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A review of power generation with thermoelectric system and its alternative with solar ponds

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ABSTRACT

By using the Seebeck effect to produce electrical voltage, thermoelectric as a highly scalable, stationary and silent heat engine has undergone a state of vigorous research. Starting with the review on thermoelectric generators, it shows that thermoelectric is gaining more attention since the past decade. Generally, the research conducted on the thermoelectric generators concentrate on the material development, mathematical and numerical model development as well as the application of thermoelectric generators. For this article, attention is given to the application research of the thermoelectric generators. From the survey conducted, most of the application research carried out is based on intermittent electrical power generation (e.g. the direct use of solar energy available or waste heat recovery). Hence, it opens an opportunity for the research on the application of thermoelectric generators by utilising a heat source that is continuously ready for thermal-electrical energy conversion, such as phase change material, geothermal heat or solar pond. In the later section, the review is continued by introducing solar pond, a facility that has been used as a supply of low-grade heat source at the remote area or industrial process heating. The research on the fundamentals of solar pond and its applications, but not limited to, the power generation has also been summarised. The ultimate idea of this review is to provide an insight that a thermal-storage based heat source (e.g. in this review, the solar pond) could be useful for small-scale electric power generation, despite its ordinary function as low-grade heat source provider via heat extraction.

1. Introduction

Countries around the globe have been aware of the rise in global average temperature and start to implement energy policies that will hopefully curb the temperature rise below 2 °C at the end of the century. Some researchers have argued that the notion of global temperature rise is invalid and using the temperature rise as an 'achievement indicator' is futile due to its incapability in fathoming human activities that undermining the earth [1]. The Kyoto Protocol set up in 1997 aimed to reduce the emission of greenhouse gasses with an average cut around 5% relative to 1990 levels by 2012. Seemingly, not all of the countries with the binding target successfully achieve the aim and overall, the change in the global CO_2 emission had increased by 11.3 GT from 1990 to 2011, with China and other developing countries contribute the most increment in CO_2 emission. It was only in the recent COP21 meeting at Paris, a clear binding agreement in reducing the in CO_2 emission and aiming to keep the temperature rise at 1.5 °C in the end of the century. Clearly, in order to achieve the mission, there is a need to speed up the move to low carbon electric producing technology and preferably renewable energy. The selection of technology in implementing renewable energy power supply is depending on the types green resource that is conveniently available due to geographical advantage, human resources or technological resources that a country readily advanced. With the abundance of heat available, either from the sources that are freely available such as solar energy, geothermal energy or unutilised energy in the form of waste heat. This paper begins with a review on the thermoelectric generators (TEGs), a device that producing electric power as a result temperature difference through the flow of heat with the focus on recent development of TEGs' application. Current development on the thermoelectric materials is impeded by thermoelectric figure of merit, ZT. Unless there is a quantum leap in the breakthrough of, otherwise thermoelectric technology in driving a primary role in the electric source is impossible and it will remain as an supplementary technology that enhances the performance of current renewable energy power generation. Then, in the later part, the review of the solar pond, a facility that collects and stores solar energy is delineated. Realising the electrical storage-based system (i.e. the use of batteries at the post-electric generation stage)

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will be the most commonly adopted method for the long term power storage. Overall, through this review, the authors would like to introduce the option of thermal storage-based electric power generation system using TEGs.

2. Thermoelectric generator (TEG)

The use of TEGs as a potential source of for both large scale electric powers as well as an alternative source for low power generation had been delineated by Rowe that presented in his publications [2,3]. From the life cycle analysis conducted, apart from being environmentally friendly, from the economics point of view, the increase in fuel cost will lead to the demand of alternative mean for power generation. The inclusion of externalities consideration will certainly favour the use of TEG as a supplement for electrical energy production [4].

2.1. Properties, material, structure, and characteristics

Due to the existence of temperature gradient, the TEG's operation is based on Seebeck effect and Peltier effect. The former phenomenon, refers to the relation between thermoelectric potential under open circuit condition and the temperature difference is correlated by the Seebeck coefficient, α (V/K). Hamid Elsheikh et al. [5] in the recent review described the important parameters that govern the performance of the thermoelectric cells. The authors analyse the parameters from the viewpoint of thermoelectric properties and material properties, and extended the discussion on the life expectancy of the thermoelectric cells. They strongly believed that the study on the relation of both electrical and thermal conductivity is the key for improving the performance of thermoelectric cells.

There are different materials available for TEG in order to cater a different range of operating temperature. Different categories of materials had been explored, such as ceramics [6], alloys [7], bulk material [8], complex crystals, oxide materials [9,10], nano-composites. Table 1 summarises the TEG materials, working temperature as well as the *ZT* value of these materials.

From Table 1, it is clearly seen that under current development, the BiTe-based material is the most suitable commercially available material to suit the need of recovering low-grade heat (< 150 °C). Although the TEGs operate base on the temperature difference across its hot and cold junction, there exists a difference in maximum electric power in spite of the fact that the temperature difference across the junction remains constant, sincethe specification of temperature difference gives two degrees of freedom for the values of cold and hot temperature. Specifically on Bi_2Te_3, which operates at temperature < 150 °C, for a fixed temperature, there exist both upward and downward concavity in the graphs of maximum power versus mean temperature (average of temperatures at the hot and cold junction). In the other words, in order to achieve similar maximum power output, for a given fixed temperature difference, the number of thermoelectric cells needed varies [14]. For the middle and high range of temperature, research had been carried out in the searching and characterisation of new thermoelectric materials [15] and reducing the cost for TEG [10].

Table 1
TEG materials and its performance [11–13].

Operating Temperature, °C	Type	Materials	Maximum *ZT*
< 150	p	$Bi_{0.5}Sb_{1.5}Te_3$	1.4
	n	$Bi_2Se_{0.3}Te_{2.7}$	1.0
	p,n	Bi_2Te_3	0.8
150–500	p	Zn_4Sb_3	–
	p,n	PbTe	0.7–0.8
	p	TeAgGeSb	1.2
500–700	p	$CeFe_4Sb_2$	1.1
	n	$CoSb_3$	0.8
700–900	p,n	SiGe	0.6–1.0
	p	LaTe	0.4

2.2. Mathematical and numerical model development of TEG

In the mathematical modelling of the TEG, often the heat transfer between the TEG and its environment are modelled by Newtonian heat transfer law with the heat transfer rate, $\dot{Q}$ is directly proportional to the temperature difference, ΔT. In order to take into account the thermodynamics irreversibility of TEG, Chen et al. [16] developed an advanced model of TEG by considering the irreversibility characteristic of TEG. The five heat transfer laws under consideration were Newtonian, linear phenomenological, radiative, Dulong-Petit as well as special complex transfer law. The study showed, external heat transfer model using Newtonian law yield highest efficiency and power output compared the other four heat transfer laws, and external heat transfer models considered will vary working electrical current that results the optimum operating condition of TEG. Besides, Montecucco et al. [17] proposed the solution to the 1-Dimension transient heat conduction equation by incorporating the internal heat generation of TEG. As a result, without fixing the hot side and cold side temperature of the TEG, the transient characteristic of TEG can be evaluated.

With the advancement of the computational method, TEG model can be accurately simulated [18,19]. When the TEG is exposed to the heat source with a temperature difference, the device is undergoing transient state before the thermal and electrical dynamically stabilise. Peltier, Seebeck, Thomson, and Joule are the main effects that taking place in the TEG. Montecucco and Knox [20] modelled the response of TEG under the changing operating condition by using a computer aided model. By taken into account of the important thermoelectric effect such as Joule heating and Peltier effect, the computer model developed will able to predict the TEG response in high accuracy. Although the model did not include the Thomson effect, however, according to Nguyen and Pochiraju [21], Thomson effect is significant in giving impact on the power generation rather than the thermal behaviour of the TEG.

2.3. Recent development on TEGs' application

The TEG can be integrated into various systems, such as, but not limited to heat exchanger system, exhaust gas heat extraction, solar heat extraction, industrial waste heat recovery, or couple with other renewable energy sources, e.g. solar photovoltaic system, forming a hybrid system for better power conversion efficiency as delineated by Kreamer et al. [22]. TEG may also be used for electricity generation for terrestrial application by using optical concentrator and solar absorber with wavelength-selective surface [23] or generating electricity from human body heat with the aid of heat sink [24,25]. Although the use of TEG for remote area power supply is far away to be realised. However, it had been shown from the experimental study that the use of TEG in powering autonomous sensor at the remote area is feasible [26]. The innovative design of heat exchanger for electric power generation using TEG had been conducted. Different design of heat exchanger were considered: (i) roll cake type heat exchanger; a helical flow system, (ii) cylindrical multi-tubes design; including counter flow, parallel flow and isothermal heat exchanger [27–29].

2.4. TEG in solar heat extraction system

As a source of green energy, solar energy can be utilised to generate electricity through the photovoltaic panel, space heating, or solar thermal energy storage via the solar collector. The research on generating electricity with TEG by harvesting the solar energy was mainly conducted base on the concentration of solar radiation in order to achieve higher hot side temperature for higher conversion efficiency. The sunlight concentration was either achieved via parabolic concen-