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Progress of thermoelectric power generation systems: Prospect for small to medium scale power generation

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ABSTRACT

This paper presents the progress of thermoelectric power generation systems and their potential to be incorporated in small to medium scale power generation systems with encouraging prospects of grid connection. To begin with this paper demonstrates the urgency and necessity of finding an alternative source of energy to replace the existing inclination of human race towards fossil fuels. Following this the potential of thermoelectric technology to be used with alternate energy sources is demonstrated. Development in the field of thermoelectric materials with high Seebeck coefficients, suitable for power generation modules is discussed in the literature review. New advanced materials and innovative techniques to utilise renewable energy for power generation using thermoelectric generators are described in the main body of this paper. Various active and passive cooling systems with thermoelectric power generation modules to enhance the performance of the system are illustrated in the paper. A brief literature survey is presented at the end about grid connection for thermoelectric generators .These advances in thermoelectric technology, places it in a comfortable position to become a major contributor to renewable and sustainable electricity production in the future, essentially replacing fossil fuels.

Contents

1. Introduction

Human need for energy has been on the rise since the industrial revolution in the 18th and 19th century. Mechanised manufacturing processes were evolved during this period and these were demanding high energy. Development in the field of technology further fuelled the demand for energy. During this period the need for energy was continuously increasing and it was realised that fossil fuel was not a permanent energy source. To support the technological development in the field of science and considering the rate at which the fossil fuels were exploited, many new technologies were evolved for alternate energy sources.

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In 1821 a German Physicist Thomas Johann Seebeck [1] observed that when two dissimilar metals were brought together and maintained at some temperature difference magnetic field is generated as evidenced by a deflection in the compass magnet. Initially he believed that it was due to the magnetism induced by temperature difference. However later he realised that it was the electrical current flowing through the dissimilar metals that introduced magnetic field. Primarily thermoelectric devices were more commonly used as heat pumps for cooling. Thermoelectric cell can be easily used in compact designs where cooling is necessary and efficiency of the system is not much of an issue. Till the middle of 20th century this technology was better known and the use of semiconductors with smaller band gap was found to perform better than just two metals [1]. This triggered the interest of researchers to explore the new materials that could have potential for thermoelectric power generation having a high Seebeck coefficient. In 1961, the National Aeronautics and Space Administration was the first organisation to implement thermoelectric technology in a real application where it was used to supply the electrical power to spacecraft [2]. Since then thermoelectric technology had found its way in the mainstream industry and has been used for various applications such as cooling and heating in trains [3,4], powering wrist watches[5], cool diode lasers [6] and many more.

During this period thermoelectric power generation was a new topic for research and it fascinated many researchers. The figure of merit of the known thermoelectric materials was quite low and hence the power generation efficiency could not compete with the then existing technology of internal and external combustion heat engines. Researchers tried many materials but were unsuccessful in exceeding the figure of merit beyond 1. This reduced the interest of research society towards thermoelectric and the future did not look bright for thermoelectric power generation to be one of the possible alternatives for fossil fuels. However during the 1990s there was an inflow of new ideas with evolution of some new materials to increase the figure of merit which once again reignited interest of researchers in the field of thermoelectrics and continued the quest for improving the figure of merit to the level where it can compete with the conventional heat engines [7–14].

Conventional bismuth chalcogenide such as Bi_2Te_3 and Bi_2Se_3 are amongst the best performing thermoelectric materials with figure of merit ranging in between 0.8 and 1.0 [15]. Lead telluride is another thermoelectric material which when doped with thallium achieves a figure of merit of 1.5 at 773 K [16]. Magnesium group compounds are good thermoelectric materials which have shown that their figure of merit is comparable with that of the bismuth chalcogenide. Figure of merit of 0.9 at 800 K for such materials has been reported by Rowe [15]. Recently skutterudite which is a cobalt arsenide mineral with variable amounts of nickel and iron has flashed the interest of the researchers for its thermoelectric properties. These materials have shown the potential for multistage thermoelectric devices which can exceed the figure of merit beyond 1 [15]. Another group of material called oxide thermoelectrics has a potential to be used at higher temperature as high as 1000 K. Example of an oxide thermoelectric material is combination of strontium titanate and strontium oxide. Figure of merit for the oxide materials is relatively lower than the conventional thermoelectric materials and was reported to be 0.34 at 1000 K by Wunderlich [17]. Half Heusler alloys have also shown a potential as high temperature thermoelectric materials especially as n-type materials. Figure of merit of 0.8 at 1000 K has been reported for MNiSn (M=Ti, Zr, and Hf) when doped with antimony [18]. Recently nanostructured materials have shown a great deal of promise in enhancing the figure of merit for thermoelectric materials beyond the limit where these devices can compete with the conventional heat engines and firm its position to produce electricity in mainstream power industry. Nanostructuring of bismuth chalcogenide has shown a significant improvement in figure of merit of the p-type material raising it up to 2.4 [19]. Quantum dots super lattice thermoelectric materials based on lead selenium and tellurium have shown an enhancement in the value of figure of merit to 1.5 which is more than the figure of merit for similar bulk material thermoelectric [20,21]. Recent research conducted in the AMES laboratory in conjunction with US EFRC programs suggests that adding small amount of rare earth metal to the thermoelectric material improves its figure of merit by distorting the local crystalline structure that enables high energy carriers to move through the material while providing the barrier to the lower energy carriers. It was shown by the researches at AMES laboratory that adding small amount of dysprosium to the thermoelectric material known as TAGS-85 increases its figure of merit from 1.3 to 1.5 [22]. Researchers at the University of Michigan along with US EFRC have also suggested that by creating a local atomic disorder in thermoelectric material would interrupt the atomic vibrations that control transport of heat and would result in low thermal conductivity[23,24].

2. Thermoelectric power generation systems

Development of new materials and extensive research on the nanostructured thermoelectrics have opened excellent avenues for thermoelectric devices to be used in the small scale to medium scale power generation applications using thermal energy. Rowe categorises thermoelectric power generators into isotopic thermoelectric generators and non-isotopic thermoelectric generators [25]. The reason for such classification of thermoelectric power generators is that the most prominent application of thermoelectric devices in stand-alone power generation system has been in the spacecraft using a heat source from a radioisotope. Use of radioisotope thermoelectric power generation system can only be justified for the spacecrafts since there is absence of oxygen in space to burn the hydrocarbons to run conventional heat engines [25]. Considerable research has been done on non-isotope thermoelectric systems for small to medium scale power generation from the renewable or sustainable energy heat sources. The next section of this paper presents the detailed review of the existing non-isotope thermoelectric power generation systems which have a potential of becoming the mainstream small to medium scale stand-alone or grid integrated power generation systems (Fig. 1).

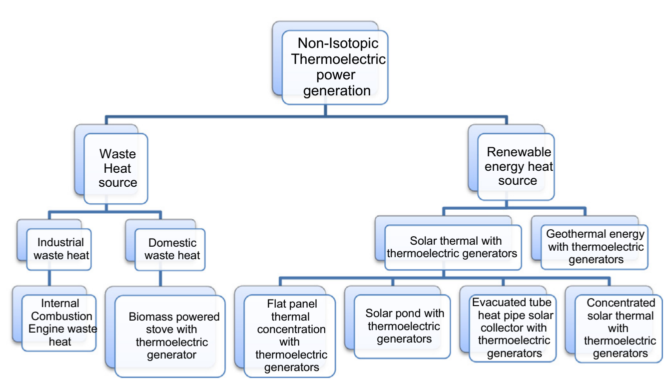

Fig. 1. Classification of non-isotopic heat sources and potential technologies related to these heat sources for small to medium scale power generation.