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A comprehensive review of thermoelectric technology: Materials, applications, modelling and performance improvement

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ABSTRACT

Thermoelectric (TE) technology is regarded as alternative and environmentally friendly technology for harvesting and recovering heat which is directly converted into electrical energy using thermoelectric generators (TEG). Conversely, Peltier coolers and heaters are utilised to convert electrical energy into heat energy for cooling and heating purposes The main challenge lying behind the TE technology is the low efficiency of these devices mainly due to low figure of merit (ZT) of the materials used in making them. The objective of this work is to carry out a comprehensive review of TE technology encompassing the materials, applications, modelling techniques and performance improvement. The paper has covered a wide range of topics related to TE technology subject area including the output power conditioning techniques. It is observed that the intensified research into TE technology has led to an outstanding increase in ZT, rendering the use TE devices in diversified application a reality. The performance improvements of TE devices have been mainly contributed by improved TE material research, TE device geometrical adjustments, design of integrated TE devices as well as the use of advanced TE mathematical models which have facilitated appropriate segmentation of TE modules using different materials. TE devices are observed to have booming applications in cooling, heating, electric power generation as well as hybrid applications. With the generation of electrical energy using TEG, not only does the waste heat provide heat source but also other energy sources like solar, geothermal, biomass, infra-red radiation have gained increased utilization in TE based systems. However, the main challenge remains in striking the balance between the conflicting parameters; ZT and power factor, when designing and optimizing advanced TE materials. Hence more research is necessary to overcome this and other challenge so that the performance TE device can be improved further.

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1. Introduction

The drastic changes in climate have driven the need for increasing research into alternative sources of energy. Those rapid changes in climate are mainly attributed to the use of fossil fuels for transport and energy generation. Due to climatic challenges, several countries around the world have pledged to reduce primary energy consumption through an increase of efficiency in production, distribution and end-use, limit carbon dioxide emissions and increase the utilization of renewable energy sources [1]. The rapid development of power electronics technologies has enabled the realization of high energy-efficient systems such as electric vehicles [2]. The U.S. Energy Administration in 2011 estimated that almost two-thirds of total demand for petroleum is from the transportation sector. With an assumption that daily production of petroleum holds steady at 63.5 million barrels, global oil reserves are conventionally predicted to last approximately fifty years [3]. In the French industry, 75% of the final energy is used for thermal purposes such as furnaces, reactors, boilers and dryers. However, around 30% of this heat is assumed to be wasted in form of discharged hot exhaust gas, cooling water and heated product [4]. Therefore, the recovery and utilization of the waste heat is believed to contribute some amount of energy to the energy needs of the society.

Research and development have been promoted on thermoelectric (TE) modules which convert heat energy directly into electrical energy. TE devices are semiconductor devices that have the ability to either generate a voltage when exposed to a temperature gradient, exploiting the Seebeck effect, or produce a temperature gradient when supplied by electricity, exploiting the Peltier effect [5]. A number of currently available and applicable low-grade waste heat recovery methods include plant/district/water heating, direct power generation (TE and piezoelectric), absorption cooling, indirect power generation (steam and organic Rankine cycle), desalination/clean water and biomass co-location [6]. TE technology is seen as one of the most promising direct power generation technique used to recover waste heat energy because of the direct conversion from thermal energy to electrical energy, unlike the organic Rankine cycle, believed to have been discovered more than 150 years ago [7]. Heat energy can be harvested or recovered using two direct electricity generation strategies: thermoelectricity and pyroelectricity. Whereas thermoelectricity is the generation of electricity using thermoelectric harvesting systems which exploit the Seebeck effect for conversion of heat energy i.e., generation of electricity due to difference in temperature of two dissimilar conductors or semiconductors connected together at two junctions, pyroelectricity exploits specific materials whose structures are modified when heat is applied on them and in turn the polarization of the material is changed, thus creating electric potential [8].

TE modules offer low cost electricity, and green energy technology without the use of moving parts or production of environmentally deleterious wastes [9]. However, the optimal performance of TE modules depends on several factors like material selection and operation strategy. A study has used an irreversible model to analyse the performance of a thermoelectric generator (TEG) with external and internal irreversibilities, providing some significant instructions for their optimal operation including the information about optimal device-design parameters, efficiency, maximum power output, etc. [10]. Most of the research by 2005 had concentrated on electronics cooling applications especially on the variation of the geometric features such as shapes, sizes, and orientations to the flow in heat transfer systems but in later years, research on TE technology has gained a lot of momentum [11].

Although energy-related GHG emissions from fossil fuel combustion account for 70% of total emissions come from heat supply and electricity generation, a relatively large portion is generated from the transportation industry [12]. Although electric vehicles (EV) powered by renewable energies are seen as a potential solution to curtail GHG from transport industry [13], TE technology is also continuously introduced in low carbon vehicles to extract waste energy from various points of the vehicle. For a typical gasoline-engine vehicle, about 40% of the fuel energy is discharged from the exhaust pipe; about 30% is lost into the cooling system,