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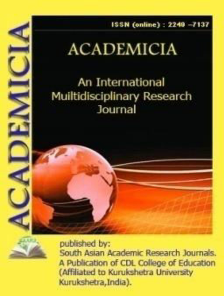

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MATERIALS, MODELS, AND APPLICATIONS OF THERMOELECTRIC COOLING

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ABSTRACT

This paper examines current developments in thermoelectric materials, modeling techniques, and applications. Thermoelectric cooling systems offer a number of benefits over traditional cooling technologies. There are no mechanical moving components, no working fluid, and the device is small, light, and reliable. Direct current is used, and the cooling and heating modes may be switched simply. In this research. The history of thermoelectric cooling has been briefly discussed initially. The development of thermoelectric materials was then discussed, as well as the accomplishments of the previous decade. Summarized. Modeling methods have been used to enhance the performance of thermoelectric cooling systems. Both thermo element modeling and thermoelectric cooler (TEC) modeling have been reported. includes one-dimensional and three-dimensional versions of the classic simple energy equilibrium model numerical compact model, and models. Thermoelectric cooling applications have now been completed. Household refrigeration, electronic cooling, scientific application, and automobiles were all examined. With summaries for commercially available thermoelectric modules and thermoelectric refrigerators, *air conditioning and seat temperature control are covered. This research is anticipated to be helpful to Design, modeling, and analysis of thermoelectric cooling systems.*

KEYWORDS: *Thermoelectric cooling Thermoelectric Material Modeling Application.*

1. INTRODUCTION

Thermoelectric cooling, also known as cooling technology using thermoelectric coolers (TECs), offers many benefits, including high dependability, the absence of mechanical moving parts, small size and weight, and the absence of a working fluid. It also has the benefit of being able to be powered by direct current (DC) electric sources such as photovoltaic (PV) cells, fuel cells, and automobile DC electric sources. The major drawbacks of thermoelectric cooling are its high cost and poor energy efficiency, which has limited its use to situations where energy availability, system dependability, and a quiet operating environment are more essential than system cost and energy efficiency. Though the thermoelectric cooling effect was discovered in the nineteenth century, it was not widely used until the 1950s, when the fundamental physics of thermoelectric materials was well established [1].

A thermoelectric module is a solid-state energy converter made up of a group of thermocouples connected electrically and thermally in series. When a voltage in the proper direction is supplied via the linked junction, a thermocouple is made up of two distinct semiconducting thermo elements that produce a thermoelectric cooling effect (PeltiereSeebeck effect). In order to improve heat transmission and system performance, thermoelectric modules often include two heat sinks connected to their hot and cold sides. Thermoelectric cooling is progressively becoming more integrated into people's everyday lives, in addition to its military, aeronautical, industrial, and scientific uses [2]. Thermoelectric cooling equipment, such as PC processors, portable food and beverage storage, temperature-control vehicle seats, and even thermoelectric air conditioners, are extensively utilized for electrical cooling. The scientific community has invested a significant amount of time and attention into thermoelectric cooling research. Modeling and analysis of thermoelectric modules, solar-based thermoelectric technologies, cooling, heating, producing electricity, and waste heat recovery are all excellent review articles on thermoelectric technology and uses. In 2004, Riffat and Ma published a review on COP improvement in thermoelectric cooling systems. Recent research suggests two possible paths to significant progress in thermoelectric cooling: 1) improving the intrinsic efficiencies of thermoelectric materials, and 2) improving the thermal design and optimization of thermoelectric cooling systems using currently available thermoelectric modules. The emphasis of this study is on the evolution of thermoelectric cooling over the last decade, with a focus on advancements in materials, modeling and optimization methods, and applications.

A good thermoelectric material should have a high Seebeck coefficient, high electrical conductivity (or high power factor), and low thermal conductivity, as indicated by themain criteria of merit ZT 14 a2 sT/k. However, since these three factors are linked, researchers must use the WiedemanneFranz rule .a Seebeck coefficient, V K1 b ratio of Thomson heat to thermal conduction DT temperature differential between hot and cool sides, K emissivity, ZT dimensionless figure-of-merit Greek symbol electrical resistivity, U m r density, kg m3 g combination heat transfer coefficient of radiation and convection in Eq. (8) W m2 K1 gratio of Joule heating to thermal conduction) s electrical conductivity, S m1 sb 5.67 108 W m2 K4 s

Thomson coefficient, V K1 f electric scalar potential, StefaneBoltzman constant n n-type thermo element p constant pressure p p-type thermo element N ambient c cold side con conduction e thermo element h hot side m mean/average max maximum n n-type thermo element p constant pressure p p-type thermo element N ambient Temperature value independent of the overbeat obtain the best ZT, adjust these conflicting settings. To some degree, the ability to decrease material thermal conductivity, particularly lattice thermal conductivity, is essential for thermoelectric material performance optimization. Bulk alloy materials such as Bi2Te3, PbTe, SiGe, nd CoSb3 are common thermoelectric materials, with Bi2Te3 being the most prevalent. A ZT value of less than one is typically processed. Increases in ZT were moderate from the 1960s through the 1990s. Theoretical predictions after the mid-1990s indicated that nanostructure engineering might significantly improve thermoelectric material efficiency.

Meanwhile, traditional bulk materials incorporating nanostructured constituents have been investigated and shown to reach excellent efficiency, thanks to current synthesis and characterisation methods. As a result, improvements in the ZT factor have come from two main methods in recent years: 1) bulk samples including nanoscale constituents, and 2) nanoscale materials themselves. Researchers have discovered that excellent thermoelectric materials are the so-called "phonon-glass electron-crystal (PGEC)" materials [3], in which high mobility electrons are free to transfer charge and heat but the phonons are disturbed at the atomic scale from transporting heat. Skutterudites, clathrates, and half-Heusler alloys are some of the most common bulk thermoelectric materials, and they're all made via doping.Low-dimensional materials, such as 2D quantum wells, 1D quantum wires, and 0D quantum dots, process the electron charge carriers' quantum confinement effect, potentially increasing the Seebeck coefficient and therefore the power factor.Furthermore, the many surfaces created will scatter phonons more efficiently than electrons, resulting in a reduction in thermal conductivity that is greater than the reduction in electrical conductivity . recently shown a liquid-like behavior of copper ions surrounding a crystalline sub lattice of Se in Cu2xSe, resulting in a lattice thermal conductivity that is inherently extremely low, allowing for high ZT in this basic semiconductor. The findings point to a new approach and direction for high-efficiency “phononliquid electron-crystal” thermoelectric materials, which involves investigating systems in which a crystalline sub lattice for electronic conduction is surrounded by liquid-like ions. ZT values of about 1.0 are presently seen in the finest commercial thermoelectric materials. According to Harman in 2005, the maximum ZT value in research is about 3. Table 1 shows that other best-reported thermoelectric materials have figure-of-merit values of 1.2e2.2 at temperatures between 600 and 800 K. Thermoelectric coolers with a ZT value of 1.0 are predicted to function at just 10% of Carnot efficiency. A device with a ZT value of 4 may achieve 30 percent Carnot efficiency (equivalent to home refrigeration). However, raising ZT to 4 has proven to be a difficult task Bell has said that if the average ZT approaches 2, thermoelectric material-based residential and commercial solid-state heating, ventilation, and aircooling systems would be feasible [4].

2. DISCUSSION:

2.1. APPLICATION:

Three-dimensional modeling captures temperature distribution along and across the thermo element, resulting in higher performance than one-dimensional modeling. More computing work, on the other hand, is needed. Simply extending to three dimensions yields the governing equation for three-dimensional modeling. Thermoelectric material characteristics are sometimes regarded as constants to minimize computational costs. constructed a transient three-dimensional constant property model for a single thermocouple (two thermo elements) with mesh grid 3146, and found that the numerical and experimental results were in close agreement. A generic three-dimensional temperature-dependent property thermo element model with temperature and electric potential field coupling was described by Temperature-dependent properties and heat losses to the environment have substantial impacts on cooling capacity and COP, according to the findings. Unstable nonlinear second-order partial differential equations must typically be solved in one-dimensional and three-dimensional models. Numerical techniques are widely used in research, and numerical analysis software tools including MATHEMATICA, COMSOL Metaphysics, and ANSYS have been used. Many studies have utilized and verified the simplified energy equilibrium model, which has a similar structure to, where a, R, and K are the Seebeck coefficient, electrical resistance, and thermal conductance of the thermoelectric module, respectively. Module cooling power output and COP may be estimated using this model after these temperature independent module characteristics are known. The producer of commercially accessible thermoelectric modules, on the other hand, may not disclose material specifications[5] for the thermoelectric module. Palacios et al. [50] developed an analytical method for extracting internal parameters from performance curves. Chen and Snyder also derived the following equations to get the thermo element Seebeck coefficient age, electrical resistivity r, and thermal conductivity k using operating parameters Qmax, DTmax, and IMAX. age 14 QmaxTh DTmax NT2 h Imax Thermoelectric modules a, R, and K are then computed using Esq. from the material's electrical resistivity and thermal conductivity. The second method to get thermoelectric module cooling capacity (Qc) and electrical power input (P) is to utilize thermo element cooling capacity (qc) and thermo element electrical power input and multiply with thermo element numbers. Because a thermoelectric cooler comprises of thermo elements, it is acceptable to numerically model each thermo element in a thermoelectric cooler for thermoelectric cooler modeling. Chen et al. published a three-dimensional numerical analysis for a small thermoelectric cooler with 8, 20, and 40 thermocouple pairs. Thermal and electrical conductivity were maintained constant whereas the Seebeck coefficient was regarded as temperature dependent. When thermocouples within a module are scaled down, the cooling power and COP of the module increase significantly, according to the forecast. However, since the mesh grids for simulating each p-type and n-type thermo element must be very tiny, this method is both computationally costly and complex. Additionally, thermal and electrical contact resistance will complicate the modeling procedure modeling the thermoelectric cooler as a single bulk is considerably simpler than modeling each thermo element separately [6].

2.2. ADVANTAGE:

Electronic equipment, such as PC CPUs, produce a significant quantity of heat during operation, posing a significant thermal management issue since electronic devices must operate at a consistent temperature. For reliable operation, the maximum electronic device junction temperature should be kept below 85 C in most instances [42,77]. A high-performance electronic package's maximal heat flow may be about 200 W, and it's still rising. Passive cooling technologies, such as the micro-channel sink, that use air or water as the working fluid cannot completely satisfy the heat dissipation requirement, and active cooling techniques must be used. Conventional bulk cooling systems are excessively large due to the restricted installation area in electronic packaging. Because of their compact size, excellent dependability, and lack of noise, thermoelectric coolers coupled with air or liquid cooling methods on the hot side have a lot of promise. Phelan et al. examined existing and prospective tiny refrigeration cooling methods for high-power microelectronics, concluding that only thermoelectric coolers are commercially accessible in small sizes at this time. The thermal resistance between the cooler and the ambient air has a considerably greater impact on the thermoelectric cooler's performance than the thermal resistance between the chip and the cooler. Naphon and Wiriyasart tested liquid cooling in a mini-rectangular fin heat sink with and without a thermoelectric cooler for the CPU and discovered that the thermoelectric cooler had a significant impact. Thermoelectric coolers work better at lower thermal loads, such as 20 W, when coupled with an air cooling device for the hot side. Instead, a thermoelectric air cooling device may not be as effective as an air cooling heat sink for a high thermal load. Thermoelectric coolers, when used in conjunction with a water cooling system in electronic equipment, often operate better at a greater thermal load, such as 57 W. Chein and Huang investigated the use of thermoelectric coolers in electronic cooling for both air and liquid cooling methods in a theoretical study. In their research, the greatest cooling capacity was found to be 207 W. Nan fluids have showed promise for liquid cooling since they are a superior alternative to water and can improve cooling power output. R134a is presently used as a refrigerant in the majority of vehicle air conditioning systems. R-134a does not deplete the ozone layer, however it does contribute to global warming. The refrigerant leakage issue in cars is far worse than in stationary air conditioners. Compact size, no moving parts or working fluid, compatibility with vehicle electrical system voltage, and ease of switching between heating and cooling modes are all benefits of thermoelectric coolers. As a result, thermoelectric coolers seem to be particularly well suited to automobile applications. Yang and Stabler provided a review of thermoelectric materials in automotive applications. A new thermoelectric air-conditioner for a truck cab was proposed by Luo et al. The cooling system's COP was found to be 0.4e0.8 at temperatures ranging from 46 to 30 degrees Celsius. They also discovered that by improving system design and manufacturing technique, cooling performance may be enhanced much further. Researchers used a thermoelectric device to regulate the temperature of the vehicle seat in addition to the air conditioning system. Hyeung-Sik et al. Created a temperature-controlled carseat system that uses a thermoelectric device to cool or heat the vehicle. Experiments were used to verify the device's performance, which was built using a one-chip microcontroller. The Climate Control Seat (CCS), created by Gentherm (formerly Amerigon), is a thermoelectric device that provides thermal comfort to automobile and truck drivers. The automobile sector has already created a significant cooling device market for thermoelectric cooling devices, which will continue to grow in the next decades [7].

2.3. WORKING:

Using fine mesh and coarse mesh in various areas, these so-called compact models can solve the multistage problem. For thermoelectric coolers, Chen and Snyder devised a compact modeling method. It is shown that a significant amount of grid has been reduced and computational speed is about 100 times faster, with results almost as accurate as the physical model (numerical study includes all coupled thermoelectric as well as components that provide losses and other parasitic effects).Techniques for enhancing the cooling system's efficiency When designing a thermoelectric cooling system, one must consider both the system cooling power output and cooling COP, as well as the performance of the thermoelectric modules and the heat sink design.

As a result, designing a thermoelectric cooling system involves a trade-off between cooling capacity and COP. There are three ways for improving the performance of thermoelectric cooling systems. The first is through the design and optimization of thermoelectric modules, such as thermo element length, number of thermocouples, thermo element length to cross-sectional area ratio slenderness ratio, and thermo element with non-constant cross section area. The second approach relates to cooling system thermal design and optimization, which includes investigations of heat sink geometry, allocation of the heat transfer area and heat transfer coefficients of hot and cold side heat sinks, thermal and electrical contact resistances and interface layer analysis, and more effective heat sinks with the operating state of the thermoelectric cooling system heat sink coolant, and coolant mass flow.

A number of system optimization techniques have been used. Optimized thermo element physical parameters (length, cross-sectional area, and number of thermo elements) using evolutionary algorithms. Limekiln and Yaakov proposed a graphical method to the design of thermoelectric cooling systems that was user-friendly and intuitive. The temperature entropy analysis was given by Chakra borty et al. to show the cooling cycle of a thermo element. Instead of the widely used iterative method, Zhang proposed a generic simple approach for optimizing thermoelectric coolers. Several writers have used the dimensional less analysis approach, which has the benefit of lowering optimal design parameters. The dimensionless entropy production number based on thermal conductance was developed by Wang et al. to assess the external irreversibility in the thermoelectric cooling system, which takes into account both the first and second laws of thermodynamics. Lee created new dimensionless groups to express key thermoelectric device characteristics including the thermal conduction ratio, convection conduction ratio, and load resistance ratio. Summaries may be inferred as follows based on the research papers mentioned in this section: Many thermoelectric cooling applications, such as electronic device cooling and air conditioning, may be satisfied by the simplified energy equilibrium model for thermoelectric cooler. To better capture the system performance when thermoelectric modules are used with time-varying temperature distribution and cooling power output, 1D or 3D transient modeling is required [8].

For simplicity, thermoelectric thermo physical characteristics are often considered as independent of temperature in 3D models. Although the See beck coefficient, electrical conductivity, and thermal conductivity of p-type and n-type thermo elements vary in one thermoelectric module, these differences are insignificant in numerical studies. As a result, in the simulation, only one set of See beck coefficient, electrical, and thermal conductivity will be utilized. It’s difficult and time-consuming to model temperature change in all thermo element to capture module performance. When modeling a system with heat sinks on both the hot and cold sides, an energy equilibrium model or compact model may be used to simplify the numerical research process. The temperature-dependent See beck coefficient is associated with the Thomson effect. The positive Thomson coefficient increases thermoelectric cooling performance by 57%, while the negative Thomson coefficient decreases cooling performance. The Thomson effect, on the other hand, is typically modest and insignificant in commercially available thermoelectric coolers. Snyder et al. proposed the ‘Thomson cooler,' predicting that with comparable ZT, a greater hot/cold side temperature differential than the conventional Pettier cooler could be obtained. Both COP and cooling capacity are affected by thermo element length, and this effect becomes stronger as the length of the thermo element decreases [9].

3. CONCLUSION

This paper examines the evolution of thermoelectric cooling over the last decade in terms of material advancements, modeling methods, and applications. Nanotechnology allows for a substantial improvement in ZT factor thanks to advancements in thermoelectric materials. Bulk samples comprising nanoscale constituents and low-dimensional materials are the two main methods. New thermoelectric materials with higher ZT factor values may lead to breakthroughs in a variety of thermoelectric device applications. In this study, several thermoelectric modeling methods have been summarized. Implicated models save time and effort while sacrificing some modeling accuracy. Model selection is heavily influenced by the modeling objective. Thermoelectric cooling device performance may be improved in three ways: 1) via thermoelectric module design and optimization, 2) through cooling system thermal design and optimization, and 3) by improving the operating state of the thermoelectric cooling system. Domestic refrigeration, electronic cooling, scientific uses, and automotive applications are among the most common thermoelectric cooling applications. Thermoelectric home air conditioning systems are being developed by researchers in the hopes of competing with their vapor-compression equivalents. The performance of thermoelectric and conventional vapor compression air conditioners was compared by Riffat and Quid. The real COPs of vapor compression and thermoelectric air conditioners are in the range of 2.6e3.0 and 0.38e0.45, respectively, according to the findings.

Thermoelectric air conditioners, on the other hand, offer a number of advantages over their vapor-compression equivalents. They may, for example, be constructed into a planar construction that can be readily handled on walls and provide a quiet operating environment, making them ideal for home usage. An experimental and computational analysis of a thermoelectric air-cooling and air-heating system was reported by Cosnier et al. [47. By providing an electrical intensity of 4 A and maintaining a 5 C temperature differential between the hot and cold sides, they were able to achieve a cooling power of 50 W per module with a COP of 1.5 to 2. Cheng et al. [104] developed a solar-powered thermoelectric generator. The temperature differential between the interior and exterior of the refrigerators is measured in degrees Fahrenheit (DT). Applied Thermal Engineering 66 (D. Zhao, G. Tan) (2014) 15e24. For green building applications, a 21 cooling module with a waste heat regeneration unit is available. The technology is capable of producing a temperature differential of 16.2 degrees Celsius between the ambient environment and the model home, according to the results. The thermoelectric device cooling COP, on the other hand, is modest, ranging from 0.2 to 1.2 in this research [10]. Thermoelectric cooling systems for small-scale space conditioning applications in buildings were explored. Under the input electrical current of 4.8 A, a thermoelectric cooling unit was constructed and produced up to 220 W cooling capacity with a maximum COP of 0.46 for each modul. Thermoelectric cooling applications, on the other hand, are not restricted to these fields. When high-quality thermoelectric materials are produced and thermoelectric cooling devices approach greater performance efficiency, more applications emerge.

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