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THERMAL ENERGY HARVESTER FOR WIRELESS SENSOR NETWORKS

BACHELOR'S THESIS

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Declarations

Declaration of acceptance

This thesis fulfills all formal and content requirements prescribed by the Faculty of Mechanical Engineering of Budapest University of Technology and Economics, as well as it fully complies all tasks specified in the transcript. I consider this thesis as it is suitable for submission for public review and for public presentation.

Done at Budapest, 13.12.2019

Dr. Josh Davidson

Declaration of independent work

I, Nahid Salayev, the undersigned, hereby declare that the present thesis work has been prepared by myself without any unauthorized help or assistance such that only the specified sources (references, tools, etc.) were used. All parts taken from other sources word by word or after rephrasing but with identical meaning were unambiguously identified with explicit reference to the sources utilized.

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Abstract

Wireless computers and mobile devices have shrunk in size and power consumption over the previous decade. Originally, these devices had high power consumption, necessitating the use of batteries as an energy source. The decrease in size and power requirements of electronics is leading to numerous new opportunities for wireless sensor networks. Sensor networks will be able to function for considerably longer periods of time at a lower cost by harvesting energy from the environment. Thermal energy harvesting is one of the options to meet these needs. A part of the energy flow can be transformed into usable power. This is accomplished by incorporating a device that harvests thermal energy into the sensor node. The temperature difference between the top collector, used as a heat source, and the cool sink, is the requirement for thermal energy harvesting. The thermoelectric device sandwiched between them used to convert the heat flow across it into electrical power. This thesis will discuss the thermal energy harvesting for wireless sensor networks, focusing on the design of the device that can harvest the energy.

Keywords: energy harvesting, renewable energy, thermoelectric, wireless sensor networks

Contents

Chapter 1

Introduction

The majority of electric-powered portable and wireless electronic gadgets are powered by traditional electrochemical batteries. Electrochemical batteries and power storage have considerably improved in recent years. Wireless technology and other electronic components, on the other hand, are continually lowering the amount of power and energy required by various applications. If electronic component energy needs fall sufficiently, ambient energy scavenging and conversion might become a feasible source of power for many applications.

Although the amount of energy harvested is in the milliWatt [mW] range, it is sufficient for wireless sensors and other low-power applications [52]. When it comes to small-scale power generation, batteries play a very significant role [3]. However, these batteries have a short lifespan and require frequent repair, making installation more difficult and challenged in all conditions.

To satisfy the energy demands at some stage, researchers are working on and evolving a comparable new concept about energy harvesting to overcome this challenge. This concept provides an alternative power source for electronic devices in areas where traditional electricity sources are unavailable.

As a result, when this system is used in wireless sensor networks (WSNs), it eliminates network-based electricity and analog batteries, reduces costs, eliminates wires, and is more environmentally friendly. It has a massive advantage in remote environments, underwater, and other difficult-to-reach locations where traditional batteries and electricity are ineffective. Energy harvesting will facilitate environmentally friendly solutions that conserve energy and minimize CO_2 pollution, making this technology critical for the development of next-generation smart cities and a healthy community.

The scope of wireless computing components and power consumption has increased drastically. The design and construction of reliable and high-performance energy harvesting systems for WSN environments is being investigated to overcome the limitations regarding the power supply of WSNs. Wireless applications have typically had high energy demands, entailing the use of batteries as a power source. However, thanks to recent advances in wireless technology, the systems use less and less power and seem promising to perform continuously. Consequently, alternative methods, including use of waste heat and environmental sources for thermal energy processing, stimulated research in Wireless Network Systems (WSNs).

1.1 Wireless Sensor Networks

If it is simply considered what WSNs are in essence, the wide interest in them can be easily understood. WSNs consist of a large number of small sensing self-powered nodes that gather information or recognize unique events and wirelessly interact with the goal of relaying their processed data to a base station [42].

A sensor network is an infrastructure made up of sensing (measurement), computation, and communication components. A system administrator can use this to instrument, watch, and respond to occurrences and phenomena in a specific region. A WSNs overall design is depicted in Fig 1.1.

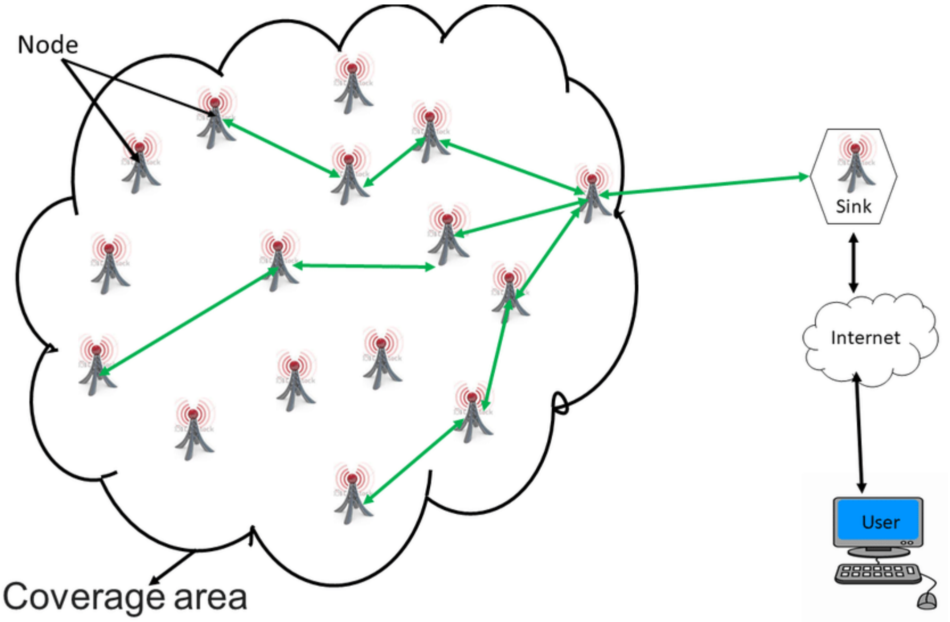


Figure 1.1: An overview on WSNs [19]

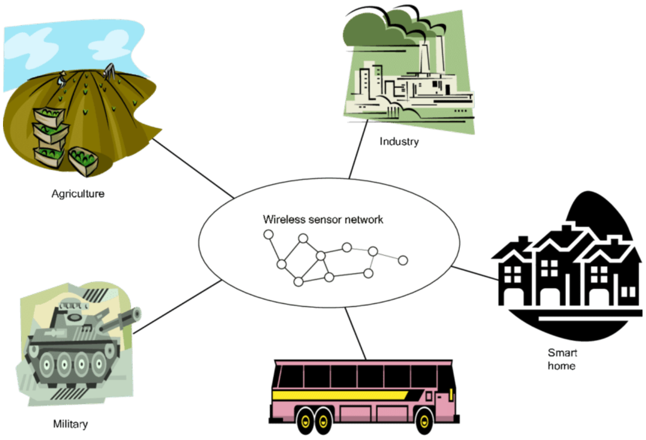
Essentially, network and networking infrastructure has been created to alleviate the complexity of wiring, as this technology has a broad range of applications and practicality in the areas of remote sensing, industrial engineering, household appliances, storage, and processing. If we compare it to the conventional wired network, WSNs offer comparable huge set of benefits, for instance, convenient network management, minimal environmental impact, low power dissipation and low cost.

If we refer to recent implementations, it is apparent, that near field wireless communications have been used extensively in past years, and the most common examples of these applications is Bluetooth, wireless local area network (WLAN), infrared, and so on. They do, however, have some drawbacks, such as complexity, high power dissipation, short distance, and a small-scale network. These technologies are undergoing substantial advancement in order to meet the need for low power dissipation and low speed. Small sensor nodes exist inside the wireless network which communicate among themselves using radio signals [15]. Sensing, transmission, and connectivity are three key components that, when combined in one tiny device, open up a world of possibilities. [49]. The sensors can be used to detect and track a wide range of physical parameters and environments, for example,

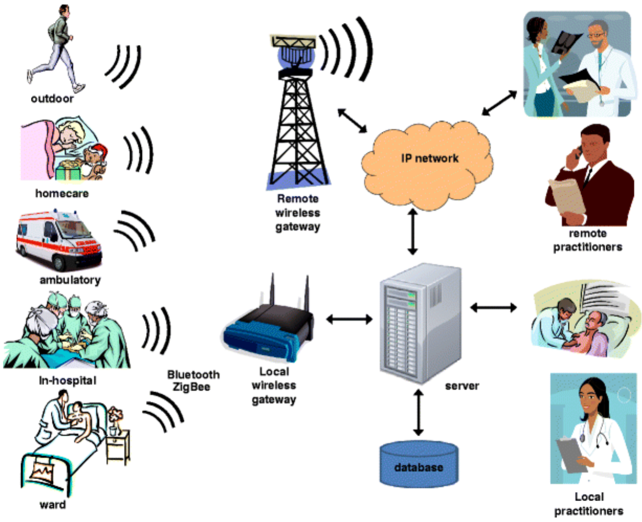
- Light
- Sound
- Humidity
- Pressure
- Temperature
- Soil composition
- Air or water quality
- Size, weight, position, speed, and direction of an object [75]

Hence, it is important to understand the aim of WSNs deployment. The vital point to mention is to find a solution for a wide variety of applications. In the majority of applications, position knowledge is a valuable or even required feature. Sensor-node localization may be done in several ways. Each sensor node has a GPS receiver that can provide precise positional data to other sensor nodes [44]. Due to heavy costs, high power usage, and environmental constraints, it is also thought that delivering GPS receivers to all sensor nodes is almost impossible and impractical.Furthermore, since GPS-equipped nodes fail in certain indoor applications, such as underground or in dense forests, self-localization is a viable alternative. Sensor nodes estimate their location using different localization discovery protocols [44]. The next figures show the application of WSNs in industry and which is met in our daily life.

WSNs enable fast setup (simple deployment), low installation costs, no cabling, and versatility, allowing adaptable sensors to be mounted almost anywhere and their observations to be transmitted over long distances through wireless networks.



(a) The application of WSNs in industry [13]



(b) Daily life application of WSNs [1]

Systems with wireless capability are becoming well liked because they do not need a connection to the primary power grid [53]. It also concerns the electronic devices without wires.

Many machines in both the manufacturing and domestic worlds are entirely powered by batteries, with the communication wires serving only to recharge the batteries. Current commercially available wireless sensors for temperature or pressure measurements use conventional primary batteries with a lifespan of 1-2 years when used according to the manufacturer's specifications. When looking at the lifespan of batteries, it's clear that the amount of energy they will produce is constrained by the amount of energy contained in their internal chemistries at the start [50], [34]. So, the endurance of sensor nodes is limited by charged batteries [46]. Despite the fact that battery manufacturing firms have greatly increased battery life, they still need annual servicing, which adds thousands of working hours to the cost. Periodic repair or replacing old batteries with new ones is expected to prolong the working life of sensors, so the service costs will be high, and it will be almost impossible to compete with as the number and scale of sensors grows. Furthermore, larger batteries with more internal chemistries to store more energy could not be installed because they would control the node's total size.

As a consequence, it is clear that alternate power sources for sensor networks/nodes are needed. In order to achieve the target, energy harvesters can be used to bypass the power supply of sensor nodes. Energy storage strategies must be consistently implemented at the sensor level in order for each node to consume, locally store, and utilize ambient energy efficiently for a long lifespan or even full WSN energy autonomy. Recent advancements in energy storage technology, secondary batteries, and low-power microcontroller units mean that truly energy-autonomous wireless sensors are on the horizon.

1.1.1 Working principle of WSNs

Hundreds or thousands of sensor systems with wireless networking, sensing, and computation capacities make up a WSN. Sensor nodes are low-power scattering devices with wireless communication and local processing capabilities. A sensor interface incorporates sensing, computation, and communication capabilities. As a consequence, the aim is to combine all of the functions mentioned above into a single processor [37]. The next Fig.1 beneath illustrates simplified block diagram of wireless sensor network node with power harvesting device.

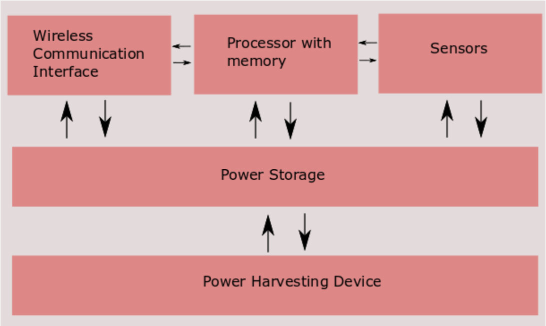


Figure 1.3: Block diagram of a typical WSN node

A WSN's small nodes are fitted with one or more sensors (which convert the physical quantity of interest into an electric signal) as well as a small microcontroller (which performs analog to digital conversion as well as computation and storage) and a wireless radio transceiver unit (providing for wireless communications capability), storage element. There exists a power scavenger/harvester. Its goal is to transform the energy from an external source (e.g. solar, thermal, wind) into electrical energy while flanking/recharging the commercial power storage unit.

The construction of energy-efficient networking protocols, in particular, is a unique problem in WSNs, with no precedent in wireless network history. In general, when a node is in transmit mode, the transceiver draws much more current from the battery than the active microprocessor, sensors, and memory chip [11]. As a result, connectivity protocols must be constructed in accordance with energy efficiency paradigms, although this limitation is less stringent for computing tasks. Then there's the problem of designing energy-efficient networking protocols, which hasn't been addressed before in the history of wireless networks.

The majority of WSN literature focuses on the development of energy-efficient protocols, ignoring the importance of energy consumed when transmitting data within the node, and concluding that the transceiver is the component that consumes the most energy. Data processing in WSNs, on the other hand, can necessitate consuming tasks to be performed at the microprocessor for much longer periods of time than a transceiver is in transmit mode [26]. This will lead the microprocessor to consume a significant quantity of energy. [11]. As a result, the general rule that communication protocol architecture is much more critical than processing task scheduling is not always accurate [11].

1.2 Objectives and Outlines of the Thesis

The aim of this project is to examine and explore strategies for optimizing thermal energy harvesters for WSNs.

A thermal energy harvester concept is designed which is capable to scavenge the energy from the thermal difference between two heat sinks made of the same material (Aluminium). The thermoelectric device, with the material of Bismuth Telluride (Bi_2Te_3), is sandwiched between these sinks and converts a fraction of the heat as it flows from the hot to cold sinks. The power output of the thermoelectric device is dependent on the amount of heat which flows through it and the efficiency at which it converts this heat into useful energy. These factors depend on the geometry of the thermoelectric devices, thus, the objective of this thesis is to investigate the optimum dimensions.

The objective this project is to find the most optimum dimensions for the thermoelectric device, to analyze the output power with respect to the thermoelectric module sizes.

Chapter 2. will discuss what the energy harvesting is, the energy sources what can be used to harvest the energy and will mainly focus on Thermal Energy Harvesting. Moreover, the energy harvesting device is designed, simulated and optimized, using the computer tool, called OpenFOAM, which is discussed in Chapter 3. The results are presented and discussed in Chapter 4 and then a number of conclusions are drawn in Chapter 5.

Chapter 2

Energy Harvesting

2.1 Energy Harvesting - Overview

The method of transforming ambient energy into electricity is called Energy Harvesting. The need for energy production in nontraditional forms has compelled and drawn researchers in pursuit of inexpensive and environmentally sustainable energy sources in recent decades. This has sparked interest in Energy Harvesting, which is the branch of science that deals with capturing energy from natural sources such as wind, rain, thermal energy, or other natural vibrations and converting it into useful energy.

Capturing, locally storing, and effectively reusing ambient energy is critical in a variety of scenarios. Harvesting-based methods are becoming more popular in the power electronics and energy conversion fields, owing to the widespread adoption of renewable energy sources. Applications range from power delivery systems that integrate solar/wind energy into residential microgrids to environmental tracking networks that use sub-watt wireless sensor nodes, which is the focus of the present thesis.

The energy is produced by an energy-to-energy conversion process [59]. Mechanical-to-electrical, for example, is used in hydroelectric and wind turbines for large-scale power generation to satisfy the needs of countries/cities, chemical-to-electrical is most widely used in batteries to provide portable electrical energy, and solar-to-electrical generates electricity using solar energy, radio frequency-to-electrical converting electromagnetic energy to electrical one, and thermal-to-electrical which is currently the technology under development [8], [20].

Harvesters, like electrical transducers, are electronic instruments with the same concepts and design. As a result, they're nothing more than transducers that are engineered to extract not just a sample of energy from physical phenomena, but the whole energy quantity available [59]. Mechanical friction, temperature differential, natural or artificial light, high degrees of noise, and pipes of air or water fluid are all examples of energy storage devices that can be used in manufacturing or other settings. This energy will then be controlled and retained so that it can be used to power an electrical system [54].

The primary goal of energy harvesting is to conserve and save collected energy for later use in the service of a plant, rather than to generate electricity on a large scale. As a result, the periodic operating mode of an energy harvesting device entails harvesting during peak energy availability time slots. *The followings are the major goals of energy harvesting technology:*

- Remove mains supply wires
- Eliminate or reduce dependence on batteries
- Increase in lifetime
- Maintain or/and increase the functionality
- Ease of installation
- Low cost
- Reduce waste

As a result, energy harvesters focused on transforming other types of energy to electrical energy have been the only feasible alternative in many applications. These harvesters often have the unusual ability to be used as instruments, such as for sensing and measuring data related to a particular incident. Energy harvesters are currently built to supply either continuous power for independent wireless sensor nodes or throb power for a single usage. Energy harvesters are designed around a local energy source (host system) and an interfacing mechanism, which is especially important for motion-based harvesting systems.

This chapter will briefly discuss energy harvesting, their principles, applications and will mainly focus on thermal energy harvesting. The details are discussed further.

2.2 Energy Sources and Harvesting Methods

There are several diverse energy fields from which to produce energy in theory:

- Radiation (light, solar, cosmic rays, electromagnetic radiation)
- Thermal
- Mechanical (potential, kinetic, elastic, fluid)
- Gravitational
- Chemical (battery, fuel cell, fossil fuels, phase change)

- Nuclear
- Magnetic (Magnetisation, currents, etc)
- Electric [7]

Hence, these several aforementioned potential energy sources among which the thermal, mechanical, solar, electromagnetic, acoustic, wind, human body, and wave can be appropriately harvested to replace conventional sources or to power electronic applications. This energy may be recycled or converted into other sources of energy.

2.2.1 Solar Energy Harvesting

Even in low-light settings, solar energy transformation has been shown to be the right approach among energy conversion technologies for electric power capturing, and it is widely employed in consumer items as well as many other applications.

Solar cells, which are well defined, can transform solar or other light energies into electrical power. The earth's surface absorbs around 1.21x017 W of solar power on average. It ensures that in less than an hour, enough electricity is supplied to meet the entire human population's energy demand [41].

The invention of these solar cells (photovoltaics) was in the United States when Daryl Chapin, Calvin Fuller, and Gerald Pearson develop the silicon photovoltaic (PV) cell at Bell Labs - the first cell capable of converting enough of the sun's energy into power to run everyday electrical equipment [21]. The rapid advancement of silicon technology in the 1950s coincided with the development of silicon cell technology, which by the 1960s had demonstrated cells with close to 15% energy conversion efficiency. For around a decade, standardization in cell architecture for space applications seems to have stifled progress, with the next explosion of activity emerging in the early 1970s [9].

The size of the solar cell limits the energy production of solar energy based energy harvesters. However, a few microWatts of power can be sufficient and can be accessed in many energy-harvesting applications.

It's important to remember, though, that solar energy conversion isn't realistic in certain situations, such as confined settings where there's never enough light. There are several considerations to remember when using Solar Cells as an energy source, including the abundance of bright sunshine, the number of sunny and cloudy days in a year, deployment conditions, power needs, and so on.

The materials used for solar cell fabrication are also considered to be selected from wide range of available materials. Various alloys, polymers, and semiconductor materials in bulk form are currently pushing the field of commercial photovoltaic (PV) around the globe, but various nanotechnology-based materials have been gaining traction as materials for solar cell fabrication since the last decade [43].

Solar cells, which transform light to usable power when exposed to light and do so for several years with no harmful effects on the natural world, have low maintenance and operating costs. Photovoltaic power generation is very reliable and involves no moving parts. One of the advantages of photovoltaic systems is that they operate quietly and do not pollute the environment. This technology is very modular and can be quickly installed, thus, the power can be generated where it is needed and without the need for transmission lines.

The photovoltaic effect is the mechanism by which a photovoltaic cell produces voltage or electric current when exposed to sunlight. The p-n junction is made up of two distinct kinds of semiconductors - p-type and n-type - that are fused together to form solar cells. As electrons travel to the positive p-side and holes move to the negative n-side when these two forms of semiconductors are joined, an electric field is created in the junction area [10]. This field leads negatively charged particles and positively charged particles to move in opposite directions [10]. Photons, which are small packets of electric radiation or electricity, make up light. As photons of a certain wavelength strike these cells, their energy is passed to an electron in the semiconducting material [5]. An electric current flows through the cell as a result of this action.

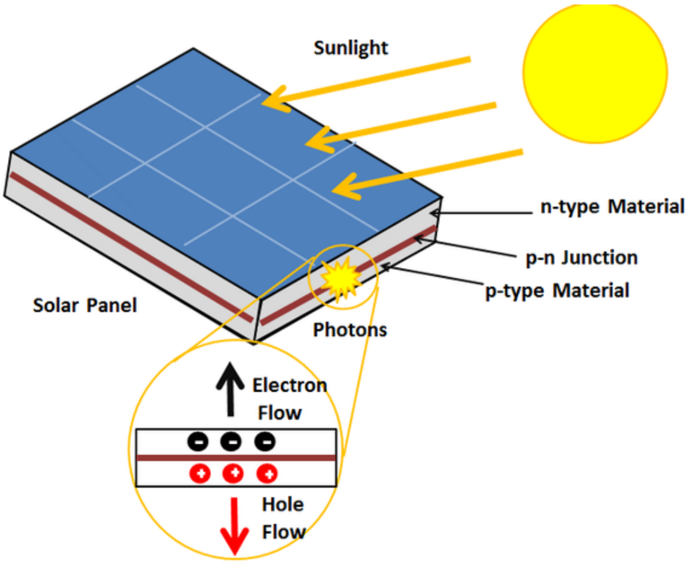


Figure 2.1: Diagram of a typical photovoltaic effect [55]

The energy produced by most photovoltaic systems will not be consumed directly and immediately. If using the power grid is not an option, a battery storage unit would be needed in most cases. PV systems are thus a stable energy supply for electrical power because of their ability to store energy. PV devices with battery capacity are now used to power lighting, video machines, switches, telephones, and even power tools all over the world [9].

2.2.2 Energy Harvesting From Piezoelectric Materials

This is the method of transforming complex mechanical energy into electrical energy. For conversion of this energy the piezoelectric material is used. The low-level energy harvesting to power the low-power electronics is the main scope of this energy harvesting form. Piezoelectricity is derived from the Greek words "piezo" (pressure) and "electric" (electricity) [18].

Piezoelectric materials typically work at significantly lower energy costs than thermal and solar energy harvesters, which can produce satisfactory amount of power. Any of the benefits of piezoelectric transduction over thermal and solar harvesting are the fact that atmospheric vibrations are often constant due to system operating conditions, so it does not depend on unreliable and erratic environmental conditions that change over time [59]. The biggest benefit of using a piezoelectric energy harvester is that it can use movements, such as muscular or mechanical tension, to power different infrastructures that would otherwise be lost. It is thus possible to transform mechanical energy (vibrations) into electrical energy using piezoelectric transducers. This produced electrical energy is alternating in nature, and it can be used immediately or deposited in a storage unit [56].

When a piezoelectric material is subjected to a force or stress, an electric charge is generated through the material [40]. The direct piezoelectric effect is what this is called. As a charge or electric field is applied to the same object, it causes a difference in strain or mechanical deformation. The indirect piezoelectric effect is what this is called. In energy harvesting, the direct piezoelectric effect is employed [47].

Hence, the main concept is to use piezoelectric material to harvest wasted energy generated by a system's vibration. These wasted vibration sources could come from a mobile host, a transportation system (such as a road, railway, airline, or runway), and so on. The crystalline structure of piezoelectric materials aids in the absorption of mechanical energy from their environment. The most frequently it is ambient vibration, and this property helps it to transform to electrical energy that can be used to power other instruments [28].

Since it can generate large mechanical strain during vibration, the cantilever beam with one or two piezoelectric material layers, known as unimorph or bimorph, is the most commonly used device configuration for piezoelectric energy generators [60]. The tip of the cantilever normally has a seismic mass added to it to shift the resonant frequency to the available atmosphere frequency, which is usually less than 100 Hz. A vibration source is used to cause dynamic strain in piezoelectric layers, and the beam is mounted on it. As a consequence, an alternating voltage is generated by the electrodes covering the piezoelectric material layers [60].

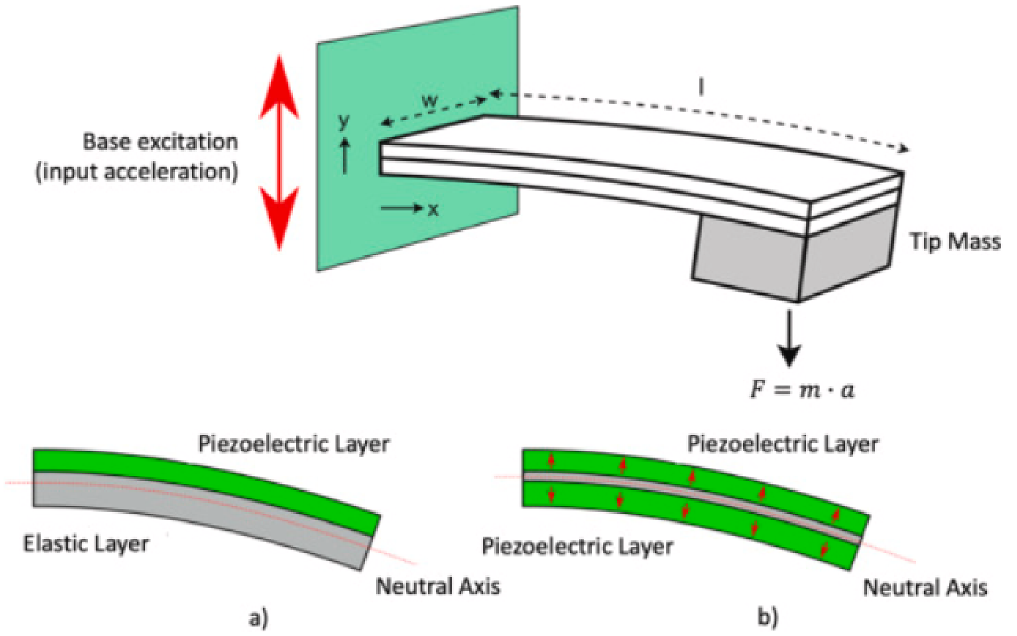
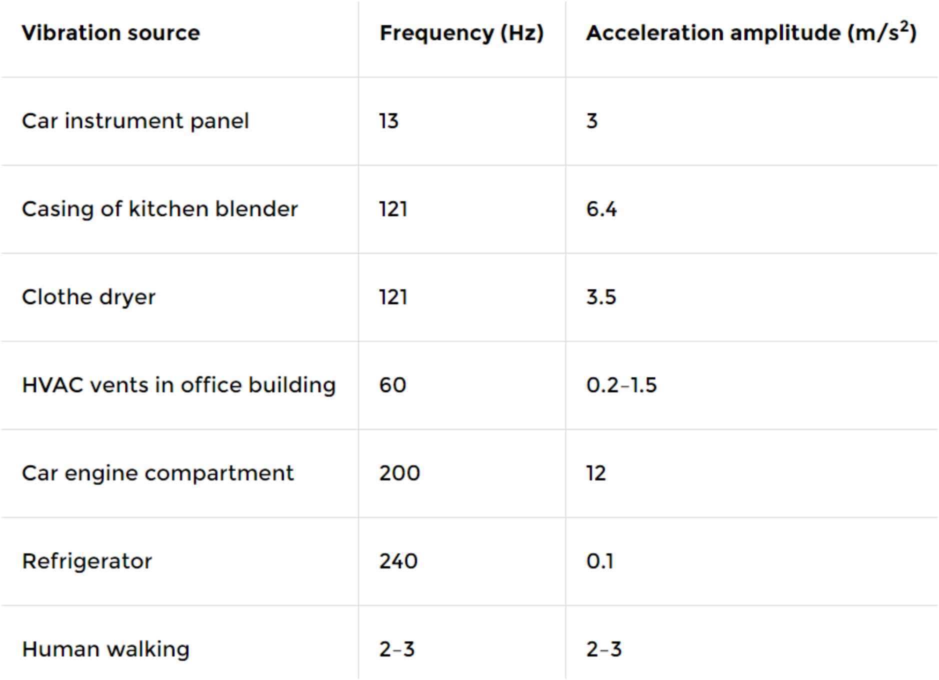


Figure 2.2: Cantilever structure of piezoelectric generators with (a) unimorph and (b) bimorph construction [54]

Ceramics, single crystals, polymers, and composites are the four categories of piezoelectric materials based on their composition features. The “ferroelectrics,” a subgroup of piezoelectrics are the majority of piezoelectric ceramics and single crystals consumed for energy processing [39]. The frequency is the most important point what the effectiveness and the density of piezoelectric energy harvesting system depends on. The reason is that since the piezoelectric consumes optimum power at its resonance frequency, the efficiency and power density of a piezoelectric vibrational energy harvesting system are highly frequency dependent [57]. As a result, the dimensions of the piezoelectric portion of a piezoelectric energy garnering device is established by the host’s foundational frequency. Roundy identified that the low frequency fundamental mode should be targeted in the design of the energy harvesting device, as opposed to the higher frequency because the potential output power is proportional to $1/\omega$, where is the ω is the frequency of the fundamental vibration mode [14].



Vibration source	Frequency (Hz)	Acceleration amplitude (m/s^2)
Car instrument panel	13	3
Casing of kitchen blender	121	6.4
Clothe dryer	121	3.5
HVAC vents in office building	60	0.2-1.5
Car engine compartment	200	12
Refrigerator	240	0.1
Human walking	2-3	2-3

Table 2.1: Frequency and acceleration of various vibration sources [62]

Within the permissible range of sizes permitted by compact electronic devices, monolithic piezoelectric ceramics are employed as the energy storage element. As a result, many strategies have been employed in order to get a lower resonance frequency in a package with a relatively small dimension. This involves piezoelectric material selection, energy harvesting element layout and design, and energy storage system reconditioning. To accommodate the application, the produced components have higher resonance frequencies. Piezoelectric ceramics are often employed for these uses because their piezoelectric characteristics are comparable to composites and polymers.

2.2.3 Radio Frequency Energy Harvesting

RF energy harvesting is a "green" self-sustaining process that has the ability to provide an endless source of energy that can be used to remotely control low-power machines [61]. It also increases the device's reliability, portability, and consumer and environmental friendliness while shrinking its size and cost. Furthermore, the finite lifespan of electrical batteries is prompting researchers to look into more solutions in the field of RF energy harvesting, as noted by Nikola Tesla, who called the ability to transmit energy between two points without the need for a physical link to a power source of "all-surpassing significance to man." [68].

The harvesting of radiofrequency energy overcomes the usual problems of other sources of ambient energy, such as low illumination, inadequate differential temperatures, and lack of vibrations; additionally, the RF energy in reception can be constantly monitored and maintained on request. As a result, radiofrequency energy can be used to not only refresh but also to upgrade batteries, which is ideal for running ultra-low-power machines.

Satellite stations, broadband internet, radio stations, and digital immersive transmissions are all sources of electromagnetic waves. A radiofrequency energy harvesting device can absorb electromagnetic energy and transform it to a continuous voltage (DC) that can be used. RF power harvesting is a method in which radio frequency energy generated by sources that produce high electromagnetic fields, such as TV signals, wireless radio networks, and mobile phone towers, is collected and converted into accessible DC voltage by a power generation circuit connected to a receiving antenna.

An antenna, a corresponding network, and a rectifier are the three key components of a standard RF energy harvesting network architecture. An antenna and a rectifier circuit, which converts RF power or alternating current (AC) into a DC signal, are the basic components of an RF energy harvesting device. The circuit systems that absorb the observed radio frequency from the antenna are made on a micrometer scale, but they can transform propagated electromagnetic waves to low voltage DC power over distances of up to 100 meters [78].

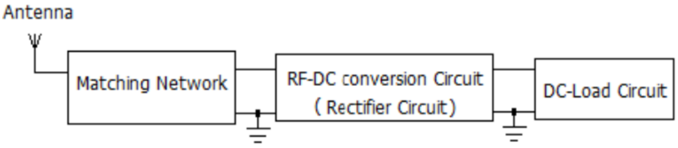


Figure 2.3: Schematic of an RF energy harvesting system
[48]

2.2.4 Human Power

Human power is described as the generation of energy from human motion or body heat to power an electronic system. Control, on the other hand, may be derived inadvertently from the user's daily behavior or deliberately created by the user. Body heat, breathing, blood pressure, texting, arm motion, pedaling, and walking will all be used to generate electricity [77]. The table bellow gives a sense of how much force the human body expends during different tasks. In general, the most interest in human power for energy harvesting is focused on two fields: human motion and body heat.

When machines are not constantly powered, only a small amount of power can be harvested without causing the user any inconvenience or annoyance. However, before it can be used for an operation, energy extracted from the consumer can need significant conditioning (storage, voltage/current or impedance conversion, etc.). Conversion quality is, in effect, a major problem for scientists and technology today.

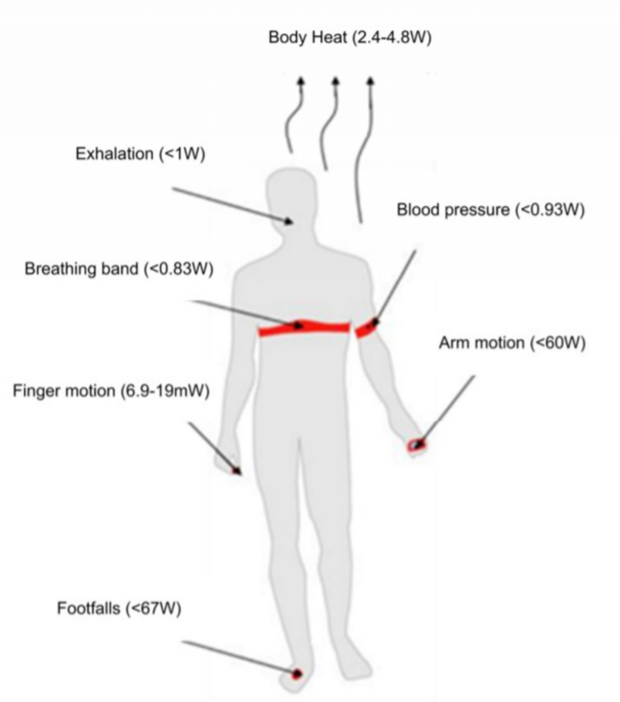


Figure 2.4: Possible power recovery from body-centred sources with total power for each action listed [28]

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2.3 Thermal Energy Harvesting

The most recent advancements in thermoelectric materials and systems have reignited interest in thermal to electrical energy harvesting, which offers a modern and appealing alternative to commercial batteries. One of the most common ways to generate electrical power from heat is to generate mechanical motion in turbines, which is a conventional process. However, this isn't the only technique to generate energy from heat. Thermal Energy Harvesting is an emerging and exciting technique that should be investigated as an alternative to the traditional mechanism.

Thermal energy recovery is the practice of collecting and bringing to use heat that is either freely available in the atmosphere or excess energy emitted by vehicles, computers, and other means. Thermal energy harvested may be used to pre-heat water for domestic use or for manufacturing processes. It may also be transformed into mechanical or electrical energy.

The conversion of heat, or more specifically a temperature differential, into electrical energy using thermoelectric generators is a form of thermal energy harvesting. These depend on the properties of thermoelectric devices, a kind of semiconductor that generates an electric potential as thermal energy passes through it from a hotter to a colder side. They're mostly used to transform temperature differences into voltage.

When a constant temperature differential occurs between the two common points, these thermoelectric generators in a loop composed of two dissimilar conductors produce an electromotive power.In this research, the operating principles of these devices will be studied in better detail.

In an attempt to achieve thermal equilibrium, a temperature differential between two positions may cause a flow of heat energy from hot to cold. Since this method is regulated by thermodynamic rules, the fundamental Carnot limit constrains its efficiency, or the ratio of useful work extracted out, W, to input heat, Q [35].

The Carnot efficiency limit applies to all heat engines and generators and can be expressed in terms of the hot, T_H, and cold, T_C, temperatures as,

$$\eta = \frac{W}{Q} = \frac{T_H - T_C}{T_H} \tag{2.1}$$

While the Carnot efficiency is ideally the highest efficiency that can be attained, it is found that in reality, the systems do not attain this high efficiency. As an example, if we want to harness energy from the available 10K temperature above the room temperature (303K), we gain the efficiency of 3.3%. Hence, the Carnot efficiency cannot be reached.

It can be shown that since the usable capacity is low, the performance of harnessing electricity would be very low. Due to the poor efficiencies, a considerable volume of heat must be transported in order to obtain and harvest the usable amount of work for the machines. Heat may be transported in three following ways: conduction, convection, and radiation. Despite taking into account the conduction case, heat will be transferred through radiation and convection at small scales and temperature gradients.

Hence, the quantity of heat transported by conduction may be calculated using the following equation:

$$q = k\frac{\Delta T}{L} \tag{2.2}$$

Where q is the heat, k is the thermal conductivity of the material, ΔT is the temperature difference and L is the length of the material. The temperature difference, ΔT is described in terms of hot and cold cases and is obtained as following:

$$\Delta T = T_H - T_C \tag{2.3}$$

2.3.1 Thermoelectric Technology

Thermoelectric materials can play a crucial role in both primary power generation and energy conservation (waste heat harvesting). Thanks to their significant benefits, Thermoelectric generators have emerged as a potential alternative to green technology. Thermoelectric energy generation has a possible use in the immediate conversion of waste heat energy to electricity generation, where the expense of the thermal energy supply is not taken into account. The use of this renewable alternative technology will also improve the total efficiency of energy conversion systems [30].

The conversion efficiency of thermoelectric devices is usually poor, with a conversion efficiency of 5%, but it was adequate for low-power applications. TEG has many benefits, including being dependable, clear, small in size, portable in power supply, environmentally friendly, and durable enough to be deployed in harsh conditions [27].

Where temperature differences occur, there is the potential for electrical energy generation using the thermoelectric effect. Electrons and holes, for example, are free to travel and carry charge as well as energy. The carriers drift from the hot end to the cold end as the products have a temperature gradient. The accumulation of charge carriers creates a net charge, which creates an electrostatic potential within the substance. The equilibrium condition is reached when the chemical potential for diffusion is balanced with the electrostatic repulsion caused by charge accumulation. This is the Seebeck effect, which is the foundation of thermoelectricity. Thermoelectricity is a physical effect in which heat energy is converted directly into electricity or vice versa depending on the temperature of the object.

In 1822, Thomas J. Seebeck discovered that electrical energy can be produced directly from thermal energy when two semiconductor materials are separated by a temperature difference [70].

The schematic particles-transport image in thermoelectric materials is seen in the next figure.

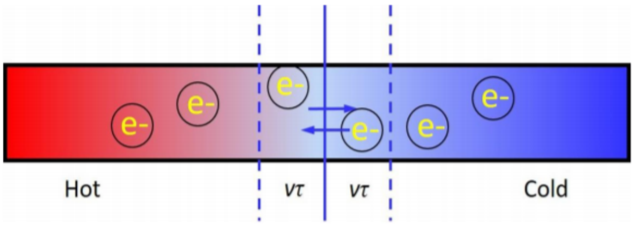


Figure 2.5: Carriers drift caused by temperature gradient [73]

As electrons travel from a lower to a higher energy level field, the Seebeck effect happens, generating an electric voltage due to temperature variations at the ends [29]. Instead of two various metals, modern thermoelectric systems use n and p type bismuth telluride semiconductors. In case a temperature differential is retained on both sides of the thermoelectric module, it is capable to create a little quantity of electricity.

The 'hot' side of the deivce, is normally connected to a heat source. The opposite side of the thermoelectric module is normally connected to a heat sink.

The thermoelectric module is illustrated in the next figure beneath:

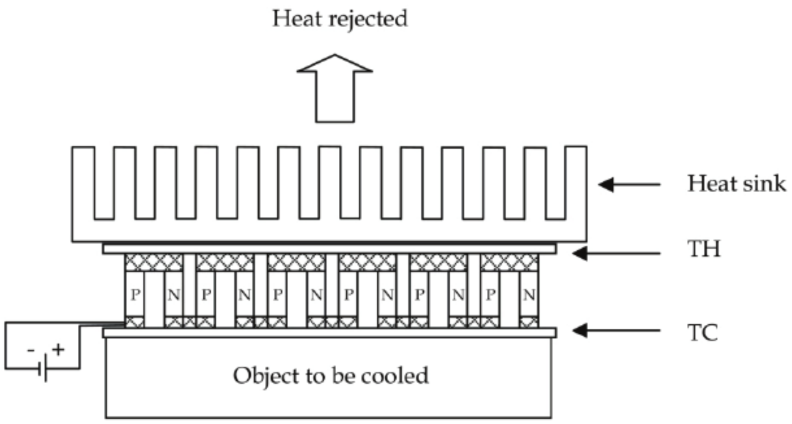


Figure 2.6: Thermoelectric module
[24]

The following equation depicts the relationship between temperature differential and induced voltage.

$$V = S(T_H - T_C)[V] \tag{2.4}$$

In the equation, V is the voltage, S is the Seebeck coefficient, and T_H-T_C is the temperature difference.

The main issue today is low efficiency, which is constrained by the properties of thermoelectric materials currently available. The explanation for this is that in order to take advantage of a temperature gradient, the thermoelectric unit must be both an electrical conductor and a thermal insulator to keep the temperature difference constant. The key argument is to maximize the electric output for a given heat source by studying the material used in depth and exploring new types of materials.

The device's efficiency is determined by the dimensionless parameter ZT, where T is the operating temperature and Z is the electric and thermal transport properties of the material [72], [2]. Engineer Edmund Altenkirch mathematically expressed the relationship between physical properties of TMs and the efficiency of a generalized thermopile or TEG for the first time in 1909 [32]. Later, in 1949-1956, Abram F.Ioffe, a well-known Russian physicist, combined these parameters into the Z category (quantity Z or parameter Z) and used the new parameter Z to measure thermoelectric system efficiency [51].

The formula for Ioffe's parameter Z is as follows [31]:

$$Z = \frac{\sigma S^2}{\kappa} \tag{2.5}$$

Here, S denotes the Seebeck coefficient or thermopower, and σ denotes electrical conductivity and κ denotes overall thermal conductivity.

The most essential feature of thermoelements, says Ioffe, is Z. [69].

This parameter was established to determine the efficiency of devices with the following characteristics [51]:

- A pair of materials A and B of the p/n variety form the unit arms.
- Each of the materials A and B has the same electromotive energy.
- It is desirable for materials A and B to have thermal and electric interaction.
- The temperature differential between the device's hot and cold junctions is extremely limited.
- The physical and chemical properties of materials A and B are steady over time.

The efficiency of conversion appears to be influenced by the thermoelectric material's performance. A thermoelectric material usually expected to have a moderate Seebeck coefficient, S, high electrical conductivity, σ, and low thermal conductivity, κ. These transport variables are not independent, and they are affected by a number of factors such as a band structure and carrier concentration [63].

The ZT value of today's one of the strongest thermoelectric material, Bi_2Te_3, is about 1, which has remained the upper limit for more than 30 years [16]. Several applications only become practical for ZT $>$ 2 [71].

The variance of these parameters with carrier concentration for bismuth telluride is depicted in next figure.

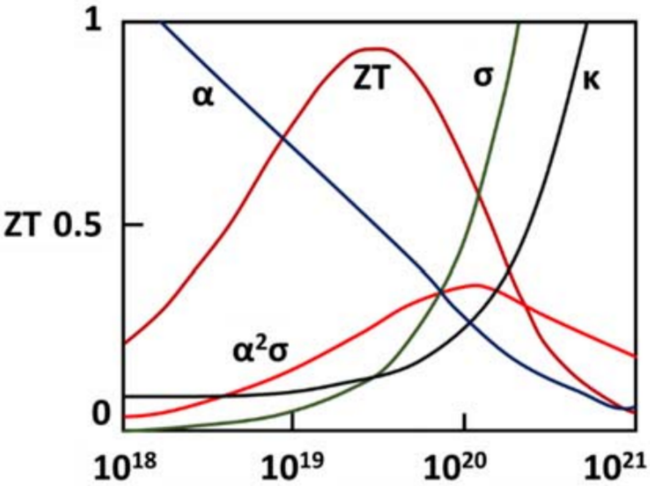


Figure 2.7: Variation of transport parameters as a function of carrier concentration [33]

With an increase of carrier concentration, it can be observed that the thermal conductivity and electrical conductivity of the material, σ and κ, increase [33]. However, Seebeck coefficient, S, has an opposite trend which is decreases by the increase in carrier concentration.

2.3.2 Thermoelectric Material

Low performance is a barrier to the advancement of thermoelectric applications, so there are three key problems that must be addressed to boost ZT value: extend the operating range, operate at higher temperature differences, and obtain low-cost materials [12].

The invention of semiconductors in the 1940s succeeded in modern thermoelectric science. The classical thermoelectric materials including Bi_2Te_3, $PbTe$, $SiGe$ working in various temperature regions. These components and alloys are now the most widely found in generators and coolers today [45][58].

Bismuth Telluride is one of the kinds of the compounds with the best ZT. It works in a few different temperature ranges [29]. Bi_2Te_3 was the first thermoelectric material with a high ZT value at room temperature that was discovered [74].

Figure 2.8: N-type P-type Bi_2Te_3 cube target [25]

The density of this material is 7.74 g/cm3, with a melting temperature of 853 K.

Since Goldsmid and Douglas suggested using Bi_2Te_3 as a thermoelectric material for refrigeration in 1954, this compound has been widely used in thermoelectric module production [23]. Since the first findings, the performance of materials based on Bi2Te3 has gradually improved. The majority of the early gains came from lowering the lattice thermal conductivity. This was accomplished by combining stable bismuth telluride solutions with isomorphic compounds such as antimony telluride and bismuth selenide [22].

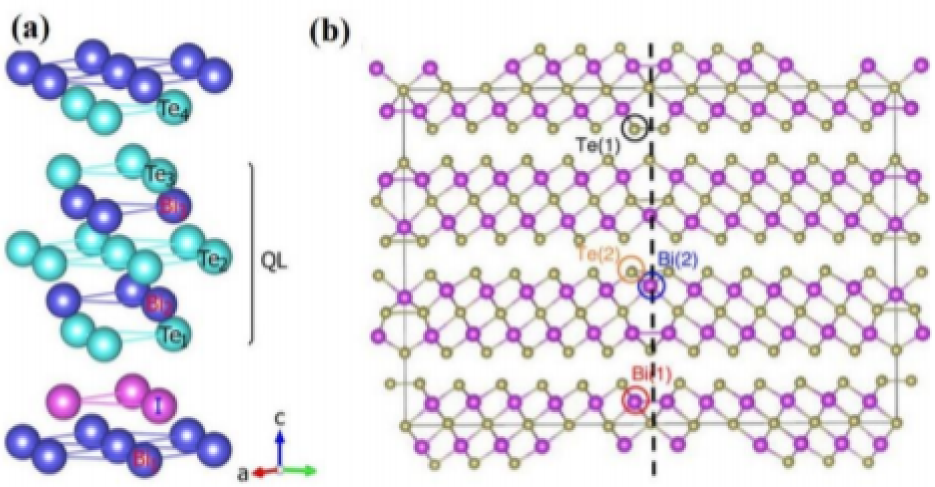


Figure 2.9: Atomic structures of (a) the unit-cell of Bi_2Te_3 [76], and (b) Bi_2Te_3 with 60° twin boundary [4]. The 60 twin border is shown by the dotted black line.

2.3.3 Relevant Prior Work and Applications

Other energy harvesting solutions for the heat engine employing thermoelectric modules have been developed.

Lemley [38] mentioned an uncommon application of a thermoelectric generator that generates energy from long-wave infrared radiation emitted from the earth's surface. The proposed proposal was for a long-range communications platform at high altitude. The earth's radiant energy would be gathered, and heat would be discharged into space through radiation. It was decided to use a thin-film arrangement. Limited tests were planned and carried out. In the design, a temperature difference of 58°C was utilised.

Benson and Jayadev [6] examined the feasibility of employing thermoelectric generators in massive installations to generate useful amounts of power from low-grade heat sources. The use of thermoelectric generators in an Ocean Thermal Energy Conversion system was one option investigated. For that situation, a temperature differential of 5–25°C was considered. In this range of temperature, it was discovered that several commercially available thermoelectric materials had a really outstanding figure of merit. The thermoelectric devices were estimated to have a 20% Carnot efficiency, which was employed in the computations.

Thermoelectric energy scavenging was studied by Thomas et al. [67] with the goal of potentially increasing the flying length of tiny air vehicles. The major implementation difficulties for this application at moderate temperatures and commercially accessible materials are maximizing thermal performance and decreasing the weight of the heat exchangers and associated gear.

The thermoelectric module was studied by EE Lawrence and GJ Snyder [36] to capture energy from the natural temperature differential between earth and air. They took the importance of shape factor into consideration and to achieve the desired electrical power output. A particular application which has been suggested in literature ([64], [65]) is to use the natural temperature differential and the thermoelectric microgenerator to slowly charge batteries at low power.

Davidson J. [17] has developed the model to estimate the power output of a thermal energy harvester to be employed across an air/water interface. The model also includes the inclusion of a collector plate, which harvests local insolation to boost production. The model was used to predict prospective power output based on location using local and global data.

This thesis focuses on developing the thermal energy harvesting device and will analyze the effect of the model geometry, such as width and thickness of thermoelectric device sandwiched between two identical sinks.

Chapter 3

The Energy Harvesting Model

In this chapter we will discuss the energy harvesting model, the design of it, the simulation of the model and the computer aided program used to make this model.

3.1 Previous Modelling

The goal is to investigate the thermal energy harvester, what has already been modeled [17], however, to extend this, the thermal energy harvester model is analyzed with respect to the effect of energy harvester geometry.

The method is modeled and based on thermal energy harvesting unit which is represented below in the next figure.

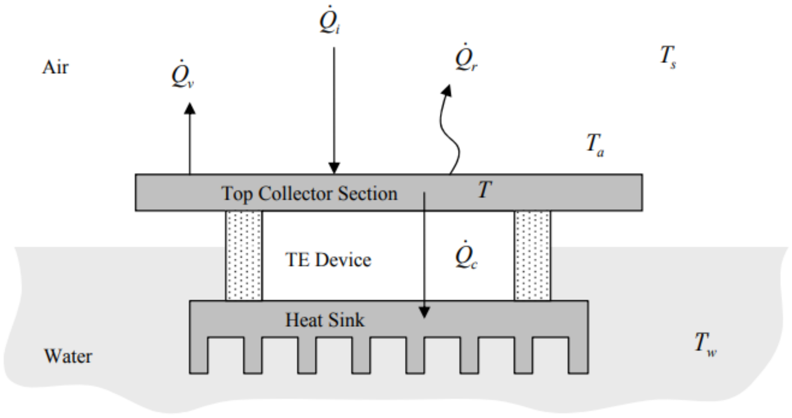


Figure 3.1: Schematic representation of energy harvesting model [17]

The energy transfer would be constrained by a poor Carnot efficiency due to the low estimated temperature difference, which is just a few degrees. Since the process' performance is poor, a significant volume of heat would need to be passed into the system in order to harvest a valuable amount of work. To attract a large amount of power, the good thermal conductor is chosen to be between the top collector sink and the bottom sink, as discussed in **Section 2.3.2**. The thermoelectric unit is insulated around the outside, which aids in its performance as an efficient heat transfer medium between the exchangers. As a result, there will be no temperature gradient in the sides of the thermoelectric unit, thus, it is expected that heat will not be lost from the sides. The temperature of the upper collector, which absorbs heat from the environment, is assumed to be the same as the ambient temperature, and the temperature of the bottom sink is assumed to be eqaual to the water temperature.

As a first assumption it is considered that there is no temperature drop between the top collector, bottom sink and the thermoelectric device. Moreover, as it is mentioned before the temperature of the exchangers are at the same temperature with their surroundings (air and water, respectively). Hence, this assumption leads to find the temperature difference across the thermoelectric device. The next formula shows the needed temperature difference:

$$\Delta T = T_a - T_w \tag{3.1}$$

Hence, knowing this temperature difference, we can find the rate of heat transfer via conduction through the thermoelectric device. The next formula illustrates the heat transfer rate due to conduction:

$$\dot{Q} = \kappa A \frac{\Delta T}{\Delta x} = \kappa A \frac{T_a - T_w}{\Delta x} \tag{3.2}$$

Where,

- κ is the thermal conductivity of the device
- Δx is the thickness of the device
- A is the area of the device

and the results are quoted as Watts per square meter. The thermoelectric device is comprised from the semi-conducting material Bismuth Telluride, and its thermal conductivity κ is $1.20W/mK$ [66].

Referring to the schematic drawing indicating the model of the Energy Harvester device, we can observe that the top sink which is the collector of the heat has 4 different heat transfer processes acting on it.

- $\dot{Q}_s$ - the incoming solar radiation
- $\dot{Q}_c$ - the conduction down through the thermoelectric device
- $\dot{Q}_v$ - convection from its top surface

- $\dot{Q}_r$ - the outgoing radiation

Hence, the heat rates of these processes can be expressed as following:

$$\dot{Q}_s = \alpha A_c I \tag{3.3}$$

$$\dot{Q}_c = \kappa A_{TE} \frac{\Delta T}{\Delta x} = \kappa A_{TE} \frac{T_a - T_w}{\Delta x} \tag{3.4}$$

$$\dot{Q}_v = h A_c (T - T_a) \tag{3.5}$$

$$\dot{Q}_r = \epsilon \sigma A_c (T^4 - T_w^4) \tag{3.6}$$

Where the A_c and A_{TE} are the areas of the collector and the thermoelectric device, respectively. I is the incoming solar insolation, h is the coefficient of convection, α is the collector plate absorptivity, ϵ is the emissivity of the collector plate, σ is the Stefan-Boltzmann's constant. T, T_w, T_a, T_s are the temperatures of the collector, water, air and effective sky, respectively.

According to the conduction heat transfer rate equation, the amount of heat transmitted through the thermoelectric system per unit time [s] is indicated. By multiplying this by Carnot efficiency, we can calculate the absolute potentially possible power scavenged from the heat flow by a thermal harvesting system. Hence, we can calculate maximum theoretically possible power output of thermoelectric device as following:

$$Power\ Output = (Rate\ of\ heat\ flux)(Carnot\ efficiency) \tag{3.7}$$

$$P_{out} = \kappa A_{TE} \frac{(T_a - T_w)}{\Delta x} \frac{(T_a - T_w)}{T_a} = \kappa A_{TE} \frac{(T_a - T_w)^2}{\Delta x T_a} \tag{3.8}$$

3.2 Model Design Approach and Solution

The model's geometry is seen in the previous section, but in order to perform the calculations, a 2D model of the Energy Harvesting device is generated in the computer aided solver, called OpenFOAM. It's a customized numerical computer aided solver for design, pre/post-processing utilities, and CFD (Computational Fluid Dynamics) issues.

The scope of this project is to deal with the heat transfer occurring via conduction, thus, other processes are not considered, however, the project can be extended to take all these processes into consideration.

3.2.1 Design and Simulation Tool

OpenFOAM

What is OpenFOAM?

OpenFOAM is a sophisticated computer application that allows you to simply write specific problems based on differential equations (continuum mechanics) and solve them numerically. It is an open source C++ library developed for basic or parallel computing to construct executable programs in solvers for a specific issue in continuum mechanics, and utilities for performing data manipulation activities.

Advantages

- Opensource
- Free
- Opencode
- Continuous evolution

The structure of OpenFOAM

The OpenFOAM source code is divided into four parts:

src: OpenFOAM's main source code;
applications: Solvers and uilities, for example, are sets of library functionality wrapped within apps;
tutorials: as a set of test cases demonstrating a wide range of OpenFOAM's capabilities;
doc: backup documentation

The instructional folder of OpenFOAM contains predefined case examples that are intended to assist users in learning essential utilities and capabilities inside OpenFOAM, such as mesh generation, multiphase modeling, turbulence modeling, parallel processing,

and response modeling.
Each case sample follows the broad pattern outlined below:

1. **Pre-processing**: guidance on how to use base case tutorials to set up the suitable case structure for a specific situation, with explanations on necessary terminology
2. **Running simulation**: instructions for using the solver and the commands that go with it
3. **Pre-processing**: ParaView, OpenFOAM's post-processing program, is used to examine the findings.

As the scope of this project is related to the heat transfer analysis, the Energy Harvesting device is designed, dimensionized and simulated by using this tool. For the corresponding model the appropriate mesh generation is done, the heat transfer via conduction is taken into consideration, further, the respective simulation is done on the device.

Using the *chtMultiRegionSimpleFoam* solver, firstly, the appropriate mesh generation is done using *BlockMesh* directory in OpenFOAM on the model and depicted in the following figure:

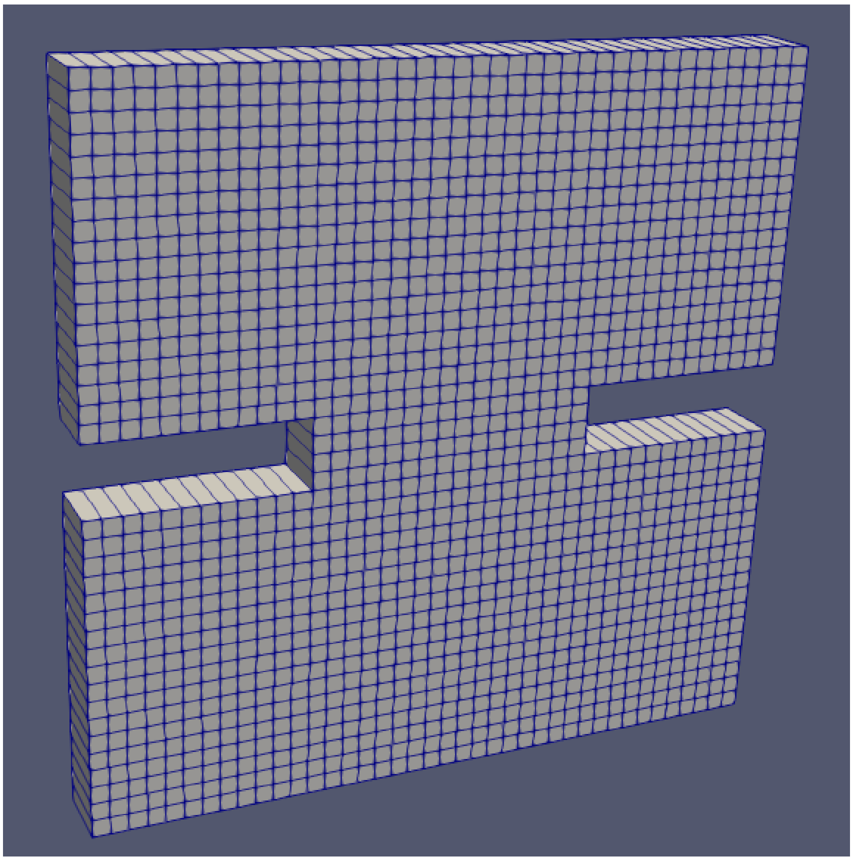


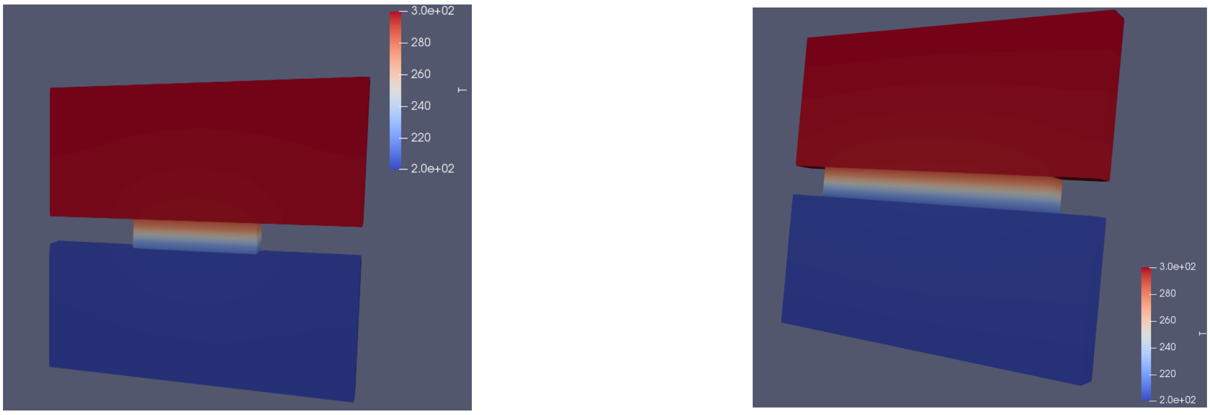
Figure 3.2: Mesh generation
[25]

All faces of the model are selected to be walls as the boundary.
The type of boundary fields of all blocks is *zeroGradient*. The type of the boundary field from middle block to the top and bottom blocks, and vice versa, is *compressible* :: *turbulentTemperatureCoupledBaffleMixed*, the special type of condition , which is mixed boundary condition for temperature.

Next, adjusting the initial temperatures for the top block to be equal to $300K$ and the bottom block to be $200K$, the simulation is run(20.000s) until reaching the steady state on both sinks, respectively.

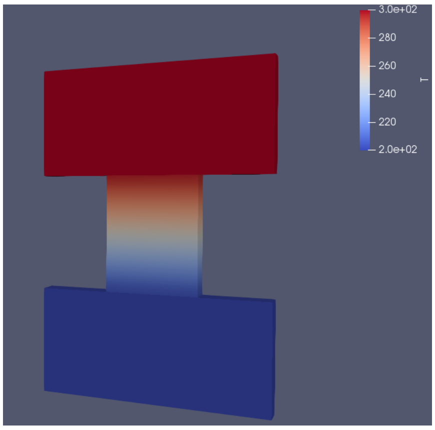
The top collector and the botom block material is selected to be aluminium, and the middle device is Bismuth Telluride.

To calculate the temperature across the thermoelectric device, 5 probes we located on the top and bottom faces. The average value of the temperatures at all points was taken into account. Hence, the heat flux was calculated by this way. The following figure illustrates the several versions for device designed in OpenFOAM and the simulated version is shown below:



(a) width=0.8m, thickness=0.2m

(b) width=1.5m, thickness=0.2m



(c) width=0.8m, thickness=1m

Figure 3.3: Schametic representation of the harvester with different width and thickness values. The initial conditions for the upper and the bottom block are $300K$ and $200K$, respectively.

The basic design is represented in this figure. The design uses two simple (1m x 2m) blocks made of aluminium as a sinks to conduct and store the incoming heat. The top collector as a heat side and bottom sink as a cold side. The thermoelectric device made of Bismuth Telluride is sandwiched between these sinks.

3.2.2 Optimizing the Thermoelectric Device Area

Hence, the model is designed, however, to go forward with the calculations of usable power outputs, the effect of ratio of the thermoelectric unit and collector sink areas must be taken into account.

It can be observed that reducing the thermoelectric unit surface area leads to decreasing the heat flow through this device, what thus, ends up with increasing of the temperature difference between the top collector and the bottom sink. The theory and experiments show that the Carnot efficiency, and hence the efficiency of energy transfer, increases as the temperature difference increases, however, the amount of energy which is available for conversion decreases as the heat flow through the thermoelectric device decreases. If the temperature difference between the top collector and the bottom plate is maintained to be high, the optimum thermoelectric unit area can be adjusted for the device.

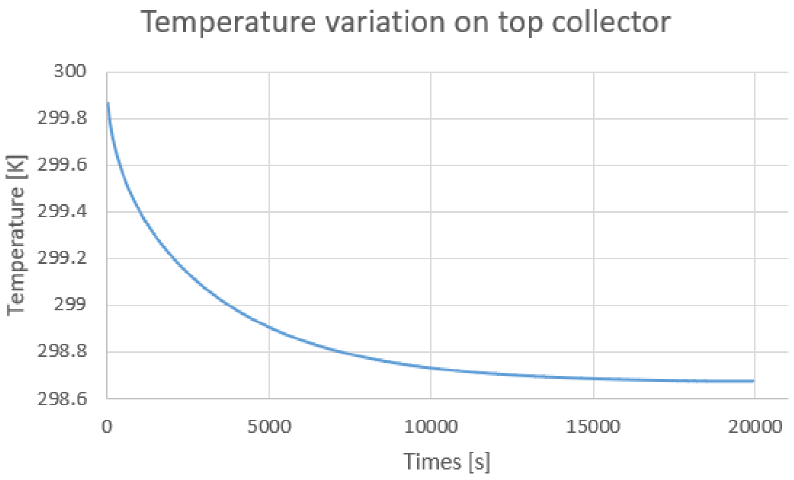
Changing the width and the thickness of the unit allows to make a good predictions for the plate to keep a high temperature difference. Some of the simulations are made to get the suitable and the proper device area, however, the thorough investigation of optimizing the thermoelectric device area is outside of the scope of this project.

Hence, a quick approximation is made by simply checking several combination of width and thicknesses for the device.

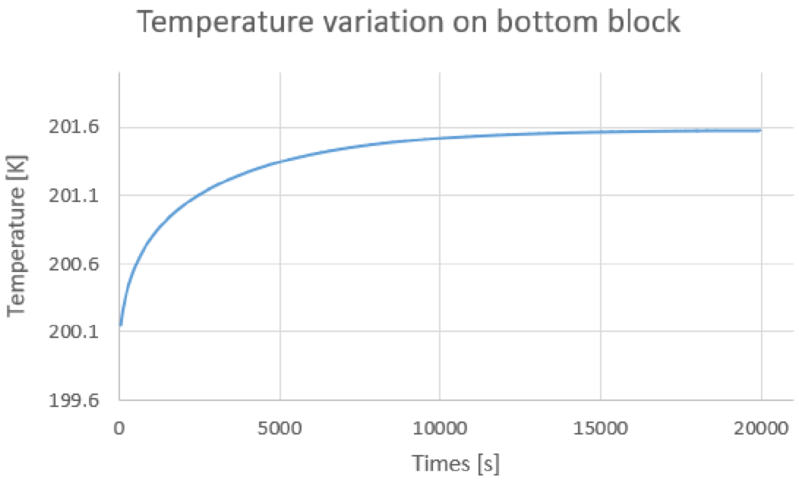
Chapter 4

Results and Discussion

The results of the model simulation performed with Open-FOAM will be given and discussed in this section.



(a) Temperature variation for certain width=0.4m and thickness=0.2m of top collector



(b) Temperature variation for certain width=0.4m and thickness=0.2m of bottom sink

It is observed that after some time (20.000sec) both blocks reach the steady state.

These are the results for particular width and thickness values of thermoelectric device sandwiched between both sinks.

Changing the width and the thickness values for the thermoelectric device will lead to determine the optimum sizes to harness the efficient output power. Firstly, the variation of temperature on both blocks with various width and thickness values are obtained, and the temperature difference between them evaluated. Hence, the variation across the middle block (thermoelectric device) is presented in the next figure:

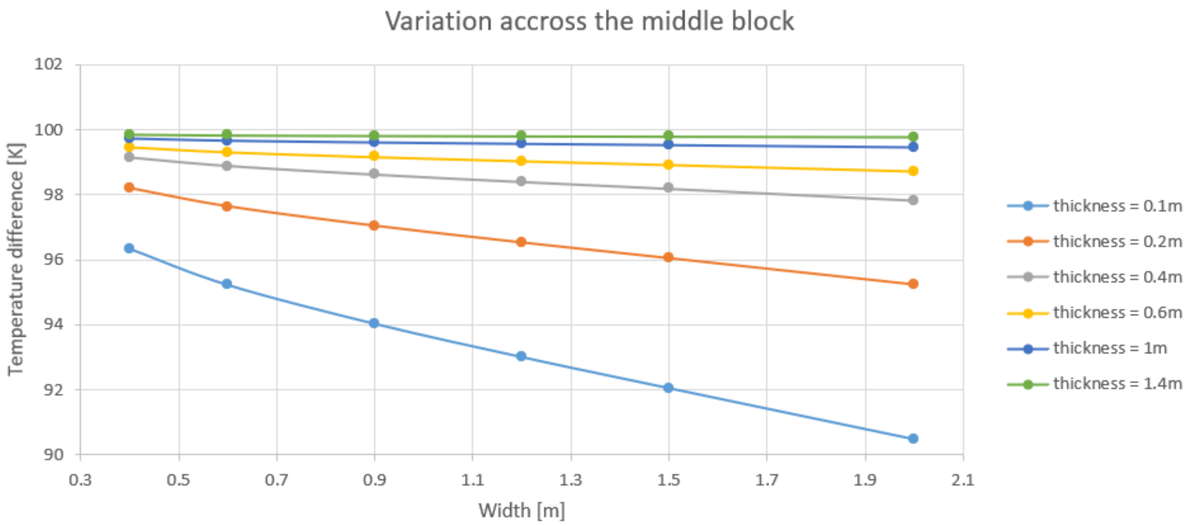


Figure 4.2: Temperature difference with respect to width values for all thickness dimensions across the thermoelectric device

From this, it is observed that the wider the thermoelectric device, the lower the temperature difference across it. This happens because the wider the thermoelectric device the greater the area of its top face attached to the sinks, thus, it leads to better heat flow across it, and the temperature difference gets lower. However, for the thickness, it is vice versa. The bigger the thickness of thermoelectric device the greater the power.

The goal of the thesis is to investigate the most suitable sizes for thermoelectric device to harness more energy, as the power output is quadraticly proportional to the temperature difference across the middle block and inversely proportional to the thickness of the device.

The next figure illustrates graph of the power output with respect to thickness with different width values:

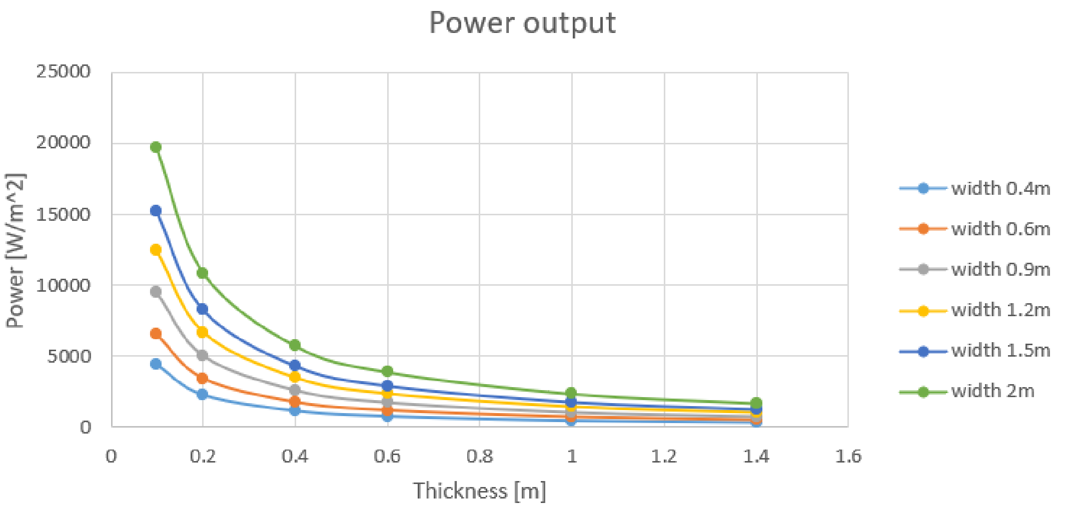


Figure 4.3: Power output available across the thermoelectric device

It is seen that the bigger the dimension of the thickness for thermoelectric device, the power output decreases, thus, the efficiency will decrease, respectively. However, decreasing the thickness will result in opposite, what makes a clear decision to make the thermoelectric device thinner. The reason is that the power output is inversely proportional to the thickness as discussed above.

Regarding the width dimension of the thermoelectric module, it is apparent that the wider the device, the greater the power output.

Chapter 5

Conclusion

Personal gadgets and wireless nodes have become smaller and consume less power, prompting a need for power sources that can run these devices continuously. While technologies like solar photovoltaics and wind turbines and wind can be used to particular areas, they are ineffective in others, such as mine shafts or areas with extensive forest cover [34]. A more simple technology has been explored in these places. These gadgets get their energy from heat variations in the environment.

The energy harvesting device to meet the modern requirements for low power applications was designed in this project. It can also be extended for high power applications if it is monitoring, for instance, the car engine, where the temperature difference could be much larger.

The simulation to analyze to dimensions of thermoelectric device on how it will behave with different sizes was done using computer aided tool, OpenFOAM.

It is observed that the thermoelectric module sizes have have an effect in power output which will be used as a useful energy for WSNs. Hence, the lower the thickness of the device, the higher power output can be converted into useful work. The wider the thermoelectric device, the lower the power output.

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