in remote areas and microsensors to be powered. Direct solar thermal energy can also be used to produce electricity.

This review begins with the basic principles of thermoelectricity and a presentation of existing and future materials. Design and optimization of generators are addressed. Finally in this paper, we developed an exhaustive presentation of thermoelectric generation applications covering electricity generation in extreme environments, waste heat recovery in transport and industry, domestic production in developing and developed countries, micro-generation for sensors and microelectronics and solar thermoelectric generators. Many recent applications are presented, as well as the future applications which are currently being studied in research laboratories or in industry. The main purpose of this paper is to clearly demonstrate that, almost anywhere in industry or in domestic uses, it is worth checking whether a TEG can be added whenever heat is moving from a hot source to a cold source.

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1. Introduction and basics

Electricity production is an important issue for our societies. Waste heat is also an important topic. It is in this context that thermoelectric generators (TEGs) are currently taking off. TEGs consist of a set of thermoelectric (TE) modules inserted between two heat exchangers. Each TE module is then composed of several tens to hundreds of pairs of TE couples connected together electrically in series and thermally in parallel, which directly convert a part of the thermal energy that passes through them into electricity.

The advantages of TEGs are numerous:

- direct energy conversion, unlike many heat engines that first convert thermal energy into mechanical energy and then convert this mechanical energy into electricity using an alternator,
- no moving parts and no working fluids inside the TEG, hence no maintenance and no extra costs,
- a long lifespan, especially when working with constant heat sources,
- no scale effect: TEG can be used for micro generation in very limited spaces or to produce kilowatts,
- noiseless operations,
- any working position is possible, making TEGs well suited for embedded systems.

Despite these advantages, for many years TEGs were limited to space applications where their extreme reliability justified their use to provide electricity to the majority of probes sent into space (Voyager, Apollo, Pioneer, Curiosity, etc.). Low efficiency and high cost have been a barrier to their development for more common applications.

Efficiency (defined as the ratio of the electrical energy produced W_{elec} to the thermal energy entering the hot face Qh) of a TE module used as a generator can be approximated by the following relationship [1–3] for an optimal electric load:

$$\eta_{TEmax} = \frac{W_{elec}}{Q_H} = \frac{\Delta T}{T_H}\cdot\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \quad \text{with}$$

$$Z = \frac{(\alpha_p-\alpha_n)^2}{\left((\lambda_p.\rho_p)^{1/2}+(\lambda_n.\rho_n)^{1/2}\right)^2}$$

with T_H the temperature of the hot side of the TE modules, T_C the temperature of the cold side of the modules, and $\Delta T = T_H - T_C$ the temperature difference. Z is the factor of merit of the TE materials and can be expressed as a function of the electrical resistivities ρ_p and ρ_n, the thermal conductivities λ_p and λ_n and the Seebeck coefficients α_p and α_n of each of the two materials of the thermocouple. $T = (T_H - T_C)/2$ is the average temperature. ZT, product of the factor of merit by the average temperature is called the dimensionless figure of merit. It is a very convenient way of comparing the properties of materials as it appears in the expression of the efficiency and plays an important role in power maximizing [4].

Currently available TE materials have a ZT of around 1 or less. In the last decades, Bismuth Telluride (Bi2Te3) has been the only material which has been used for industrial thermoelectric modules. For these modules the average value of ZT is between 0.5 and 0.8. Fig. 1 shows that the effective efficiency for industrial applications is a few percent. ZT = 1 is the average value which is expected for the next years. The outlook for laboratories is to develop materials with a ZT of 2 in order to have an efficiency over 10%.

As this low efficiency is an obstacle to development of TEGs, researchers and manufacturers have tried to improve three main issues: improving ZT, increasing the operating range of materials to work with higher temperature differences and, finally, searching for low-cost materials to counteract the negative effect of low efficiency. The results in terms of TE modules will be presented in paragraph 2.

The design and optimization of TEGs is also an important issue and will be addressed briefly in paragraph 3.

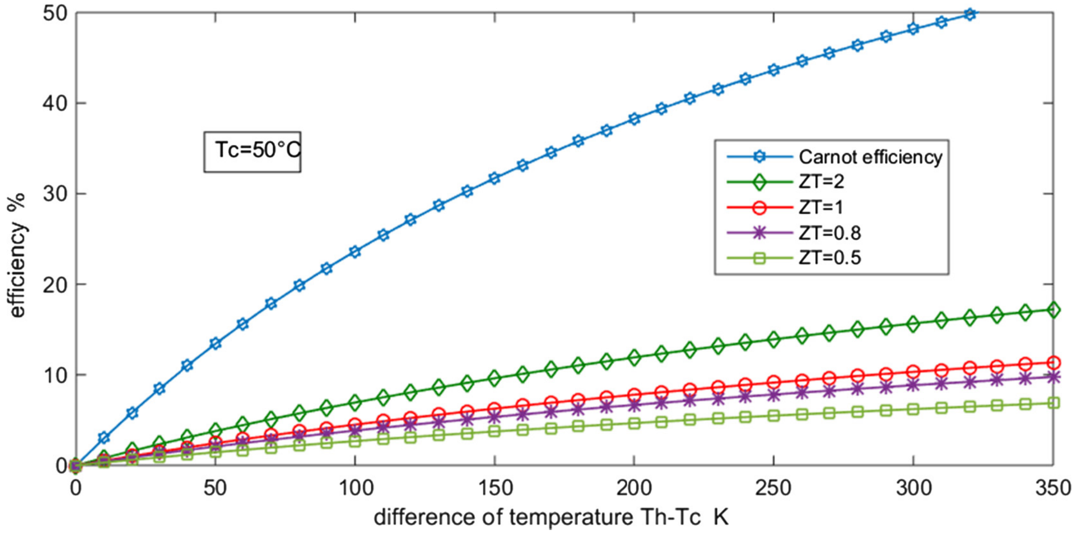

Fig. 1. Typical values of TE efficiency for different values of ZT.