IJRAR.ORG E-ISSN: 2348-1269, P-ISSN: 2349-5138

INTERNATIONAL JOURNAL OF RESEARCH AND ANALYTICAL REVIEWS (IJRAR) | IJRAR.ORG

An International Open Access, Peer-reviewed, Refereed Journal

Enhancing Thermoelectric Performance through Water-Based Thermal Management with Aluminum Oxide Additives

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Abstract: Thermoelectric energy conversion holds great promise for sustainable energy technologies, enabling the direct conversion of waste heat into electricity. Thermoelectric generators (TEGs) are at the forefront of this field, yet their widespread adoption faces challenges such as inefficient heat dissipation and limited thermoelectric performance. In recent years, water-based cooling techniques have emerged as an effective approach to enhance heat dissipation in TEGs. Concurrently, aluminium oxide (Al2O3) nanoparticles have garnered attention for their potential to improve the thermal properties of cooling fluids. In this study, we investigate the integration of water-based thermal management with Al2O3 additives for enhancing thermoelectric performance. The objectives encompass evaluating TEG performance challenges, assessing the suitability of Al2O3 as additives, optimizing dispersion methods, conducting experimental studies, and developing theoretical models. Our findings demonstrate that Al2O3 additives significantly enhance heat transfer capabilities, leading to improved thermoelectric efficiency, electrical conductivity, and overall, TEG performance. The proposed approach holds promising implications for waste heat recovery, automotive exhaust systems, and portable energy harvesting devices, contributing to more efficient and sustainable energy conversion technologies.

***Index Terms* – TEG, Water, Aluminum Oxide, Thermal management.**

I. INTRODUCTION

Energy is crucial for enabling society, economies, and businesses to flourish. However, utilising excessive amounts of conventional energy like petrol and diesel can be bad for the environment. People are therefore seeking for novel ways to produce energy, such as converting heat into power. This might help us meet our energy needs while posing fewer risks. However, using this novel technique known as thermoelectric conversion, we may convert heat something that is constantly present around us - into electricity. It's like figuring out a more environmentally friendly and effective way to produce the energy we require to light up our houses, power our gadgets, and maintain the functioning of our planet. We can strive towards a greener, more sustainable future as we investigate these cutting-edge power generation methods.

The Seebeck effect, named after Thomas Johann Seebeck who first discovered thermoelectricity in 1821, involves observing that when two dissimilar metals are coupled and one end is heated while the opposite end is cooled, a temperature difference occurs between the junctions. Thermoelectric devices leverage this effect and are useful for converting waste heat into useful energy [1]. The application of thermoelectric power generation has mainly been in domains where reliability and quiet operation are crucial. While not widely recognized by the public, this method is utilized for deep-space probes in radioisotope-heated generators [2-5]. This technology has been used in generators powered by fossil fuels to meet the power needs of the military in the field [6].

Ongoing discussions are exploring the potential of using thermoelectric technology for ocean thermal energy conversion (OTEC). Thermoelectric generators (TEGs) have versatile applications, including measuring heat flux from a heater as cryogenic meters and detecting water condensation through a newly developed sensor using a Peltier element. Various sensors based on the Seebeck effect are designed to measure different physical quantities and are divided into fluid flow sensors and infrared sensors. Additionally, power can be harnessed from solar energy by using the temperature of a heated fluid through a passive thermosiphon system. Integrating a heat pipe and solar water heater can result in highly reliable and cost-effective TEG systems. Thermionic generators show promise in producing electromotive force (emf) at high temperatures with high efficiency. Besides, there are potential applications of thermoelectric generation in geothermal harvesting, solar-powered cold storage, roof solar collection, biomass-fired stoves, and more [7]. To increase energy efficiency and cut emissions, the car industry is rapidly investigating waste heat recovery systems using thermoelectric generators (TEGs) and heat pipes. Heat is efficiently transferred from high-temperature vehicle components using heat pipes, as opposed to TEGs, semiconductor devices that turn heat directly into electricity. With case studies illustrating their potential, researchers concentrate on optimising TEG and heat pipe materials, designs, and performance. Improved waste heat recovery systems can promise a more sustainable vehicle future while overcoming obstacles like cost and integration [8].

Based on this literature review, it is evident that thermoelectric generators hold substantial promise for diverse future applications. Extensive research has been conducted to identify materials capable of withstanding a wide range of temperatures, making them suitable for the creation of thermoelectric generators. Additionally, theoretical investigations have focused on optimizing the design of the heat exchanger within these generators, proposing mathematical models under ideal conditions. The proposed approach integrates a nonideal plate-type heat exchanger and considers novel factors crucial for an efficient thermoelectric generation system. Four main factors were analysed: the amount and quality of heat, composition of the heat stream in liquid phase, and convective losses. Understanding these factors is vital in designing effective test setups, leading to necessary modifications in the proposed system.

This study uses aluminium oxide additives in a water-based thermal management framework to optimise a thermoelectric system for effective heat-to-electricity conversion. The ideal concentration and dispersion of aluminium oxide in the water combination to improve thermal conductivity, defining the system's long-term stability and durability with these additions, and assessing potential environmental and safety implications are among the key research gaps. Research gaps have also been highlighted in the areas of scalability, cost-effectiveness, integration with renewable energy sources, alternate thermoelectric material exploration, and performance evaluation of the system under various environmental circumstances. In order to ensure the effectiveness, sustainability, and further integration of the planned thermoelectric system into the energy environment, it is imperative to close these gaps in knowledge.

This research investigates novel techniques to increase the effectiveness of thermoelectric materials. The study includes a thorough examination of thermoelectric characteristics, prospective advantages and difficulties of water-based thermal management, and the effect of adding aluminium oxide additions on thermoelectric performance. The suggested water-based thermal management system with aluminium oxide additions will be used in experimental work to characterise and optimise thermoelectric and thermal properties. The research findings are meant to promote thermoelectric technology for better energy sustainability and possible uses in waste heat recovery and renewable energy systems.

Desiging of the TEG system:

In the system under investigation, the TEG is positioned between two heat-exchanging ducts responsible for transferring heat. This exchange is made possible through the forced circulation of a fluid composed of a mix of water and aluminium oxide, flowing within a hydraulic circuit. The ducts facilitate efficient heat transfer essential for converting heat. Tracking the fluid's inlet and outlet temperatures in these ducts serves as a measure of the heat received from the source and released to the surroundings. The material utilized possesses a characteristic of heat retention during temperature elevation and subsequent release during temperature decline. The heated fluid in circulation acts as the heat carrier and doubles as a heat reservoir, akin to a heat battery, capable of releasing heat as needed.

Certainly, the circulation of the specialized fluid, enriched with aluminium oxide, essentially acts as the lifeblood of the thermoelectric generator system. This engineered fluid efficiently shuttles heat, embodying a pivotal role in the thermoelectric conversion process. The strategic placement of the TEG module within this flow path allows it to harness the temperature differences in the circulating fluid, consequently generating electricity.

Furthermore, the hydraulic circuit governing the fluid's movement offers a controlled and optimized flow, enabling seamless thermal exchange and enhancing the overall efficiency of the energy conversion. The fluid, owing to its unique composition and additives, serves not only as a medium for thermal exchange but also as a reservoir for heat, enabling a dynamic and responsive system capable of releasing stored heat when demanded.

This methodology capitalizes on the fundamental principle of sensible heat, capturing the temperature fluctuation of the specialized fluid as it is supplied and subsequently expelled. By effectively utilizing this principle, the thermoelectric generation system stands as a testament to harnessing temperature differentials to produce sustainable and environmentally conscious electrical power.

Experimental setup and procedures:

The investigation involved the utilization of four TEG modules placed between heated and cooled ducts. The TEG element exhibited an internal resistance of about 4 Ω. The conduit through which the fluid, composed of 20 liters of water mixed with 20 grams of aluminium oxide, flowed in the heated and cooled ducts, had a circular cross-section with a diameter of 0.5 inches. The TEG modules were constructed from bismuth telluride. The ducts made of aluminium had a rectangular cross-section measuring 170 mm × 90 mm. The fluid flow in the heated and cooled pipes exhibited a laminar characteristic. Initially, an experiment was conducted in a thermoelectric system that was assembled simply, testing counterflow configurations. The heat source was simulated by a heater. The experimental setup was schematically illustrated in Fig. 2.

To conduct the experiments, a plate-type heat exchanger was utilized (depicted in Fig. 1), comprising two rectangular ducts facilitating heat exchange through the partition. The TEG module was placed between the two ducts: heated and cooled. The fluid, a mixture of 20 litres of water and 20 grams of aluminium oxide, was continually heated by the heater and circulated within the heated fluid circuit. On the other hand, the cooled fluid maintained a continuous flow within the respective circuit, effectively representing a real operational scenario. The temperature was meticulously monitored using six digital thermometers with an accuracy of 0.5°C along the flow path, considering the average as the temperature for the heated and cooled ducts. The flow rates of the heated and cooled fluids were gauged using a rotameter with a functional range from 0 lpm to 12 lpm. Measurements of the inlet and outlet temperatures were taken at 1-minute intervals. The overall measurement uncertainty for the conversion efficiency in this experiment stood at 7%. Likewise, the uncertainty in measuring the supplied heat was determined to be 5%.

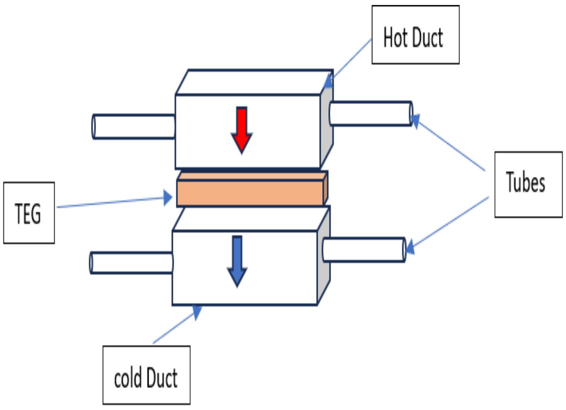

Fig. 1. Schematic diagram of thermoelectric generation system.

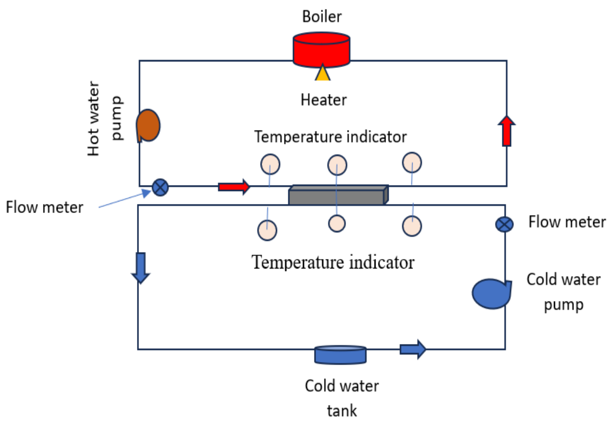

Fig. 2. Schematic diagram of circulation-based thermoelectric generation system.

Result and Discussion:

Effect of Quality of Heat on Power Generation

Dependence of Power on Temperature Difference

The difference in temperature between the hot and cold ducts in the defined system is relevant. The mean of the temperatures recorded by the six temperature gauges placed along the flow path were used to represent the temperatures of the hot and cold ducts.

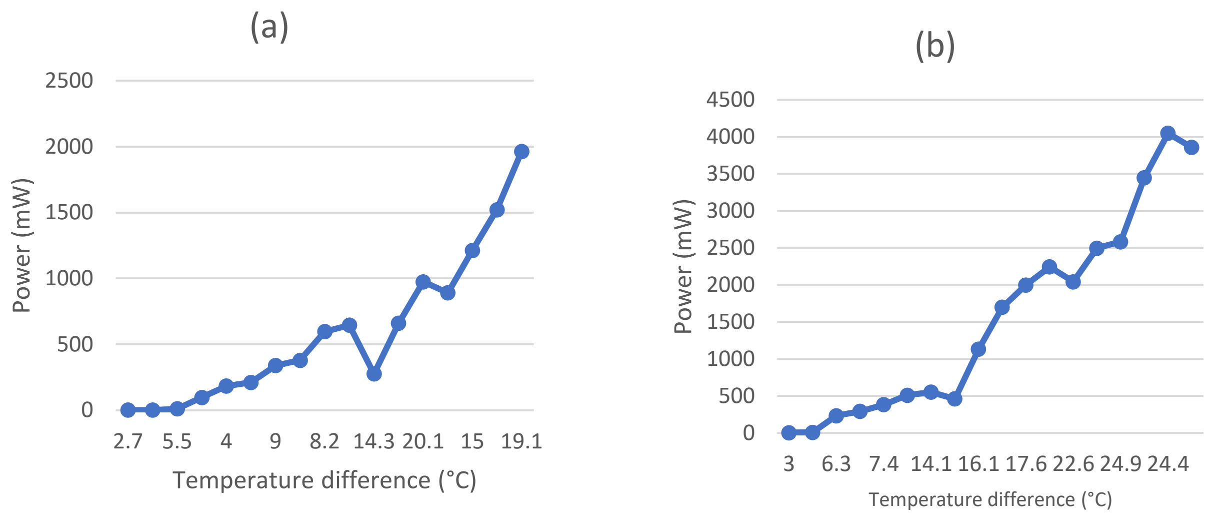

Fig. 3. Variation of power with temperature difference when working fluid is (a) water (b) water mixed with nano particle of aluminium oxide.

Figure 3a shows the variation for counter flow configuration with water as working fluid. In this case the power output increases as the temperature difference (ΔT) increases. At lower temperature differences (around 0.9°C to 5.5°C), the power output is relatively low, ranging from 0 mW to 200 mW. This suggests that the efficiency of generating electricity from a smaller ΔT is limited. In the middle range of temperature differences (around 8.2°C to 15.8°C), the power output substantially increases, reaching values between 1500 mW and 2500 mW. This demonstrates a more efficient energy conversion process due to the larger ΔT. At higher temperature differences (above 15.8°C), the power output continues to increase, peaking at approximately 2500 mW. However, the rate of power increase begins to plateau, indicating that, beyond a certain ΔT, the system's efficiency might not significantly improve with further temperature difference.

Figure 3b shows the variation for counter flow configuration with water mixed with aluminium oxide as working fluid. At lower temperature differences (around 3°C to 7.4°C), the power output is relatively low, ranging from 0 mW to 400 mW. This suggests limited power generation efficiency when the temperature difference is smaller. In the middle range of temperature differences (around 15°C to 22.4°C), the power output substantially increases, reaching values between 2500 mW and 4500 mW, indicating more efficient energy conversion due to the larger ΔT. At higher temperature differences (above 22.4°C), the power output continues to rise, reaching peak values at around 4500 mW. However, just like in the previous dataset, there seems to be a diminishing return on power output as the ΔT increases beyond a certain point.

Conclusion:

The comparative analysis between thermoelectric power generation with water as the working fluid and water mixed with aluminum oxide nanoparticles reveals crucial trends in relation to temperature difference and power output. In the case of thermoelectric power generation with water as the working fluid, the anticipated correlation between power output and temperature difference, in line with the Seebeck effect, is evident. Lower temperature differences result in relatively modest power output, emphasizing the presence of an optimal operating range for maximizing efficiency. Meanwhile, in the thermoelectric power generation scenario utilizing water mixed with aluminum oxide nanoparticles, a similar trend emerges, but consistently higher power outputs are observed at equivalent temperature differences, indicating an enhanced thermoelectric system efficiency. These findings underscore the paramount importance of optimizing temperature differentials for efficient power generation and carry substantial implications for the design and operation of thermoelectric systems, notably in applications like waste heat recovery and the integration of renewable energy sources.

Acknowledgment

The authors sincerely acknowledge BIT Sindri for the development of the experimental setup. We also acknowledge Prof. N.P. Choudhry of the Mechanical Engineering Department, BIT Sindri, India for providing valuable suggestions and help. This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors.

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