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DEVELOPMENT OF PIEZOELECTRIC POWERED ULTRAVIOLET PORTABLE WATER CLEANING SYSTEM

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Approval of the Graduate School of Natural and Applied Sciences, Atilim University.

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Prof. Dr. Ali KARA

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I certify that this thesis satisfies all the requirements as a thesis for the degree of **Master of Science in Electrical and Electronics Engineering Department, Atilim University.**

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This is to certify that we have read the thesis DEVELOPMENT OF PIEZOELECTRIC POWERED ULTRAVIOLET PORTABLE WATER CLEANING SYSTEM submitted by DERDA ERDEM ŞALA and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

DEVELOPMENT OF PIEZOELECTRIC POWERED ULTRAVIOLET PORTABLE WATER CLEANING SYSTEM

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M.S., Department of Electrical and Electronics Engineering

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Nowadays, because of the rapid increment of industrial regions and population, environmental contamination became a serious danger to human well-being. Especially, water resources are most affected by this situation. In literature, there are several water disinfection systems that using UV disinfection and they can be categorized into two; electrical power source and UV light source. UV water disinfection systems using piezoelectricity as a power source and including UV LEDs as a UV light source may provide sustainability, portability, and efficiency. A patent owned by the author of the thesis has been filed recently for such a portable UV disinfection system. The proposed system aims to harvest electricity from human hand shake via a piezoelectric harvester. Then, it uses generated electricity to supply UV LEDs for water disinfection. This study covers the detailed design and parameter optimization of the system. In this manner, the system parameters and mathematical model of the system is developed. Lastly, the objective function (OF) is derived, and design parameters are specified for optimal operation of the system. For this cause, Genetic algorithm (GA) is used for optimization. The results of single and multi-objective optimization using Genetic Algorithm (GA) are presented. Finally, the design parameters are derived for three different cost scenarios.

Keywords: Piezoelectric Energy Harvesting, UV disinfection, Genetic Algorithm, Design Optimization

ÖZ

PİEZOELEKTRİK İLE GÜÇLENDİRİLMİŞ TAŞINABİLİR ULTRAVİYOLE SU TEMİZLEME SİSTEMİNİN GELİŞTİRİLMESİ

Şala, Derda Erdem

Yüksek Lisans, Elektrik ve Elektronik Mühendisliği

Tez Yöneticisi: Prof. Dr. Ali KARA

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Günümüzde, sanayi bölgelerinin ve nüfusun hızla artması nedeniyle çevresel kirlenme insan sağlığı için ciddi bir tehlike haline gelmiştir. Bu durumdan en çok su kaynakları etkilenmektedir. Literatürde UV dezenfeksiyonu kullanan birkaç su dezenfeksiyon sistemi vardır ve bunlar iki şekilde kategorize edilebilir; elektrik güç kaynağı ve UV ışık kaynağı. Güç kaynağı olarak piezoelektrik kullanan ve UV ışık kaynağı olarak UV LED'leri içeren UV su dezenfeksiyon sistemleri sürdürülebilirlik, taşınabilirlik ve verimlilik sağlayabilir. Bu özelliklere sahip taşınabilir bir UV dezenfeksiyon sistemi için yakın zamanda tezin yazarı tarafından patent başvurusu yapılmıştır. Önerilen sistem, piezoelektrik üretici vasıtasıyla insan el çalkalamasından elektrik üretmeyi amaçlamaktadır. Ardından sistem, su dezenfeksiyonu için UV LED'leri çalıştırmak için üretilen elektriği kullanmaktadır. Bu çalışma, sistemin detaylı tasarımını ve parametre optimizasyonunu kapsamaktadır. Bu şekilde, sistem parametreleri ve sistemin matematiksel modeli geliştirilmiştir. Son olarak, objektif fonksiyon (OF) türetilmiş ve sistemin optimum çalışması için tasarım parametreleri belirlenmiştir. Bu nedenle optimizasyon için Genetik algoritma (GA) kullanılmıştır. Genetik Algoritma (GA) kullanılarak tek ve çok amaçlı optimizasyon sonuçları sunulmaktadır. Son olarak, tasarım parametreleri üç farklı maliyet senaryosu için türetilmiştir.

Anahtar Kelimeler: Piezoelektrik enerji üretimi, UV dezenfektasyon, Genetik algoritma, Dizayn optimizasyonu.

To my parents and my love

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PZT	Lead Zirconate Titanate
UV	Ultraviolet
LED	Light Emitting Diode
ε	Electrical permittivity
g_{33}	Piezoelectric Voltage Constant
k_{33}	Electromechanical Coupling Factor
K^T	Relative Dielectric Constant
OF	Objective Function
GA	Genetic Algorithm

CHAPTER 1

1. INTRODUCTION

Safe and quickly accessible water is a very important factor for public health. For example, it is used for drinking, medical use, food production, or domestic purposes. Improved water supply and sanitation, and better administration of water assets, can help nations about poverty struggle, and can contribute to monetary development.

In 2010, the UN General Assembly explicitly recognized the human right to water and sanitation. Everyone has the right to sufficient, continuous, safe, acceptable, physically accessible, and affordable water for personal and domestic use [1].

Although, reaching safe and clean water is a globally recognized human right, this fact is not fully supported. According to WHO report, "785 million people lack even a basic drinking-water service, including 144 million people who are dependent on surface water, globally, at least 2 billion people use a drinking water source contaminated with faeces, contaminated water can transmit diseases such diarrhea, cholera, dysentery, typhoid, and polio. Contaminated drinking water is estimated to cause 485 000 diarrheal deaths each year, by 2025, half of the world's population will be living in water-stressed areas" [2].

Various methods have been created for many years to overcome this problem. Although some water treatment techniques were developed by the end of the 1800s, the first important steps were taken in the early 1900s. Firstly, chlorination, a chemical water treatment method, was used. To give an example, permanent water chlorination began in 1905, when a faulty slow sand filter and a contaminated water supply caused a serious typhoid fever epidemic in Lincoln, England [3]. This method is used to kill certain bacteria and other microbes in tap water as chlorine is highly toxic. But it is also harmful in terms of human health above a certain rate. During the same period, the ozonation water treatment method was used as the chemical water treatment method. On the other hand, Niels Ryberg Finsen proved that UV lights can be used for disinfection and awarded the 1903 Nobel Prize for Medicine with this

work. The first UV light disinfection system was planted in 1910 Marseille, France [4]. But prototype facility was shut down after a short period because of poor reliability. In 1955, UV water sanitation facilities were applied in Austria and Switzerland; in 1985 around 1,500 plants were active in Europe. In 1998 it was revealed that some protozoa types like giardia and cryptosporidium were extra vulnerable to UV light. This advance opened the way to the widespread use of UV water treatment in Europe. By 2001, more than 6,000 UV water sanitation plants were working in Europe [5].

The ultraviolet disinfection method is a purely physical water treatment process. This method is effective to disinfect even parasites such as cryptosporidium or giardia, which are tremendously resistant to chemical disinfectants [6]. Because of that reason UV light water treatment is a more comprehensive and reliable method. Nevertheless, UV water treatment systems are expensive and they consume huge electricity when used for large scale water treatment. UV water treatment systems can use UV mercury lamps, these lamps have some disadvantages. They are expensive, mechanically large, and they consume more energy. In California, approximately 8% of the state's electricity consumption is being used for sanitization and transportation of water [7]. In addition, UV lamp-based systems work with AC electricity so they need electricity networks to work. Because of these reasons, UV lamp-based water treatment systems are not an efficient choice for personal consuming, however development in the LED technology can change this situation. Over the last decades, some innovations occurred in LED technology, therefore now it is possible to develop energy efficient water systems in small sizes.

In spite of these improvements, UV LED-based water treatment systems need still a certain amount of electrical energy to achieve proper water disinfection. UV LEDs work with DC electric, this means it can be operated with several energy sources. Some of these are; battery, solar energy, electric dynamo, piezoelectric, etc. Nowadays, given the increasing need for clean and sustainable energy, some of the energy sources are more suitable than others. Considering these factors, piezoelectric is thought to be a decent energy source because it is sustainable and can be portable

when needed. Since piezoelectric matter can be produced in small sizes and by nature of the piezoelectric, the material can produce electricity when you apply pressure on the material. Consequently, UV LED can be used as a UV light source while piezoelectric material may be an appropriate choice for and energy source in a water treatment system. A patent owned by author of this study has been filed recently for such system design [8]. The proposed system generates its power using piezoelectric harvesting-based electrical power generated by simply user shaking.

Accordingly, this thesis gives further explanation about the design and parameter optimization of the system in [8]. It is planned to have optimal design parameters of the system for possible production. The proposed design has three characteristic sub-systems which are mechanical sub-system, piezoelectric energy harvesting sub-system, UV LED disinfection sub-system. Then, from the design and optimization point of view, the system has fairly complex design, and includes a combination of physical, geometrical and biochemical parameters. Hence, design parameters of each sub-system are determined firstly, and essential physical-mathematical models are enhanced. In this manner, overall system parameters and mathematical model of the system are improved. In conclusion, objective function (OF) is formulated, and optimal design parameters are specified for optimal operation of the system. To this end, Genetic algorithm (GA) is employed in single and multi-objective optimizations [9],[10],[11].

1.1 Research Problem

The need for clean water is raising day by day due to the environmental pollution caused by industrialization and the increasing population. Many solutions have been found to solve this problem and people are still working on it. Nonetheless, most of the solutions are for large scale water treatment so they have expensive plantation costs. Because of that, many countries cannot provide clean water properly to their own people. At the least, there is some home type solutions to water cleaning but some of them are expensive while others are not quite effective on water disinfection. Besides, there is no comprehensive solution for group of people that

have inadequate resources such as soldiers on the field, medical staff in the fields, immigrants.

Due to the above-mentioned reasons, people and institutions need a water treatment system that is good at disinfecting water, portable, and energy efficient.

1.2 Research Questions & Objectives

This thesis fundamentally aims to investigate and answer following question:

What are the parameters of the proposed system for efficient and effective design?

This question leads to numerous sub-questions like:

- What are the mechanical parameters of the proposed system considering portability and producibility?
- What are the physical and electrical parameters of piezoelectric energy harvester for an efficient and adequate energy generation process?
- What is the suitable UV dose for proper UV LED-based water disinfection system?
- What are the possible cost options of the proposed system?

1.3 Research Significance

Problems with access to clean water are growing steadily around the world. Contrary to popular belief, this problem is not only the problem of least developed or developing countries. There are also important problems in accessing clean water in developed countries. According to the United Nations 2019 Water Report, 30% of people in developed countries can only access basic purified water [12]. This means if an epidemic occurs, 30% of the population is vulnerable to the chemical resistant viral diseases. On the other hand, although most of the countries signed Biological Weapon Convention (BWC), a few countries did not agree with the convention [13]. Thus, the biological attack still is a risk for people living in the countries and armed forces of nations. Therefore, new ways to provide clean water is very important.

1.4 Study Limitations

This study is basically related to two main topics which are UV light water disinfection and piezoelectric energy harvesting. Although there are a lot of researches about UV light water disinfection with UV lamps, studies about water disinfection with UV LEDs are limited. This is one of the limitations of the study. The reason for this limitation is the fact that LEDs that can generate effectively on UV bands are commercially new. Although several kinds of researches have been done, there is still no confirmed standard about UV LED-based water disinfection in the world. Thus, the results of researches may change slightly from study to study.

Another key limitation is about the mechanical design of the system which is primarily related to mechanical engineering. However, this study is conducted by researchers in electrical & electronics engineering. Additionally, low wavelength UV LEDs and high energetic piezoelectric material cannot be produced in Turkey. Accordingly, these materials must be bought from abroad. This is another limitation because of custom legislations and cost of materials. Therefore, this study has been conducted in a theocratical manner.

CHAPTER 2

BACKGROUND INFORMATION AND LITERATURE REVIEW

In this chapter, some explanations about terms and concepts are given, which are important to understand the fundamental of the thesis. Then some studies in literature related to this study are mentioned.

2.1 Ultraviolet Light

Ultraviolet (UV) is a type of electromagnetic wave with a wavelength between 10 nm to 400 nm. In a comparison with other types of electromagnetic radiations, UV light has a wavelength shorter than visible light but longer than X-Rays as illustrated in Figure 2.1.

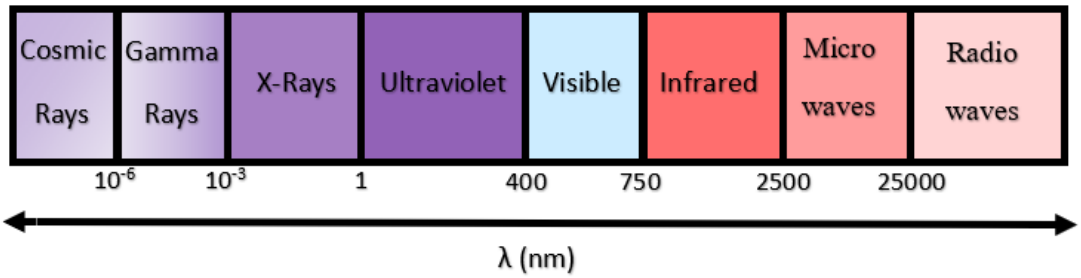


Figure 2.1: Electromagnetic radiation spectrum

Also, UV light is divided into four sections in the electromagnetic radiation spectrum. These are Vacuum, Short Wave (UV-C), Middle Wave (UV-B) and Long Wave (UV-A) as illustrated in Figure 2.2

UV light sources can be separated into two with respect to the source of light. The first one is natural sources, another one is artificial sources. By nature, extremely hot

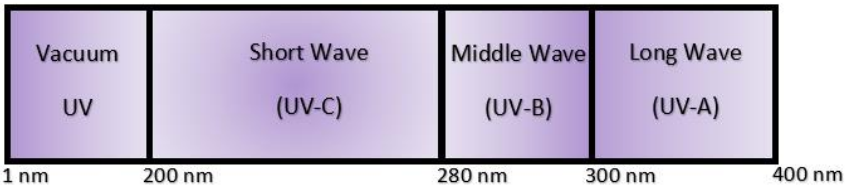


Figure 2.2: Ultraviolet radiation spectrum

objects radiate UV light. Although there is a lot of UV light sources in the universe, in our solar system the only natural UV light source is the Sun. Thus, the exosphere of the earth includes nearly 10% UV light of its own volume [14]. But the atmosphere prevents most of the UV light to go through the surface; prevention ration is nearly 77%. When the wavelength of light decreases, light absorption of the atmosphere relatively decreases as well. Therefore, sunlight includes only 3% UV light on the surface of the earth and this 3% is composed of UV-A and UV-B [15].

On the other hand, there are several human-made UV light sources. These are black lamps, UV lamps, gas-discharge lamps, UV lasers, and UV LEDs. Black lamps emit two types of lights; background light works like normal fluorescent and UV-A light. UV lamps emit UV-C band light with two different wavelength options which are 253.7 nm and 185 nm. UV lamps contain mercury to generate UV-C band light. They are inefficient because typically efficiency ratio is around 40%. Gas discharge lamps include different types of gases to generate UV light at different radiation spectrums. Generally, gas discharge lamps are used for scientific researches. UV lasers emit light that covers all UV band and they use some gases to produce UV light. Their area of application has spread to medicine, biochemistry, and communication. Another type of UV light source is UV LEDs. Recent developments in LED technology have led to commercially available UV-C LEDs. UV-C LEDs use semiconductors to emit light between 255 nm-280 nm. UV LEDs can emit different wavelengths with respect to the input current hence it can be said that UV LEDs are flexible to use different applications. Despite low input/output energy efficiency of UV LEDs, they have many advantages like wavelength flexibility, small physical sizes, and low power consumption. Also, LED technology is still developing, therefore UV LEDs will become more popular and useful for different applications.

2.2 Ultraviolet Disinfection

Ultraviolet germicidal irradiation (UVGI) is a disinfection technique that kills or inactivates microorganisms using UV-C band radiation. UV-C band radiation affects

protein-based structures (nucleic acids, DNA, RNA) of microorganisms hence prevent to harmful activations of them [16].

Specifically, when UV-C band radiation hits the DNA or RNA structure of microorganisms it disrupts pyrimidine dimers so it prevents reproducing [17]. The reason for that is the fact that DNA and RNA principally absorb UV light between 200 nm and 300 nm with a peak absorbance at about 260 nm [18]. Still, even if their DNA is damaged, some microorganisms have DNA-repair mechanisms (dark repair or photo-reactivation) [19]. Obviously, DNA repair is an undesirable process for the disinfection so there must be another way to get powerful disinfection. The DNA-repair mechanism can be dysfunctional by disrupting repairing enzymes with more absorbable UV radiation [20]. Furthermore, the maximum absorption wavelength of proteins is 280 nm so UV radiation at this wavelength can damage the DNA-repair enzymes [21].

However, the wavelength of UV radiation is not the only factor that can affect the UV disinfection process. Fundamentally, the UV disinfection process obeys the Bunsen-Roscoe reciprocity law and the law tells the photochemical effect of UV disinfection is dependent on total energy dose [22].

$$\text{UV Dosage} = \text{Radiation Intensity } (uW/cm^2) \times \text{Exposure Time(s)} \qquad (2.1)$$

Accordingly, Equation 2.1 states that UV dose is related to the three main variables. These are flux power, surface area, and exposure time. This equation is proven with a study on bacteriophages are Φx174, MS2, and B40-8 by Regina Sommer in 1998 [23]. Simultaneously, the same scientist found a deviation from this rule when he was doing research about the UV disinfection of E. coli bacteria. This result demonstrates that UV disinfection is not only the photochemical process but it is also related to biological reactions. Even though there are some deviations on Bunsen-Roscoe reciprocity law, the rule is still effective and accepted.

As a result of these studies, NSF (National Science Foundation) International which is a company founded for product testing, inspection, and certification organization published a standard for ultraviolet microbiological water treatment systems. When

the standard was created, ultraviolet lamps had been taken as a UV light source and degree of cleaning had chosen as 4-log (99.99% disinfected). Specifically, the standard is NSF/ANSI 55 and includes two types of water disinfection. These are Class A and Class B. They suggest two different UV doses for water disinfection process [24].

Class A: UV dose must be 40.000 uW-sec/cm^2 for disinfecting microorganisms containing bacteria and viruses. Class A may claim to disinfect water that may be contaminated with pathogenic bacteria, viruses, Cryptosporidium, or Giardia.

Class B: UV dose must be 16.000 uW-sec/cm^2 for supplemental bacterial treatment of public or drinking water that has been deemed acceptable by the local health agencies. Class B systems may claim to reduce normally occurring nuisance microorganisms.

2.3 Piezoelectric Effect

Piezoelectricity is an electromechanical phenomenon that occurs when mechanical stress is applied to a certain material. When mechanical pressure is applied to the piezoelectric substance, crystal structural symmetry disperses, hence an electromotive force emerges [25]. The first appearance of piezoelectric as a theory emerged in the field with the studies of brothers Pierre Curie and Jacques Curie in 1880 [26]. However, the first practical usage of piezoelectric was created for a sonar device during first World War in 1917, in France. The utilization of piezoelectricity in sonar, and the achievement of that venture, made extraordinary enthusiasm for the improvement of piezoelectric gadgets. Throughout the following years new piezoelectric materials, and new applications for those materials were investigated and created [27]. Then during the second World War, many independent research groups in the USA, Japan, and Russia created new synthetic materials that showed piezoelectric constants higher than natural materials. Therefore, these studies led to comprehensive research that improved barium titanate, and lead zirconate titanate. Thus, many applications related to piezoelectric had been opened. In other words, first studies were conducted with natural piezoelectric materials then scientists

discovered synthetic piezoelectric materials. Natural and artificial piezoelectric materials are classified in Table 2.1.

Table 2.1: Natural and artificial piezoelectric materials

Natural	**Artificial**
Silk	Lead zirconate titanate (PZT)
Rochelle salt	Gallium orthophosphate ($GaPO_4$)
Dentin	Potassium niobite ($KNbO_3$)
Sucrose	Sodium tungstate (Na_2WO_3)
Tendon	Langasite ($La_3Ga_5SiO_{14}$)
Topaz	Lead titanate ($PbTiO_3$)
Enamel	Lithium tantalite ($LiTaO_3$)
Quartz	Barium titanate ($BaTiO_3$)
DNA	Zinc oxide (ZnO)

Although all piezoelectric materials have a different structure and building blocks, they have a common structural property. This property, which is a structure with center of symmetry, is an obligation to reveal piezoelectric effect from the crystal [28]. Therefore, a pressure applied to the crystal will adjust the distribution of negative and positive charge blocks in the structure. This means the crystal surface has a net polarization of charges. The relation between pressure and polarization is linear in practice, i.e. polarization changes with the applied magnitude of physical pressure, so that the stress on the crystal will generate an electromotive force.

Considering producibility and efficiency, one of the most popular piezoelectric material is PZT. PZTs are polycrystalline ferroelectric materials/ceramics with the perovskite crystal structure. The structure of PZTs is a tetragonal/rhombohedral structure like cubic shape. Structure of PZTs are represented by A^{2+} B + $O^{2-}{}_3$ formula in which A denotes a large divalent metal ion like lead or barium, B denotes a tetravalent metal ion like zirconium or titanium. PZTs have cubic symmetry when the temperature of them is higher than the distinct point. This point is the Curie point that defines the temperature boundary for structure. If the temperature of PZT is

above the Curie point, structure of ceramic has simple cubic symmetry (Figure 2.3a), otherwise it is tetragonal symmetry (Figure 2.3b). However, tetragonal symmetry is a type of structural symmetry in which there is no symmetry for the charge of elements.

Hence, this type of symmetry provides ceramic piezoelectricity potential when stress is applied to the ceramic. Because when pressure is applied to the ceramic, each element of the ceramic structure becomes dipole. These dipoles are not randomly oriented in the structure, each dipole aligns with the others known as the Weiss domain. In the Weiss domain, because of the aligned dipoles, structure has a net dipole moment ($\bar{P}$). Thus, this net dipole moment gives a voltage difference between the top and bottom surface of ceramic (Figure 2.4b).

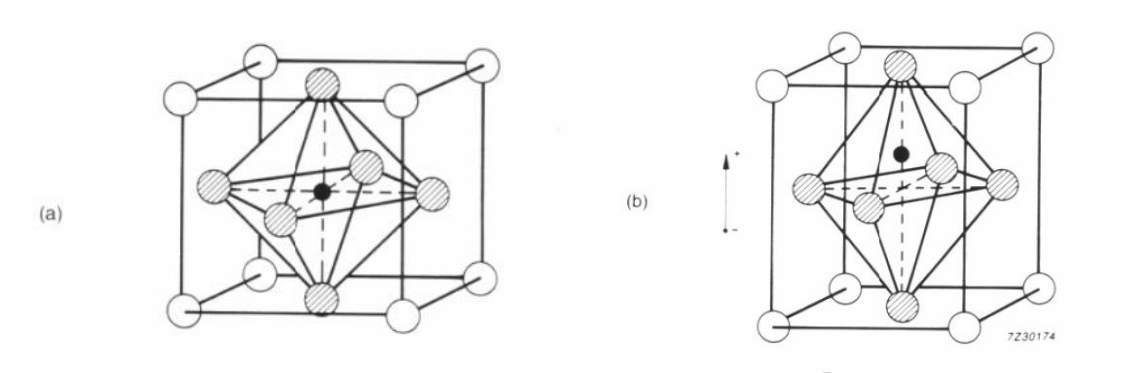


Figure 2.3: (a) Cubic symmetry of PZT (b) Tetragonal symmetry PZT [29]

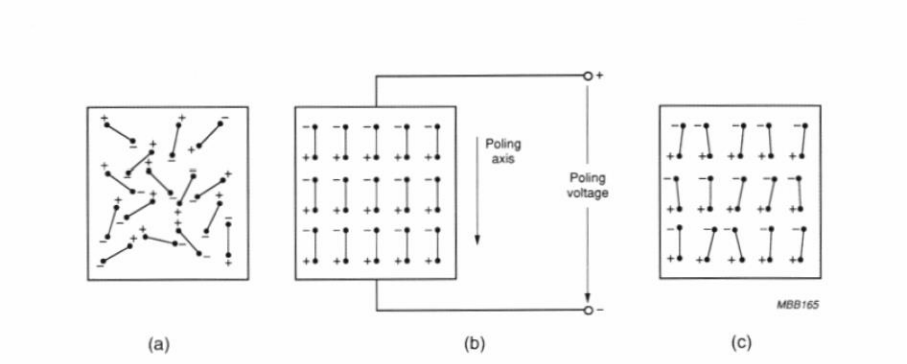


Figure 2.4 Electric dipole moments in Weiss domains [30]

This voltage direction depends on the direction of the pressure vector, the pressure vector creates dipoles with their own direction. Clearly, Weis domain net dipole moment has the same direction with pressure so electrical displacement ($\bar{D}$) occurs with the opposite direction. With respect to electrical permittivity(ε) and top-bottom distance (d) of the ceramic, magnitude of electrical displacement vector causes voltage difference (V) between the top and bottom surface of the ceramic.

$$V = \frac{|\bar{D}| * d}{\varepsilon} \tag{2.2}$$

Also, several other electrical parameters are calculated with respect to these variables. One of these is electrical field ($\bar{E}$):

$$\bar{E} = \frac{V}{d} \tag{2.3}$$

Then, capacitance of the ceramic is calculated using dimensional variables.

$$C = \frac{A * \varepsilon}{d} \tag{2.4}$$

Therefore, with respect to these formulas and variables many other electrical properties of piezoelectric materials can be derived.

On the other hand, these properties depend on the other two parameters. These are the shape of the piezoelectric ceramic, and the axis of applied pressure. For example, PZT ceramics can be produced in several shapes, these are; disc, rectangular plate, hemisphere, cylindrical tube, cylindrical rod, etc. The shape of the PZT directly affects the electrical parameters of ceramic because area of the ceramic is used in the calculation of several parameters. Axis of applied pressure is another important factor in piezoelectricity because PZTs are not isotropic materials. Hence a lot of

electrical parameters of PZT depend on the axis of applied pressure. Thus, the parameters are mostly given in two subscript indices which denote the direction of the two related quantities. The first subscript denotes the direction of the electrical displacement ($\bar{D}$) and the second one denotes the direction of electrical field ($\bar{E}$): To give an example, electrical permittivity of PZT under stress from 3 direction represented by ε_{33}.

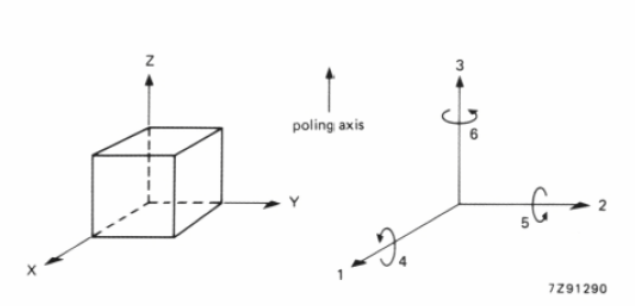


Figure 2.5: Axes and orientation of PZT [31]

2.4 Piezoelectric Energy Harvesting

Piezoelectric energy harvesting is a process which generates electrical energy from mechanical energy using piezoelectric materials. As mentioned before, piezoelectric materials generate electromotive force when mechanical effects are applied on them. In other words, the applied strain (force, pressure, stress, etc.) reasons the crystal/ceramic to become electrically polarized therefore the crystal/ceramic produces a voltage. Hence, the piezoelectric material is a suitable choice for a lot of studies about energy harvesting with this property.

Considering the properties mentioned above, piezoelectric ceramic/crystal can be used as a power source like a battery. But piezoelectric materials can produce only impulse like voltage due to their nature. These produced impulses can be converted to AC signals with periodic mechanical stress. The Figure 2.6 is representing periodic mechanical stress on a PZT ceramic and Figure 2.7 is representing output voltage of PZT ceramic. As it is seen, sinusoidal mechanical stress produces AC voltage output.

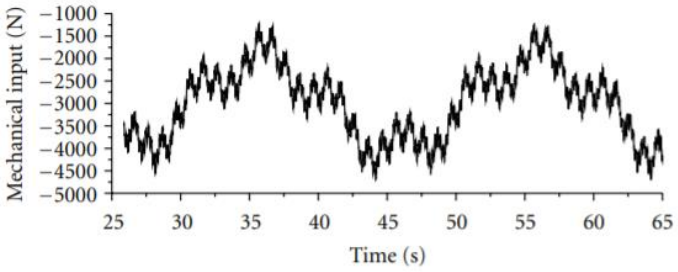


Figure 2.6: Periodic mechanical input [32]

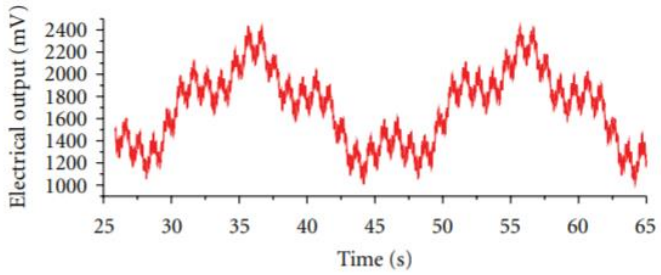


Figure 2.7: PZT voltage output [32]

Still, signals need a rectification to get DC signal, so this operation can be provided by using bridge rectifiers. Full-wave bridge rectifier (FWBR) is a structure that has four diodes (or P-N junction block) to provide the same polarity of the output signal. Full-wave bridge rectifier gives the same output polarity, independent of input polarity. Full-wave bridge rectifier structure is represented in Figure 2.8.

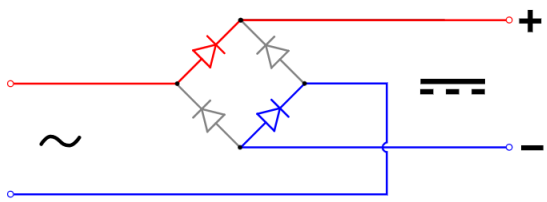


Figure 2.8: Full-wave bridge (FWBR) rectifier

With using full-wave bridge rectifier, output of piezoelectric ceramics almost transform to DC signal. Figure 2.9 represents the input of the full-wave bridge rectifier and Figure 2.10 represents the output of the full-wave bridge rectifier. Consequently, the signal can be used as a DC source for any application.

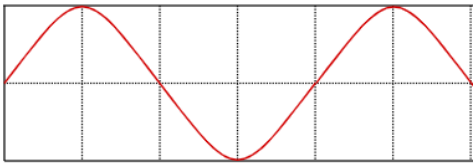


Figure 2.9: FWBR input signal

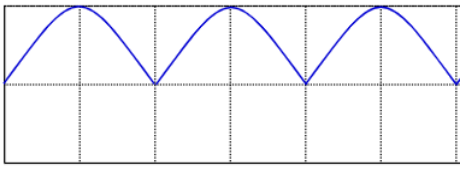


Figure 2.10: FWBR output signal

2.5 Systems in Literature

In this chapter, water disinfection systems in the literature are examined. Firstly, the proposed system in this thesis is a unique study and patent application has been done to the TÜRK PATENT in 28.12.2019 [8]. Thus, in literature review, directly similar studies cannot be found. However, there are still comparable studies in the literature. These systems have some similarities and differences in disinfection methods or energy sources.

2.5.1 Chemical Water Disinfection Systems

Chemical water disinfection is the most common water disinfection method, namely, conventional disinfection. Chemical water disinfection concept includes many methods like Chlorine disinfection, Chlorine dioxide disinfection, Chlorination, and Ozone disinfection etc. All these methods aim to disrupt cell structure of harmful microorganism via chemical reactions. However, these chemical ingredients can get into unwanted chemical reactions with other organic particles [33]. Chemical water disinfection method is generally used for large-scale disinfection operations like obtaining clean municipal water sources. But there are some examples for portable small-scale water disinfection.

To give an example, a system, which has patent application number US6736966B2, offers a portable disinfection system [34]. System has oxidant generator to compose a chlorine or chlor-oxygen and this generator is supplied with battery. Using the generator, chlorine or chlor-oxygen is created; hence contaminated water is cleaned

using chemicals. Nevertheless, this system and other chemical disinfection systems have some disadvantages which are listed below:

- Ineffective to destroy some microorganisms like Cryptosporidium and Giardia.
- Storage/Transportation of chemical ingredients is expensive and difficult.
- After the chemical disinfection process, harmful sediments remain.
- Chemical process can change the taste of water.
- Chemical reactions exhibit corrosive effects on the system (needs maintenance).

2.5.2 UV Mercury Lamp Based Water Disinfection Systems

This type of water disinfection system uses the UV light disinfection method. As stated in section 2.2 UV band light is an effective method to kill or inactivate microorganisms. Especially, the UV-C band is appropriate to disinfection because of the absorbance level of microorganism's cell structures like DNA, RNA, and enzymes. Theoretically, UV mercury lamps can radiate between 180-600 nm but practically the lamps are efficiently usable around 250 nm and 400 nm. Therefore, UV mercury lamps can be used in water disinfection system.

In the literature, some examples are available. One of these examples is a portable water purifier with ultraviolet source [35]. The system is a portable water disinfection system that includes UV mercury lamp inside. The lamp is covered by transparent plastic to prevent water leakage. In the bottom of the system, an electrical input is designed for energy source connection. Nevertheless, the energy source type is not indicated. Consequently, this system and other UV mercury lamp disinfection systems have some disadvantages which are listed below:

- Energy consumption of UV mercury lamps is high, so systems require electrical grid or huge batteries as an energy source.
- UV mercury lamps include mercury, and mercury is toxic to human.

- Size of UV mercury lamps is big so they are not a suitable choice of portable systems.
- UV mercury lamps have narrowband spectrum so they have less disinfection efficiency for different microorganisms.
- The system requires maintenance because the lifetime of mercury is relatively short.

2.5.3 Battery Powered UV LED Based Disinfection Systems

This type of disinfection system uses UV LED as a UV light source. UV LEDs have wide bandwidth; from this aspect they are suitable for creating UV disinfection systems that have large disinfection spectrum [36]. Although UV LEDs have wide bandwidth, their output flux power is less than UV lamps. LED technology is still developing so LEDs are producing with more flux power. On the other hand, UV LEDs have a better choice for portable disinfection systems because their sizes are small and they have less power consumption. From this point of view usage of the UV LEDs is becoming more popular in new UV LED disinfection studies.

A study offered a system that is a water bottle that has a UV LED embedded cap in 2015. [37]. The cap has UV LED at the bottom side to radiate through the water. It has a battery inside to drive UV LEDs. Literally, the system is a battery powered UV LED disinfection system. Although this system has many advantages because of the UV LED, battery-powered systems may cause some disadvantageous. These disadvantageous are listed below:

- Lifetime of typical batteries is limited by their chemical life (2-3 years).
- Batteries are unstable in extreme temperature conditions.
- Batteries need recharge so the system is useless for long time outdoor activities.
- Batteries can contaminate water chemically because of their ingredients [38].
- Batteries occupy a big place in the system.
- Because of the batteries internal structure system must have overcharge protection circuit.

2.5.4 Solar-Powered UV LED Based Disinfection Systems

Solar energy is a mainstream renewable energy and it can be transforming to electrical energy. This transformation is provided by photovoltaics. Photovoltaics is a type of semiconductor which can exhibit photovoltaic effect under the solar light. In other words, photovoltaics can transform photons to free electrons. Hence, photovoltaic cells (PVC) are used for solar power energy harvesting. Harvested electrical energy can be used for powered UV LED disinfection system. The advantages of UV LED are stated in previous sections.

In the literature, one of the available examples is a solar-powered portable water purifier [39]. The study offers a portable water purifier using the UV disinfection method. The system includes one contaminated water input and one clean water output. Fundamentally, contaminated water flows in UV lightened environment, so disinfected water is gathered. The system is powered by photovoltaic cells that are located on top to get more solar radiation. Although solar power is clean and renewable energy, solar-powered disinfection systems have some problems. These are listed below:

- Photovoltaic cells are physically fragile so they are not suitable to extreme conditions.
- If PVCs are dirty, their efficiency is less so they need maintenance.
- Major disadvantage of solar-powered systems is that they are completely useless without sunlight if they do not have storage block.
- If they have a battery for storage, all disadvantageous are listed section 2.5.3

2.5.5 Solar Energy Concentrated Disinfection Systems

This type of disinfection system has no electrical power source, they use direct sunlight for UV disinfection. When sunlight reaches to the surface of the earth, it includes UV-A and UV-B band UV light. But the sunlight has not much UV light because of the atmosphere. Thus, sunlight must be concentrated to get efficient UV disinfection. Generally, the sunlight concentration process is done by optic materials.

In the literature, some studies are available and one of these is apparatus for solar-based water disinfection [40]. The system is a portable water container and it is composed of transparent denser material. The aim of the system is to concentrate sunlight through contaminated water to UV disinfection. Hence, the system has zero energy consumption and it is almost completely renewable. Although the system has advantages about energy handling, it also has many disadvantages. They are listed below:

- Sunlight does not have UV-C band light hence comprehensive disinfection is not possible.
- Optic systems used for sunlight concentration are fragile so the system is not suitable for outdoor usage.
- Generally, this type of systems needs a certain temperature level so it is not a suitable choice for cold places.
- They are useless in the palaces without sunlight.
- Disinfection process directly depends on sunlight so the duration of disinfection process is unpredictable.

2.5.6 Summary of Literature Review

To sum up, portable water disinfection systems in literature are examined in five main titles and their disadvantageous are mentioned. The proposed system in this thesis designed considering these disadvantages hence the developed system took a step further in a portable water disinfection concept. By name, the proposed system is the Piezoelectric Powered Ultraviolet Portable Water Cleaning System. The system offers a water disinfection system which uses the UV disinfection method and is powered by piezoelectric materials. The system aims to disinfect a certain amount of water using UV LEDs and harvest enough energy for the disinfection process using human arm movement via piezoelectric materials.

In the proposed system piezoelectric materials are used as a power source. This provides some advantages that are listed below:

- Piezoelectric materials provide the ability that transforms mechanical power to electrical power. Hence using piezoelectric materials can be used to transform body movements to electrical energy. It is renewable and clean energy.
- Because of solid structure and wide operation temperature, they are suitable for operating in extreme conditions.
- Does not need complex mechanical systems for generating electrical energy, simple applied force is enough.
- Piezoelectric materials can be produced with different shapes and sizes.
- Do not need maintenance or recharge.

The system uses UV LEDs for the disinfection process so this provides several advantages that are listed below:

- UV LEDs generate flux in a wide wavelength range so they are suitable for comprehensive disinfection.
- UV LEDs have low power consumption.
- They can be produced in small sizes.
- They have long lifetime (17 years for 8h daily working).

Besides, the proposed system has many other advantages because of mechanical design, UV disinfection method, and energy harvesting method. These are explained next chapters.

CHAPTER 3

SYSTEM DESIGN

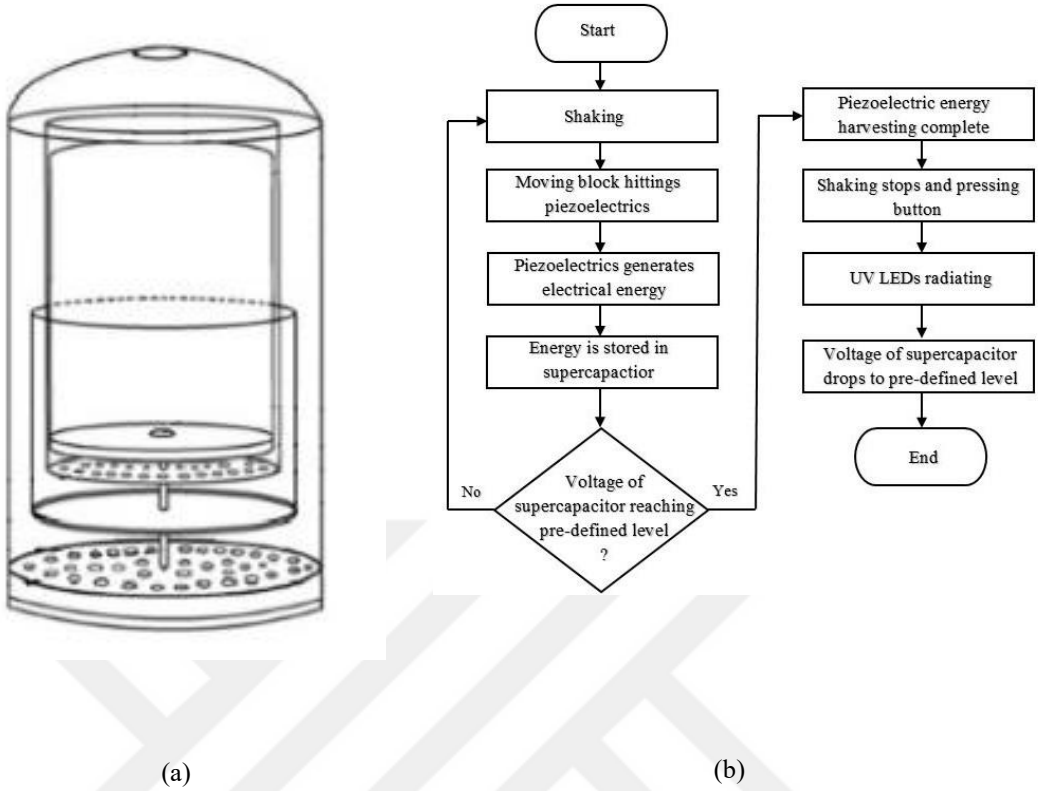
This section designates the theoretical model of the piezoelectric powered portable UV LED water disinfection system which is proposed in [8]. Furthermore, in this section parameters of the sub-systems are specified.

3.1 Operation of the System

Generally, the proposed system aims to harvest electricity from human hand shake via a piezoelectric harvester which is embedded to the body. It uses generated electricity to supply UV LEDs for UV water disinfection.

In more detail, operation begins with shaking the system up and down with hand. In every up and down motion, bottom of moving part hits piezoelectric blocks. Thus, mechanical energy is converted to electrical energy by piezoelectric materials which are located on the piezoelectric blocks. Piezoelectric blocks are connected by a bunch of cables. The generated electricity is continuously being stored in a supercapacitor which is part of piezoelectric harvester. Supercapacitor voltage level is shown by a digital panel voltmeter. Accordingly, a user can follow the voltage level from the screen, therefore, when voltage level reaches to a certain level, user can stop shaking the bottle.

After energy harvesting process is finished, user can push the button to start water disinfection process. The button electrically connects supercapacitor and UV LED block. Finally, UV LED block, which is located under the transparent drinking glass, radiates through the water and UV disinfection process continues until voltage level of the supercapacitor decreases to a certain level. Shown in Figure 3.1b is flow of system operation.



(a) (b)

Figure 3.1: (a) Illustration of main components [8] (b) flow showing operation of the system.

3.2 Modelling of the System

This section covers design details with the theoretical background and determination of system parameters. Broadly, the proposed system is composed of three sub-systems. These are; mechanical system, piezoelectric energy harvester, UV disinfection system. Fundamentally, the mechanical system is responsible for covering all of the sub-systems and transferring mechanical movement (M) of the human arm to piezoelectric energy harvester. Piezoelectric energy harvester transforms mechanical energy (E_M) to electrical energy (E_E) and stores the energy. The stored energy is used for water disinfection (D) by the UV disinfection system. Conceptual approach of operation flow is illustrated in Figure 3.2.

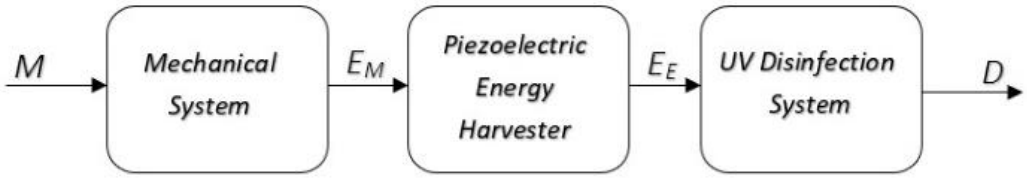


Figure 3.2: Operation flow

3.2.1 Mechanical System

The mechanical system consists of three main structures. These are; main body, moving block, and transparent drinking. The main body covers all the systems from inside to outside and presents mounting areas for embedding moving block, transparent drinking glass, and lower/upper cap.

The key part of the mechanical system is moving block. Mainly, the moving block is a hollow cylinder and it moves up/down inside the main body. The moving block provides an ability that applies the force (*F*) on piezoelectric blocks when the main body is shaking. This process enables the energy harvesting from piezoelectric materials. The mechanical force of the moving block is affected by two parameters, which are the mass of the moving block (*m*) and main body shake acceleration (*a*). Mass of the moving block is affected by the inner-outer radius of the block (r_2, r_1), the height of the block (h_1), and density of the block constituent (*g*). Body shake acceleration constraints are specified experimentally by using a mobile accelerometer application. In the experiment, a smartphone was shaken up and down for a while, and the accelerometer application recorded the acceleration values. A section of acceleration data is illustrated as a graph in Figure 3.3. In regard to the experimental data, body shake acceleration is assumed.

$$F = m\,a \tag{3.1}$$

$$m = g\,\pi\,[h_1(r_1^2 - r_2^2) + r_2^2\,(r_1 - r_2)] \tag{3.2}$$

Another part of the mechanical system is the transparent drinking glass. The most important parameter of this part is its floor radius (r_3) since the radius directly affects the UV dosage.

Still, all parameters must be specified mathematically for the selection of proper and efficient design. Sizes of the moving block are determined considering portability and producibility. The outer radius of the block is specified as a constant. With respect to this constant, constraints of the inner radius are assumed. In addition to portability and producibility criteria, limitations of the height of the moving block are specified considering the certain amount of mass to produce sufficient mechanical pressure. Another parameter of the moving block is the density of the substance that is chosen as a type of steel alloy 3D filament. The final parameter in the mechanical system is floor radius (r_3) of a transparent drinking glass that is determined with respect to the minimum of the inner radius of the block. All the parameters are depicted in Table 3.1.

Table 3.1: Mechanical system parameters

Parameter	**Value**
Shake acceleration	$25 \leq a \leq 35$ (m/s^2)
Height of the moving block	$0.06 \leq h_1 \leq 0.1$ (m)
Outer radius of moving block	$r_1 = 0.036$ (m)
Inner radius of moving block	$0.031 \leq r_2 \leq 0.035$ (m)
Floor radius of the drinking glass	$r_3 = 0.03$ (m)
Density of the block constituent	$g = 3500$ (kg/cm^3)

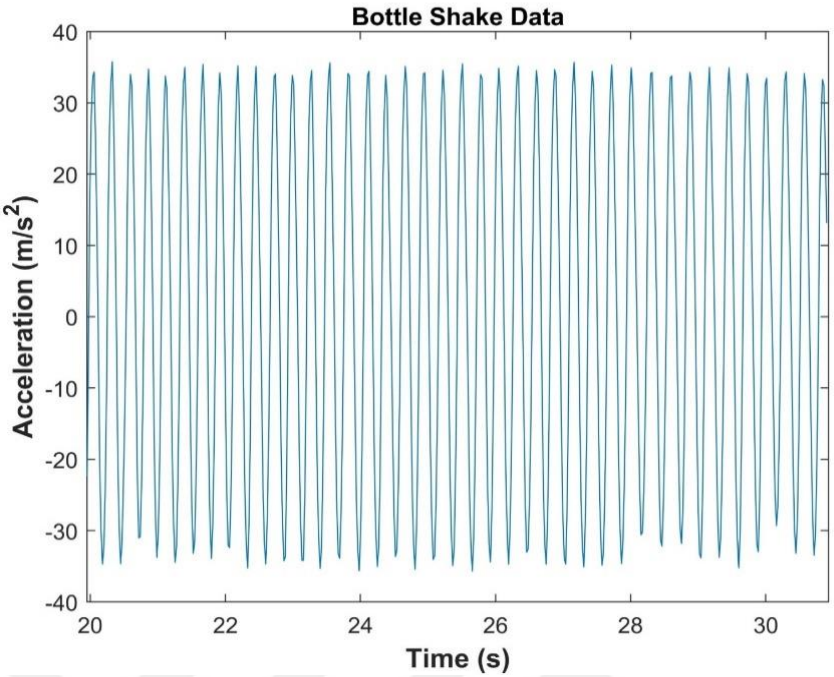


Figure 3.3: Acceleration data

3.2.2 Piezoelectric Energy Harvester

In general, energy harvesting can be identified as collecting small amounts of energy from ambient energy sources and storing them. Vibrations are considered as ambient energy sources and they can be absorbed by a harvester that has a transduction mechanism. One of the significant mechanisms is piezoelectric energy harvester because they are naturally capable of transforming mechanical energy to electrical energy [41]. Piezoelectric materials are tight and they have almost three times higher energy capacity as compared with counterparts [42]. In addition, they are lighter and their production is comparatively simple. These features make piezoelectric energy harvesters a suitable candidate for portable and energy-efficient applications. Accordingly, several piezoelectric energy harvesters are developed in the past [43],[44],[45].

This study offers a novel piezoelectric energy harvester system because of the system structure. As mentioned before, one of the aims of the systems is to turn the mechanical energy of the moving block to electrical energy. Respectively, the design of the piezoelectric energy harvester must be suitable for this aim. Thus, the

piezoelectric energy harvester has two piezoelectric blocks; the first one is located at the bottom of the moving block and the second one is located above the moving block. Consequently, the moving block moves up and down when the bottle is shaking. Thus, piezoelectric blocks are subjected to mechanical pressure.

In every hit of the moving block, piezoelectric materials generate certain amounts of AC signal [32]. Then, the generated AC signal is transformed by a full-wave bridge rectifier to store harvested electrical energy. Distinctly the proposed piezoelectric energy harvester has extra two diodes in the output of the piezoelectric blocks. These diodes are responsible for the prevention of reverse voltage to avoid reverse piezoelectric effect and energy loss. Consequently, generated electrical energy is canalized to the storage part directly. In the system, the storage part is chosen as a supercapacitor because there are several advantages of supercapacitors. These are; broad operating temperature range, charge–discharge efficiency, and long lifetime [46].

The piezoelectric energy harvester system has several parameters. Principally, parameters of piezoelectric material are essential because the piezoelectric materials are used as a power source in the system. In this study, Navy Type II PZT circular shape ceramics are chosen as piezoelectric materials. Fundamental properties of Navy Type II PZT for mod_{33} (thickness mode) are tabulated in Table 3.2.

Table 3.2: Navy Type II PZT properties

Property	**Value**
Damping ratio	$\zeta = 0.01$
Piezoelectric Charge Constant (10^{-12} m/V)	$d_{33} = 400$
Piezoelectric Voltage Constant (10^{-3} Vm/N)	$g_{33} = 24.8$
Frequency Constant (Hz-m)	$N_T = 2040$

As well, PZT ceramic sizes are important in energy harvesting operation. PZT ceramic dimensions are thickness (h_2) and diameter (r_3). They are chosen regarding the size of piezoelectric blocks and producibility of ceramics. Obviously, other important parameters are the number of PZT ceramic (N) and bottle shake frequency

(f_s) since they directly affect total harvested energy. f_s is specified as around 6 Hz with respect to experimental results which are illustrated in Figure 3.3. However, in realistic design f_s can be lower because of varieties in mechanical design. Therefore, *fs* is estimated less than experimental results. The piezoelectric energy harvester parameters are listed in Table 3.3.

Table 3.3: Piezoelectric energy harvester parameters

Parameter	**Value**
Thickness of PZT ceramic	$0.001 \leq h_2 \leq 0.003$ m
Diameter of PZT ceramic	$0.01 \leq r_4 \leq 0.02$ m
Number of PZT ceramic	$0 \leq N \leq 10$
Bottle shake frequency	$3.5 \leq f_s \leq 5.0$ Hz

Another important parameter is the generated electrical power from one PZT ceramic. In previous studies, a piezoelectric energy harvester is mathematically modeled in the general form in [47]. Then regarding this mathematical model, a generic Equation 3.3 is derived for piezoelectric energy harvester.

$$P = \frac{m\,\zeta\,V^2\left(\frac{w_s}{w_n}\right)w_s^3}{(1-(\frac{w_s}{w_n})^2)^2 + (2\zeta\frac{w_s}{w_n})^2} \tag{3.3}$$

At low frequencies denominator of the Equation 3.3 approaches one, at that point it can be ignorable. Accordingly, it can be expressed as below.

$$P = m\,\zeta\,V^2\left(\frac{w_s}{w_n}\right)w_s^3 \tag{3.4}$$

The formula includes four sub-formulas, these are; mass (m), natural frequency (w_n), system frequency (w_s), and generated voltage (V). Equation 3.2 expresses mass (m) of the system and it is calculated in section 3.2.1. Other formulas are introduced below respectively.

$$w_n = 2\pi N_T / h_2 \tag{3.5}$$

$$w_s = 2\pi f_s \tag{3.6}$$

$$V = \frac{4 g_{33} h_2 F}{\pi r_4^2} \tag{3.7}$$

3.3.3 UV LED Disinfection System

As mentioned before a standard is developed for UV mercury lamp-based (254 nm) UV water disinfection in the name NSF/ANSI 55 [24]. The standard presents Class A UV disinfection dose to achieve 4-log (99.99%) disinfection. The standard claims 400 W*sec/m2 UV dosage enough for 99.99% water disinfection. Although extensive knowledge is available about UV mercury lamp-based UV water disinfection, there is no well-proven standard for UV LED-based UV water disinfection. Moreover, several studies showed that the disinfection performance of UV LED and UV mercury lamp may differ for the same wavelength. The comparative disinfection performance (4-log) of UV LED and UV mercury-lamp with three wavelengths is tabulated in Table 3.4 which includes the performance on six different microorganisms.

Table 3.4: 4-log disinfection performance of UV LED and UV lamp

Microorganism	Wavelength (nm)	UV Source	K (cm^2/mj)	Ref.
Φx174	254	UV lamb	0.396	[48]
Φx174	255	UV Led	0.360	[49]
Φx174	280	UV-Led	0.578	[49]
E. coli	254	UV lamb	0.506	[48]
E. coli	255	UV-Led	0.300	[50]
E. coli	280	UV-Led	0.290	[19]

Table 3.4 (cont.)

T7	254	UV lamb	0.232	[48]
T7	255	UV-Led	0.195	[50]
T7	280	UV-Led	0.235	[50]
Bacillus subtilis	254	UV lamb	0.059	[48]
Bacillus subtilis	255	UV-Led	0.051	[51]
Bacillus subtilis	280	UV-Led	0.120	[52]
Qβ	254	UV lamb	0.084	[48]
Qβ	255	UV-Led	0.080	[49]
Qβ	280	UV-Led	0.035	[49]
MS2	254	UV lamb	0.055	[48]
MS2	255	UV-Led	0.038	[50]
MS2	280	UV-Led	0.033	[49]

In the system, two UV LEDs are used. One of these has 255 nm wavelength to get the maximum disinfection performance on DNA and RNA. Another one has 280 nm wavelength to get the maximum disinfection performance on DNA-RNA repair enzymes. Hence, the comparative methodology can be followed to determine suitable UV lethal dosage. UV lethal dosage ratio between UV LEDs (255 & 280 nm) and UV lamb can be calculated using data in Table 3.5.

Table 3.5: Comparison of UV LEDs dosages w.r.t UV mercury lamp

Microorganism	**UV dose at 255 nm**	**UV dose at 280 nm**
Φx174	10% more	32% less
E. coli	68% more	74% more
T7	19% more	0.02% less
Bacillus subtilis	15% more	50% less
Qβ	0.05% more	204% more
MS2	44% more	66% more

Principally, according to NSF/ANSI 55, 400 W*sec/m^2 UV dosage is enough when using the UV mercury lamp for 4-log UV disinfection. Therefore, to determine UV

dosage with respect to Table 3.4, halves of UV dosage for 255 nm and another half of the UV dosage for 280 nm can be chosen. Moreover, to guarantee 4-log disinfection performance regarding Table 3.5, 90% extra UV dosage (180 W*sec/m^2) can be added to each wavelength. In other words, to adapt the standard of NSF/ANSI 55 to UV LED, 180% UV dosage can be applied for each wavelength, then appropriate protection can be provided. Consequently, 360 W*sec/m^2 must be applied with each of the UV wavelengths so UV dosage for two UV LEDs became 720 W*sec/m^2. However, as it is seen from Table 3.4, UV dosages can change in different microorganisms. To overcome this problem, 15% safety margin can be added to predefined UV dosage. Accordingly, total UV dosage (D_{UV}) can be chosen as 792 W*sec/m^2. After specifying D_{UV}, two parameters remain for determination. These are UV LEDs power consumption (P_d) and UV LEDs flux power (ϕ). Power consumption and flux power of UV LEDs are specified with respect to off the shelf products. UV LED disinfection parameters are tabulated in Table 3.6.

Table 3.6: UV LED parameters

Parameter	**Values**
UV LEDs power consumption	$1.5 \leq P_d \leq 2.5$ (W)
UV LEDs flux power	$0.005 \leq \phi \leq 0.01$ (W)
UV dosage	$D_{UV} = 792$ (W*sec/m^2)

CHAPTER 4

OPTIMIZATION

Optimization is a mathematical procedure to obtain minimum or maximum output when adjusting input parameters. The optimization process is conducted by an optimization algorithm that is responsible for searching possible suitable solutions. The aim of this section is to demonstrate the applicability of the optimization with some major parameters defined in Chapter 3.

4.1 Shake Duration

Considering user viewpoint, the shake duration (T_S) can be taken as the first objective function (OF). This helps to estimate the minimum shake duration for typical ranges of all design parameters in suitable limits. The OF can be derived dependent upon mechanical aspects, energy harvesting, and desired UV disinfection performance of the system. Then, the harvested energy can be expressed as

$$E_h = P\ N\ T_S \tag{4.1}$$

where N is the number of PZT ceramic, T_S is bottle shake duration.

Following, the dissipated energy can be written as

$$E_d = P_d\ T_d \tag{4.2}$$

where P_d is the average power of UV LED, T_d is the duration of the UV disinfection process. Furthermore, T_d can also be derived in terms of the predefined UV dosage together with UV LEDs flux power (ϕ) using

$$T_d = \pi\ r_3^2\ D_{UV}\ /\phi \tag{4.3}$$

where D_{UV} is the UV dose given in Table 3.6. Therefore, 4.2 can be re-written as

$$E_d = \frac{2.25\,P_D}{\phi} \tag{4.4}$$

By equating Equations 4.1 and 4.4, the shake time can be represented as follows

$$T_S = \frac{2.25\,P_D}{P\,N\,\phi} \tag{4.5}$$

By expanding the terms using Equations 3.1, 3.2, 3.4, 3.5, 3.6, and 3.7, the power, *P*, can be re-written as

$$P = \frac{1.61{*}10^6\,h_2^3\left(0.001296\,h_1 - h_1 r_2^2 + 0.036\,r_2^2 - r_2^3\right)^3\,F_S^4\,a^2}{r_4^4} \tag{4.6}$$

Finally, replacing the power in Equation 4.6, the shake duration can be written as

$$T_S = \frac{2.25\,P_D\,r_4^4}{1.61{*}10^6\,N\,\phi\;\;h_2^3\left(0.001296 h_1 - h_1 r_2^2 + 0.036\,r_2^2 - r_2^3\right)^3\,F_S^4 a^2} \tag{4.7}$$

4.2 Cost of the System

Fundamentally, the cost of the system is affected by two main components. These are UV LEDs and PZT ceramic. In addition, these components take a major role in both piezoelectric energy harvesting and UV disinfection processes. The next objective function (OF) is the cost of the system and it can simply be derived regarding the market price changeability of these components. Firstly, considering market prices of PZT Navy type II ceramic (*N*) of 4$ - 5$, the cost of the ceramic can be expressed, as a linear function of the number of ceramics (*N*), as follows

$$C_1 = 4.5N \tag{4.8}$$

Following, when the market price of UV LED is examined noted that flux power (ϕ) of UV LEDs affects the prices linearly. As per the dosages given in Table 3.6 and considering the market prices of UV LEDs of 9$ -50$, the cost of two UV LEDs can be expressed as

$$C_2 = 529\phi \tag{4.9}$$

At that point, the total cost of the system can be represented as

$$C = 4.5N + 529\phi \tag{4.10}$$

4.3 Genetic Algorithm

In the literature, there are various optimization algorithms such as direct method, gradient-based, geometric programming, and genetic algorithms (GA). In this study, the genetic algorithm has been used as an optimization algorithm. GA is created using evolutionary mechanisms of living beings [53]. GA optimization has several advantages over traditional optimization algorithms. Such GA can be used to solve non-linear problems and it does not need derivative information [54]. GA optimization presents a global optimization solution when minimizing or maximizing OF [53]. Besides, GA optimization is directly used for optimizing system parameters in many studies [55],[56]. Therefore, these properties make GA optimization a suitable candidate for optimal design problems like in this study. GA optimization has a specific process flow as represented in Figure 4.1. The first stage of the GA algorithm is the generation of initial populations. Primary populations (chromosomes) are chosen randomly obeying the constraints. The second step is evaluating the fittest OF using each chromosome and ranking the results. Then, the evaluated chromosomes are chosen to form a new generation considering their fitness performance. There are several selection methods available in theory, and the stochastic uniform selection is employed in this study. The method ensures diversity in the population so it prevents insufficient preterm solutions [57]. Subsequently, the crossover operation begins respecting the selection of fittest parent. The crossover is used to exchange some part of the chromosomes to produce a next generation offspring [58]. Finally, mutation period starts to alter chromosomes randomly. Both the crossover and the mutation are performed regarding with the constraints of system parameters. All procedures are performed continually until the targeted termination criteria is reached.

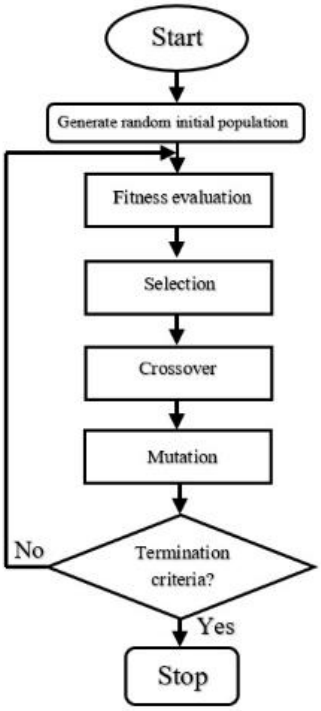


Figure 4.1: GA optimization flowchart

CHAPTER 5

RESULTS

Initially, single objective optimization is realized. At that point, the cost of the system is neglected, and the shake duration is chosen as the OF. The minimum shake duration along with an optimal set of the parameters are specified regarding the range of constraints on the input parameters. Shown in Figure 5.1 is the variation of fitness value in GA optimization.

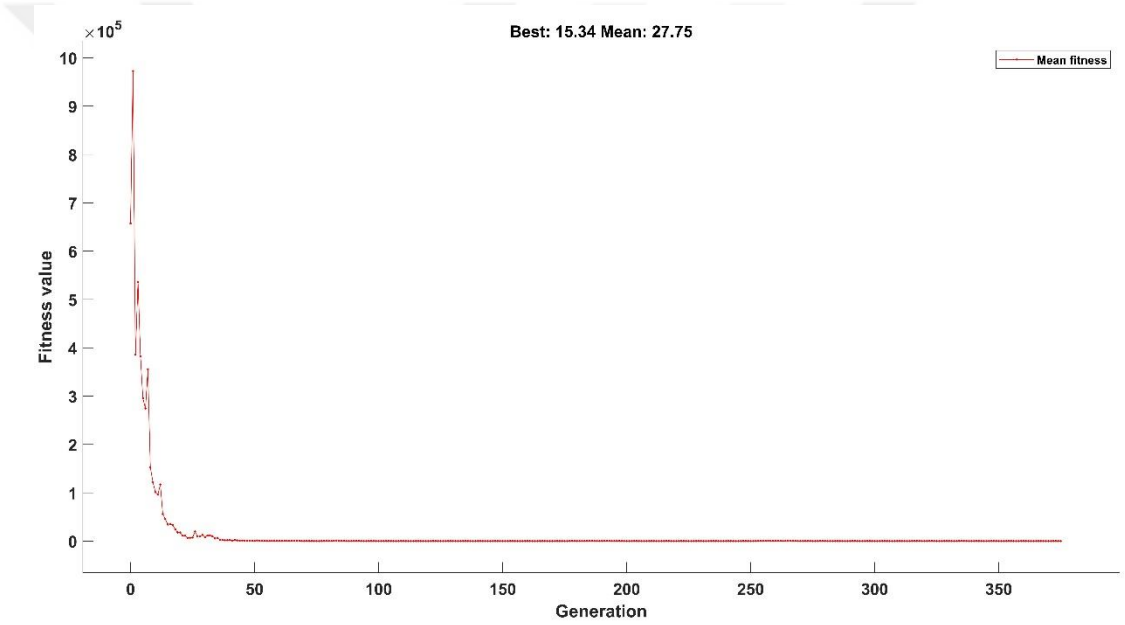


Figure 5.1: GA optimization process

The fittest T_s value is found as 15.34 seconds in 375th generation. GA optimization creates the optimal values of the design parameters with the derived parameters as tabulated in Table 5.1.

Table 5.1: Optimal system parameters (OF: shake duration)

Definition	Parameter	Value
Power dissipation of UV LEDs	P_D	1.5 W
Number of PZT ceramic	N	10
Flux power of UV LEDs	ϕ	0.08 W
Bottle shake frequency	F_s	5.5 Hz
Bottle shake acceleration	a	35 m/s^2
Height of moving block	h_1	0.1 m
Piezoelectric ceramics thickness	h_2	0.003 m
Inner radius of moving block	r_2	0.031 m
Piezoelectric ceramic diameter	r_3	0.01 m
Mass of the moving block	m	0.42 kg
Applied force on PZTs	F	14.74 N
Generated voltage	V	13.96 V
Total harvested energy	E_h	42.19 J
Disinfection duration	T_d	27.9 s

The result of the optimization reveals that if nine fundamental design parameters (first nine parameters) selected and applied as in the Table 5.1, 15.34s shaking period will be satisfactory to harvest enough energy for UV LED water disinfection. Additionally, the piezoelectric harvester generates 42.19J electrical energy while shaking the bottle for 15.34s. At that point, the stored energy is dissipated by the UV LEDs within 27.9 s for disinfection of the water. This optimal set of parameters may give an opinion about the cost of the system. Nevertheless, it is better to optimize the shake duration and cost together. Next, multiple-objective optimization is performed by including the cost of the system. In the present case, both OFs need to be optimized together. Now, there may be three different scenarios (cheap, average, expensive) for the cost as the components used in the cost function is pretty varied in the market. By analyzing the range of the cost and the shake duration, it is found that there are 175 different couples. At that point, the multi objective GA is employed as

shown in Figure 5.2. Then, the optimal values of the design parameters are listed in Table 5.2.

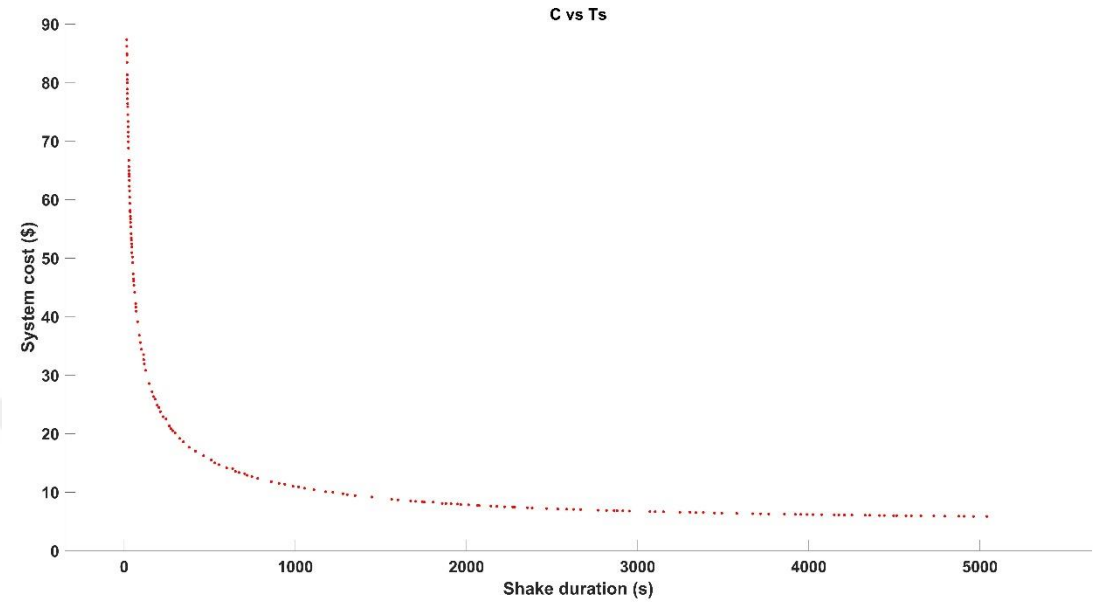


Figure 5.2: Multi objective GA optimization for the shake duration and the cost

Table 5.2: Optimal system parameters for three cost scenarios

Cost Option	***C* ($)**	T_s **(s)**	P_d **(W)**	***N***	ϕ **(W)**	***fs* (Hz)**	***a*** (m/s^2)	h_1 **(m)**	h_2 **(m)**	r_2 **(m)**	r_3 **(m)**	T_d **(s)**
Cheap	5.82	5040	1.5	1	0.0025	5.49	34.98	0.099	0.003	0.031	0.01	895.7
Average	34.39	100.6	1.5	4	0.034	5.49	34.99	0.1	0.003	0.031	0.01	65.9
Expensive	87.32	15.4	1.5	10	0.08	5.5	35.0	0.1	0.003	0.031	0.01	27.9

CHAPTER 6

CONCLUSION

In this thesis, development of a piezoelectric powered portable UV LED water disinfection system is presented. Operation of the proposed system is designated based on the filed patent of the thesis author. Mathematical models of mechanical, electrical and biochemical components of the system are entirely developed from the system design point of view. Then, the models are used in optimization of the design parameters. The results of single and multi-objective optimization employing Genetic Algorithm (GA) are presented. Finally, the design parameters are specified for three different cost scenarios. Cost of the system and the shake duration are taken critical design parameters of the system. For the three cost scenarios, optimal shake duration is quite various, from 5000 s to 87 s. Nevertheless, it should be noted that the impact of some other parameters on both cost and shake duration might also be considered. This thesis elaborates full theoretical design and modeling of the system, and it might be improved based on some other parameters in realization of the system, and the realization of the system might require further engineering work.

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