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EXPLOITING UNDERUTILISEDWASTE HEAT TO GENERATE ENVIRONMENTAL FRIENDLY ENERGY

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ABSTRACT

The growing concern over the continued usage of fossil fuels for electrical energy generation and hence the need to significantly reduce reliance on this non-renewable energy source as well as the requirement for long-lived power supplies have necessitated the pragmatic shift towards the realization of cleaner, safer, and renewable energy sources.The increasing interest in space exploration, satellite activities, structural health monitoring and terrestrial monitoring in harsh and inaccessible environments place a high demand for energy sources for autonomous systems. The existing battery technologies that can be utilized for autonomous systems are plagued by short-life, low energy storage density, associated unwanted maintenance burdens of recharging or replacement and disposal of unwanted batteries which poses a threat to the environment. Autonomous energy sources from waste heat for home appliances and industrial machineries will also mitigate the effect of global warming which threatens the environment as a result of fossil fuel energy based sources that release undesirable carbon-monoxide into the atmosphere. Thermoelectric energy generation, based on Seebeck effect, an innovative approach to convert heat energy into usable forms can significantly contribute towards sustainable energy development and meet the growing need for power in small scale applications due to its relative advantages over other sources of energy generation. This paper presents an insight into various ways by which underutilize waste heat can be exploited to meet the growing energy demand. While there is growing concern for generation of 'clean' energy, and it is a relief that there is a large amount of underutilise or waste heat capable of generating 'clean' energy.

KEYWORDS: Autonomous Systems, Energy, Fossilfuels, Seebeck Effect, Thermoelectric

INTRODUCTION

The increasing interest in space exploration, satellite activities, terrestrial monitoring in remote areas and hermetic environments place a high demand for energy sources for autonomous systems. Availability of autonomous energy sources for home appliances and industrial machineries will also mitigate the effect of global warming which threatens the environment as a result of fossil fuel energy based sources that release undesirable carbon-monoxide into the atmosphere.

The dependent of human being on energy is synonymous to human existence since energy is required for survival especially during extreme weather conditions; also access to energy is crucial for development in technological. Advancement in manufacturing technology in the past 20 years has resulted in the development of various types of micro-scale devices in the range of millimeter to nanometer. However, it has been challenging to make the same progress in developing miniaturized or micro power source [1]. The conventional batteries still being used for most of the micro-scale and nano-scale devices bring about bulky systems and frequent recharging or replacement of batteries in addition to low energy density and limited life span [2]. A critical requirement for the success of autonomous systems in applications such as environmental monitoring and civil infrastructure health monitoring, is the realization of miniaturized power sources with long life span, especially for sensor networks in harsh and inaccessible environments where battery replacement would be expensive or practically impossible.

An autonomous system is designed to operate or function as long as possible in known or unknown environments providing, elaborating and storing information without being connected to a power grid. The system could operate in external natural or industrial environments. Autonomous systems such as wireless sensor networks, actuators, and ambient intelligence devices have the ability to operate with less than hundreds of micro-watts (μW) of power within less than some cubic centimetre [3].Energy sources on a macro scale for autonomous operations are batteries, solar panels, fuel cells and radioisotope generators. These power sources have their relative strengths and weaknesses.

Solar panels, especially the modern ones have the capacity to provide abundant power however solar panels have their associated drawbacks some which are: very large and fragile constructions that are vulnerable to damage from external factors that include solar flares and meteorites or even just mechanical failures, relatively expensive to build, they need to always be pointed at the sun, which means they are not useful when blocked by planets or other objects.

Power generated becomes inadequate the farther the satellite is from the sun since the intensity of light from the sun decreases with the square of the distance between the satellite and sun. Fuel cells have a longer lifespan compared to batteries and do not require recharging since it can be refuelled. Theoretically, a fuel cell will produce electricity as long as fuel is being supplied constantly.

They are extremely efficient, simple to design, have virtually no emissions, and they run silently since no moving part is involved [4]. Fuel cells are already in use in the space shuttle and are quite useful in other near-Earth missions. However, despite their merits they are relatively expensive since long flights require considerable amount of fuel. They also run very hot (400–1000 F), and the waste heat is often a huge problem to manage [5].

Batteries are reliable and have a well-understood technology, however, batteries have the down side of short life span, and rechargeable batteries being utilized in remote areas need to be recharged by other source of power such as solar panels [6]. Besides the inadequacy of short life span and reliance on other power source for recharging purposes, size is also a drawback.

Thermoelectric energy generator which utilizes waste heat offers an alternative source of power generation due to the following merits: extremely reliable, simple, compact, environmentally friendly, not position-dependent, runs silently because of no moving parts [7]

THERMOELECTRIC ENERGY GENERATORS

Thermoelectric Generator (TEG) is a solid state device that converts temperature gradients directly into electricity using the Seebeck effect [8]. TEG components do not require moving parts or any kind of fluids; these attributes make TEG very versatile for stand-alone nodes of wireless sensor networks with harvesting capabilities. TEGs are reliable sources of energy and produce no noise or vibration since there are no mechanical moving parts; they have small size and light in weight [9]. TEGs run quietly, they are compact, highly reliable and environmentally friendly. Owing to the aforementioned features coupled with relatively low operating and maintenance costs, TEG have found a large range of applications, however despite the high-points of TEG, it is plagued by its relatively low heat to electricity conversion efficiency [10].A schematic diagram of a simple thermoelectric generator operating on Seebeck effect is shown in figure 1.

As a result to the temperature gradient between the heat source and the heat sink, electric power will be generated in a resistive load which is connected across the thermoelectric materials (n-type and p-type semiconductors) output terminals. The electrons in the n-type semiconductor (negative charge carriers) absorb heat from the heat source of the thermoelectric couple and transfer the heat to the heat sink while similarly, the holes in the p-type semiconductor (positive charge carriers) absorb heat from the heat source of the thermoelectric couple and transfer the heat to the heat sink. It is the movement of the heat and charge carriers that create an electrical voltage which is known as the Seebeck voltage

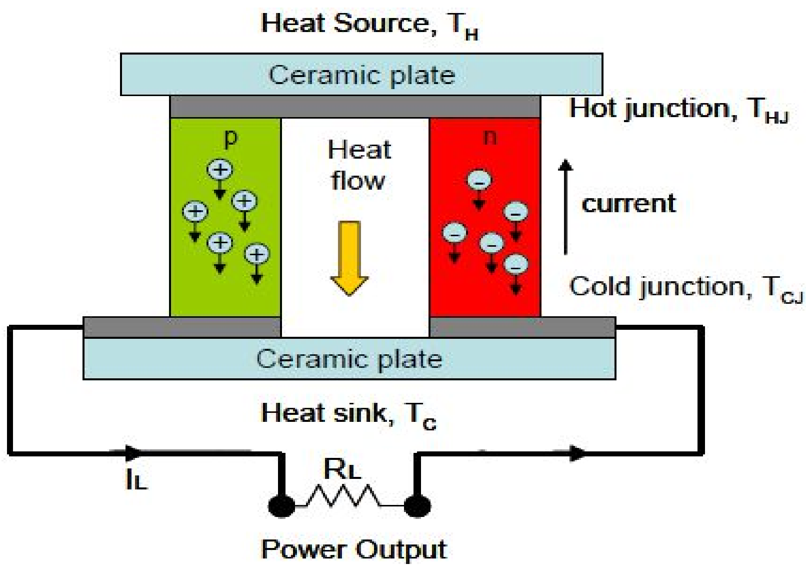

Figure 1: Schematic Diagram Showing the Basic Concept of a Simple Thermoelectric Power Generator Operating on Seebeck Effect [11]

The efficiency of a TEG can be conveniently expressed as function of the temperature over which it is operated and a 'goodness factor' which is also known as thermoelectric figure-of-merit **Z** which is expressed as [11]:

$$Z = \frac{\alpha^2}{\rho\lambda} \tag{1}$$

where α is the Seebeck coefficient, ρ is the electrical resistivity, and λ is the thermal conductivity.

The Seebeck coefficient of metals is usually between 0 and 50 μmK^1, whereas the Seebeck coefficient of semiconductors could be over 350 μmK^1 [10].

The relationship between the conversion efficiency and operating temperature difference for a range of values of the material's figure-of-merit was investigated [12] and confirmed that an increase in temperature provides a corresponding increase in conversion efficiency as shown in figure 2. Also, increase in figure-of-merit yields corresponding increase in conversion efficiency. The figure-of-merit is often expressed in its dimensionless form by multiplying *Z*byT (the average absolute temperature of the hot and cold junctions of the thermoelectric module), i.e.

$$ZT = \frac{\alpha^2 \sigma T}{\lambda} \text{ and } T = \frac{T_H + T_L}{2} \tag{2}$$

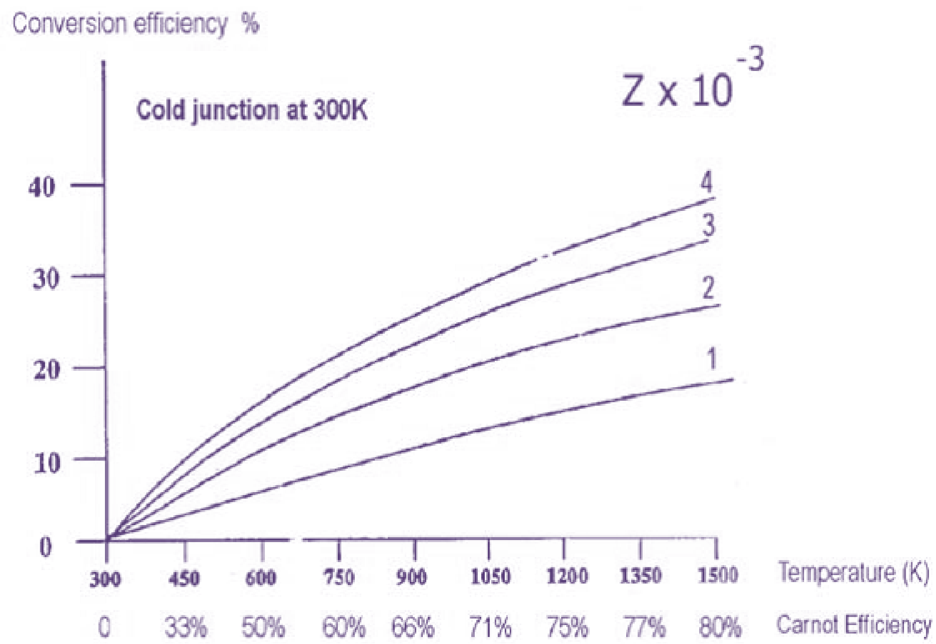

Figure 2: Efficiency as a Function of Temperature and Figure-Of-Merit [12]

The performance parameter *ZT*is very useful in Seebeck sensing devices, such as infrared thermal detectors [8].When a temperature difference exists between two thermal surfaces (hot and cold junctions of two dissimilar materials that can either be metals or semiconductors), an open circuit output voltage V_G, is generated according to the following equation:

$$V_G = N\alpha\Delta T \tag{3}$$

where, *N* is the number of thermocouples, α is the Seebeck coefficient of the TEG materials and ΔT is the temperature difference applied.

The core element of a TEG is the thermopile [13]. A thermopile which is also known as a module, is a device formed by a large number of thermocouples placed between a hot plate and a cold plate and connected thermally in parallel and electrically in series as shown in figure3.The significance of the series and parallel arrangement of the thermocouples is to enhance reliability by minimizing the effect on total power due to an open circuit or short circuit failure in a single thermocouple [15]. The most widely used thermocouples are bismuth telluride (BiTe), lead telluride (PbTe), lead tin telluride (PbSnTe), silicon germanium (SiGe) and tellurides of antimony, germanium, and silver (TAGS), however, many more other materials have been used while some are still being investigated with the hope of finding ideal thermocouples that have the capability of higher efficiency, lower mass, and more stable performance over longer operating lifetimes [16]. Another performance factor of a TEG known as the electrical power factor is defined as the electric power per unit area through which the heat flows per unit temperature gradient between the hot and cold junctions and it is expressed as:

$$\alpha^2\sigma \tag{4}$$

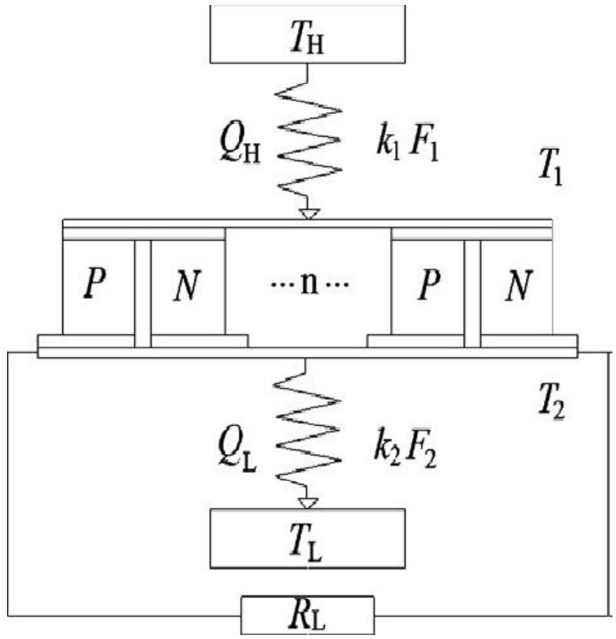

Figure 3: Schematic Diagram Showing the Basic Concept of a Simple Thermoelectric Power Generator Operating on Seebeck Effect [14]

The power output for most of the commercially available TEGs range from microwatts to multi-kilowatts [7]. Generally, TEGs exhibit low efficiency due to the relatively small dimensionless ***ZT***of currently available thermoelectric materials [11]. The efficiency of a TEG which is defined as the ratio of the energy delivered to the load to the heat energy absorbed at the hot junction [12] which can be expressed as [11]:

$$\eta = \frac{\dot{Q}_H - \dot{Q}_L}{\dot{Q}_H} = \frac{\dot{W}e}{\dot{Q}_H} \tag{5}$$

where $\dot{W}e$ is the electrical power output.

APPLICATIONS OF THERMOELECTRIC GENERATORS

Vast quantities of waste heat are discharged into the environment with great part of it at temperatures which are too low to recover using conventional electrical power generators. Waste heat are generated by kerosene lamps, exhaust pipes from automobiles, human body, cooling towers, incinerated municipal solid waste and radioactive wastes. Utilization of power generated from heat conversion is not new. Conversion of heat into energy was first discovered in 1822 by Thomas Seebeck.

The first TEG was built in the former USSR (Soviet Union) in 1942 with efficiency of approximately 2%. However the discovery of semiconductors, the increasing the demand for energy and the threat to environment by other sources of energy generation is for the use of TEGs, there is growing interest in the utilization of TEGs.

- **Electrification of Isolated Rural Homes**

Exploitation of residual heat thrown away by firewood home stoves to generate electricity was studied experimentally [17]. TEGs capable of being operated by non-technicians users for electrification of rural homes were developed. The simplicity of the prototype developed confirms the potentiality of local development of this technology. The developed TEG constitute an option of sustainable electricity generation (its operation being based on residual heat which otherwise would have been wasted) which could be developed in rural economies. The simplicity of its design and low operating cost makes the developed TEG an attractive option for low-income rural homes.

- **Self-Powered Residential Heating System**

A thermoelectric self-powered residential heating system was developed and a good applicability of thermoelectric generation to the heating equipment was demonstrated [10]. The developed TEG has a capacity of 550W. The TEG takes advantage of heat generated by a gas burner. The temperature gradient between the hot junction (heat from burners) and the cold junction (room environment) was approximately 535 ^{o}C. It was found that an increase in the temperature gradient bring out an increase in the power output. The TEG output was adequate to power all electrical components for the residential heating system, thus achieving self-powering. Excess power can be used to charge batteries or provide electricity for other electrical loads. It was asserted since for certain applications, electrical efficiency is not always the most important criterion, that the electricity generation is essentially 100% efficient since in this case for a thermoelectric self-powered heating system, the dissipated heat is recovered for . Consequently, thermoelectric self-powered heating systems could be economically competitive and provide a means of reducing greenhouse gas emissions.

- **Heat-Powered Wristwatch**

The temperature gradient (1 to 3 ^{o}C) between ambient and body temperatures was exploited by Seiko Instruments Inc. of Japan to develop and commercialize heat-powered wristwatch SEIKO THERMIC in 1998 [18]. The wristwatch utilized micro-thermoelectric device based on Bismuth Telluride materials. The user's arm serves as the hot end and dissipates heat to the back lid of the watch, while the wristwatch case which efficiently emits heat from the back lid serves as the cold end.

- **Space Exploration**

TEG has safely and reliably provided continuous power over the past three decade in regions of space where the use of solar power is not practically feasible. Heat generated from the spontaneous decay of radioactive materials into nonradioactive ones has been exploited via radioisotope thermoelectric generators (RTGs) to generate hundreds of watts of electrical power through either a static or a dynamic energy conversion system using the Seebeck effect [19]. A typical RTG consists of three basic elements: the radioisotope heat source that provides the thermal power, the converter (thermocouples) that transforms part of the thermal power into electricity, and the radiator which rejects most of the remaining amount of untransformed thermal power to space [19]. The first RTG which generated 1.8 mWe electrical powers was conceived and built in 1954 by two researchers, K.C. Jordan and J.H Birden, working at what was then known as the US Atomic Energy Commission's (AEC's) Mound Laboratory [20]. Since then RTGs have been enhancing and/or enabling challenging space missions. The United State department of energy has used RTGs for space in the last three decades. The Apollo to the Moon, Viking to Mars), Pioneer, Voyager, Ulysses, Galileo and Cassini (to outer Solar System). The National Aeronautics and Space Administration (NASA) missions that have utilized RTGs are documented by [15]. Although not properly documented, the former USSR has also utilized RTGs for her space missions.

- **Other Applications**

TEGs have also found applications in the Military [21], sensors (gas and heat) [22] and remote telecommunication, navigation and instrument protection [23].

THE PROSPECTS OF APPLICATIONS OF UNDERUTILISE WASTE HEAT

The demand for energy sources that are compact, lightweight, high energy density and long-life on a smaller scale for micro-scale devices in autonomous systems application such as sensors for toxic gas and sensors in inaccessible remote areas for environmental monitoring or in hermetic environments such as extreme heat, cold, or corrosive conditions has significantly increased in recent years. Energy scavenging means of harvesting ambient energy such as wind and solar are being exploited in order to reduce this current effect of global warming to the environment. However, the availability of these means of energy scavenging at micro level is posing a great challenge in addition to their inherent drawbacks. The conventional electrochemical batteries cannot meet the requirements due to their limited energy density and adverse effects on the environment upon disposal [24].The innovative approaches to convert available energy into usable forms on micro-scale can significantly contribute towards sustainable energy development and meet the growing need for power in small scale applications. Operation of a micro-system in which the power supply does not dominate the volume requires compact power sources with long life span and high power density.

CONCLUSIONS

Vast amounts of underutilise heat which is discharged to the environment can be exploited to generate electric power. Thermoelectric energy generation is an environmentally friendly technology which can convert this unused heat, and in particular low temperature heat, into electricity. Although TEGs are plagued by conversion of efficiency of approximately 6%, however the trade-off between conversion efficiency and power output in order to minimise cost is reflected in turn by a trade-off between the construction and running costs.

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