A Review of the Thermoelectric Generation for Technological up-gradation for Enhancement of Acceptability as Alternate energy source

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Abstract- Energy conservation and clean technology is the need of the hour to combat the problem of energy deficit, global warming. Rise in energy demands with depletion of resources, the utilization of clean natural primary energies are now focus areas gaining importance. Continuous advancement in thermoelectric technology has been reported as an alternative to energy sources. Thermoelectric module has the capacity to produce electric power if a temperature gradient is maintained across its terminals.

This paper presents a comprehensive review on thermoelectric technology, its advancements, means and ways for its utilization as Thermoelectric Generator (TEG) as an independent entity or hybridized with other sources where heat is a waste/unutilized bi-product. The review is partially focused for utilization of thermoelectric module as TEG for improving efficiency of system like waste heat recovery in automobiles and Thermal/Gas power plants, Methane based power plants, active heat sinking in electronics and photovoltaic etc.

1. INTRODUCTION

Technological development of thermoelectric phenomenon were initiated in 1821 through Seebeck effect which states that an electromotive force could be produced by heating a junction between two metals. If two metals a and b are joined together so as to make a junction and if this junction is heated and other junction is kept at some reference temperature then the open circuit voltage ΔV is developed at this reference junction i.e. cold junction.

Extension to Seebeck research, in 1834 Peltier, discovered that the passage of an electric current through a junction between two dissimilar conductors in a certain direction produces a cooling effect.

A correlation between the Seebeck and Peltier coefficients was experimentally proven by Thomson and is known as Thomson effect. This effect co-relates the heating or cooling in a single element when current passes through it in the presence of a temperature gradient.

Seebeck effect is based on thermal diffusion principle which causes flow of charge carriers along temperature gradient in conducting material and generates electrical potential in open circuit condition.

Peltier effect theory indicates flow of energy in different conductors and heat absorbed or evolved at metal junction. Thermoelectric effect states that thermal energy can be converted to electrical energy or vice versa in conducting or semiconductor material.

Rayleigh introduced application of thermoelectric technology in electricity generation in 1885, in continuation to this Atenkirch gave a more meaningful and result oriented theory of thermoelectric generation and refrigeration in 1911 [1]. The technology was developed slowly till 1930's. In the late 1930s interest in thermoelectricity accompanied the development of synthetic semiconductors that possessed Seebeck coefficients in excess of 100 μV/K and in 1947 Telkes constructed a generator that operated with an efficiency of about 5% [2]. In 1949 Ioffe developed a theory of semiconductor thermoelements and in 1954 Goldsmith and Douglas demonstrated the cooling from ordinary ambient temperatures down to below 0°C[1]. Revolutionary developments first occurred in the US space program, the thermoelectric generators have been used by National Aeronautics and Space Administration (NASA) of USA to provide electrical power for spacecraft since 1961[2]. Due to awareness of green house effect due to the depletion of the ozone layer, a general public interest in environmentally friendly energy sources is developed. Thermoelectric generation as a potential source received importance due to environmental friendly operation, and large-scale electrical power generation using waste heat later in late 80's. Thermoelectric technology finds its application in cooling electronic circuits [4].

2. THERMOELECTRIC DEVICES

Thermoelectric devices can be operated in heating/cooling or generation mode based on Peltier effect or Seebeck effect. When Semiconductors are used as the material it is popularly known as thermoelectric module (TEM) [4]. A single stage TEM as shown in Fig.1.1 consists of an array of positively doped (p-type) and negatively doped (n-type) semiconductor pellets which are connected electrically in series and thermally in parallel, sandwiched between two electrically insulating but thermally conducting ceramic plates to form a module. Each adjacent pair of p-type and n-type pellets forms one of the N thermocouples in a TEM. Ceramic is used to electrically insulate pellets and it is thermally conductive so heat is transferred to and from the pellets. Copper conducting strips are soldered to pellets for electric conduction.

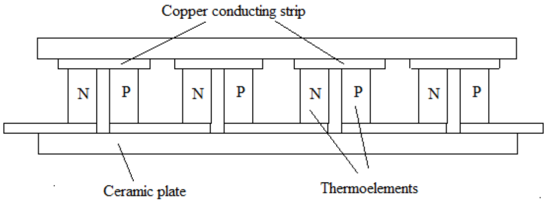

Fig.1 Basic single stage thermoelectric module

When a temperature difference is maintained across two junctions of the module, electrical power will be delivered to an external load and the device operates in generation mode as shown in Fig.1.2.

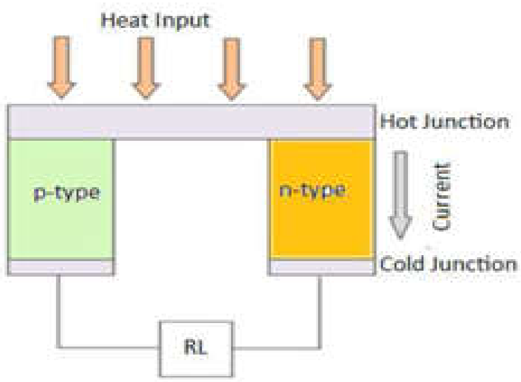

Fig.2 TEM used as generator

Conversely, when an electric current is passed through the module, heat is absorbed at one face of the module, rejected at the other face, and the device operates as a refrigerator as shown in Fig. 1.3

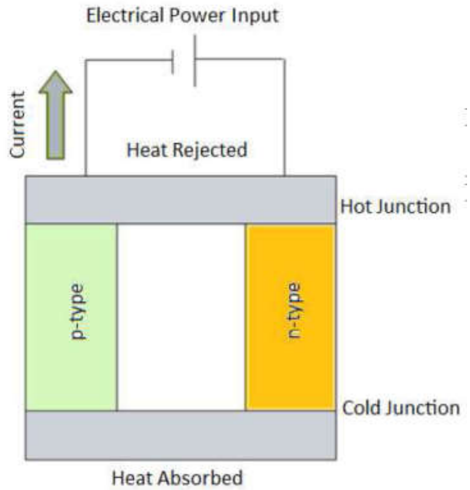

Fig.3 TEM used as refrigerator

For the thermoelectric generator efficiency is defined as the ratio of electrical power delivered to the load with respect to the heat absorbed at the hot junction.

$$\eta = \frac{\text{energy delivered to the load}}{\text{heat energy absorbed at the hot junction}} \quad (1)$$

In a thermoelectric generator the efficiency of conversion of heat into electricity depends upon the temperature difference ΔT over which the device operates and on the performance of the thermoelectric material through its figure-of-merit. The figure of merit of thermoelectric material is defined as

$$Z = \alpha^2\sigma/\kappa \quad (2)$$

where α is the Seebeck coefficient, κ is the thermal conductivity and σ is the electrical resistivity of the material.

Whereas the performance of TEM as a refrigerator is usually assessed in terms of a quantity known as the coefficient of performance (COP) and which is defined as

$$COP = Q_c/W \quad (3)$$

where Q_C is the cooling power and W is the rate at which electrical energy is supplied.

3. THERMOELECTRIC MATERIAL

Selection of a material for thermoelectric application is dependent on the figure of merit. This parameter has to be maximized over the temperature range of interest. Materials can be classified based on application as a generator or heater/cooler. For refrigeration application the most suitable material available is Bismuth Telluride (Bi2Te3), a semiconductor alloy that has highest figure of merit and have operating temperature of around 450 K. For generation purpose alloys based on lead telluride and silicon germanium are used. Lead telluride has the next highest figures-of-merit with silicon germanium alloys having the lowest. Lead telluride and silicon germanium are used in generator applications with upper operating temperatures of around 1000 and 1300 K, respectively [3]. In a bulk thermoelectric material, the three ingredients in the figure of merit, α, σ, and ʎ, are dependent on each other, and this impedes the optimization of *Z*. Good thermoelectric material should have large Seebeck coefficient, to retain heat at junction it should have low thermal conductivity and to minimize Joule heating its electrical resistance should be low. If higher density electrons are used to enhance electrical conductivity then this results in decrease of Seebeck coefficient. Use of small particle size compacted material to reduce the lattice thermal conductivity by phonon-grain boundary scattering was postulated by D.M. Rowe in 1968[5]. But in case of small grain size compacts due to reductions in lattice thermal conductivity resulted in electrical conductivity. Ioffe demonstrated that ratio of thermal to electrical conductivity can be decreased if thermoelectric element is alloyed with an isomorphous element or compound.

Thin film deposition technique like electroplating, co-deposition, MBE with Bismuth Telluride as base material were developed but successes of this technology depends upon material performance and manufacturing technology.[22-23].

Glen Slack proposed the material known as electron crystal phonon glass (EPCG) where a skutterudite crystal can be imagined as structure that contains loosely bound atoms. Tests on such structure have shown ZT values of about 2.5, a huge step closer to cooling efficiencies comparable to a regular refrigerator. Table 1 shows improvement in figure of merit of thermoelectric material with new technologies.

Sr no	Material	Figure of merit(ZT)	Temperature range (K)
1	Bulk ZnSb	0.3	300-700
2	Bulk PbTe	0.5	400-900
3	Bulk Bi_2Te_3	1.0	300-500
4	Filled skutterudites Zn_4Sb_3	1.5	300-700
5	Bi_2Te_3/Sb_2Te_3 superlattice	2.5	300-600
6	PbSeTe/PbTe quantum dots	3.5	300-500

Table 1. Development in figure of merit of thermoelectric material with developing technology.

Carbon nanotubes (CNTs) are promising for use in advanced composites and interfaces requiring high thermal performance and mechanical compliance. In spite of the high conductivity of individual carbon nanotubes, the interface resistance of the CNT-substrate contacts often significantly reduces the thermal performance of CNT films and their composites below its potential value [7]. The complicated structure of these interfaces at the nanoscale strongly affects the interface resistances and is highly dependent on the interaction, adhesion, and wettability of the CNT and substrate materials, which is typically a metallic layer or dielectric. The nanoscale features in the contact further complicate the interface resistance by modifying the phonon transport physics, for which there are no established models. Further data are needed for the interface resistance between CNT interfaces with metal and dielectric films and its temperature dependence to improve upon the thermal performance of CNT arrays and develop models for the thermal transport in nanostructure contacts.

4. APPLICATIONS

Used as a Generator- For operating TEM as a generator source of heat can be fossil fuel, isotopic and waste heat.

The first fossil fuel powered generators were used to power radios in remote regions[8]. The development of systems for nuclear auxiliary power (SNAP) was begun in the United States in 1955. The first application of radioisotope power in space accompanied the successful launching of a generator in June 1961. The thermoelectric power of 4 watts generated was a fraction of the satellite requirement. Since 1961 the United States has deployed Radioisotope powered thermoelectric generators (RTG) for space systems [3].

The majority of Soviet thermoelectric generators deployed in space relied on small nuclear reactors referred to as nuclear power plants (NPP) to provide heat. Typical reactor outputs were 100kW thermal producing 6kW electric in the NPP-Topaz systems launched in 1987-88.

There are many sources of waste heat in the industry and in everyday electrical household appliances. Using TE modules it is possible to generate electric power even if the temperature of the heat source is only a few degrees higher than the ambient temperature. The electric power can be used to supply auxiliary equipments.[9-13]

One application for of utilization of waste heat from Industrial furnace using radiation heat transfer is developed by Author[14]. The cascaded thermoelectric modules are installed on the surface of the water jacket which is set inside the electric industrial furnace. The surface of the cascaded thermoelectric module facing the in-furnace heat insulators is heated by the radiation. The other side of the cascaded thermoelectric module is cooled by the water jacket. In the condition that the temperature difference of the unit becomes 564K, the efficiency of the unit was able to obtain 7.5%. As a result, the electric power efficiency of the system is improved 5%.

Up to 40% of the energy consumed by a gasoline internal combustion engine is lost in the form of heat exhausted from the tailpipe. A thermoelectric generator (TEG) can be used to convert waste heat directly into electricity. This would reduce the load on the vehicle's alternator, the traditional source of the electricity that a vehicle needs for keeping its battery charged and for powering all of its on-board electric circuits. This in turn reduces the engine's workloal. Vehicles fuel economy could increase by about 5% [17].The alternator could also be made smaller and might eventually be eliminated, with the TEG along with PV panel supplying the entire vehicle's electrical need.

Used as cooler in Electronic Industry-Cooling of heat dissipating electronic equipments-Ultra-large scale integration at the chip level coupled with increased packaging density led to substantial increases in chip and module heat flux over the past 40 years, particularly in high-end computers. To limit the chip temperature rises above the ambient coolant temperature in order to ensure satisfactory electrical circuit operation and reliability [18]. Thermoelectric cooling may be considered a promising technology for cooling enhancement.

5. RESEARCH ON THERMOELECTRIC TECHNOLOGY GOING ON GLOBALLY-

The exploitation of the thermoelectric applications soon became a new hot research subject in USA Europe and Japan. Revolutionary developments first occurred in the US space program, the thermoelectric generators have been used by National Aeronautics and Space Administration (NASA) of USA to provide electrical power for spacecraft since 1961.

At about 1995 the U.S. Department of Energy (USDOE) initiated a project with Hi-Z Technologies to develop a thermoelectric generator (TEG) demonstrator to convert the waste heat from a heavy-duty Class 7-8 diesel engine directly to electricity. With the temperature difference of 207^0C power output of 500 W for TEG is achieved [20].

Research and Development of thermoelectric power generation have been carried out in government institutes, universities and private industries. The new energy and industrial technology development organization (NEDO) have developed TE system using exhaust gas of gasoline engine vehicle during 1994-98. Research on high efficiency thermoelectric technology is conducted by NEDO in 2000. Solar Hybrid system is a joint research project by Chinese and Japanese institutes started in October 2004. Institutions involved in this project are Japan Aerospace Exploration Agencies(JAXA), Foundation for promotion Japanese Aerospace Technology(JAST) ,Toshiba, Tohoku University, Mitsubishi Research Institute(MRI) which are working on System design, operation, evaluation, control system design and market research whereas in china institutions like WuHan University of Technology, WuHan University of Technology Shanghai Institute of ceramics Chinese Academy of Sciences are involved in this project work on thermoelectric material. Beijing Zhongmei Chengxin Technology Ltd is looking into combining photo and thermoelectric technology but with an alternative thermo-electric conversion method called tunnel effect. There are three other companies looking into leveraging the tunnel effect for thermoelectric conversion one in Gibraltar and two in USA but no companies have arrived at a commercial product [21].

CONCLUSION

Thermoelectric module can be used as Coolers (or heaters), Power generators, Thermal energy sensors. The thermoelectric generator has no moving parts, no position-dependence, high life expectancy [8], and adaptability for various sources and types of fuel. For power generation application solar thermal power, waste heat can be used. Operation of thermoelectric devices in generation and cooling/heating mode doesn't produce any green house gas. So this technology is environment friendly and can be used as a flexible source of electricity to meet a wide range of power requirements. Accuracy is important parameters for use of any device as a sensor or detector. As thermoelectric device provides high accuracy it finds its application as a sensor or detector. TEM contain no chlorofluorocarbons therefore there is no chance of ozone depletion. There are no specific working environment criteria for operation of this device. They can work efficiently in hazardous environment.

The concept of Thermo electric Generator and Cooler has been extensively adapted to some extent across the globe due to its major advantages like simplicity, reliability and eco-friendly nature.

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