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FUNCTIONAL MATERIALS FOR ENERGY HARVESTING: A REVIEW OF THE FOLLOWING THEMOELECTIC AND PIEZOELECTRIC MATERIALS

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ABSTRACT

Smart materials have grown prominent in the past thirty years. Piezoelectric materials have proven important properties for usage in engineering, as in sensors and actuators for use in industry. Piezoelectric materials with high piezoelectric charge and voltage coefficients have been tried in renewable energy applications because they are very good at converting mechanical energy into electrical energy and vice versa. The piezoelectric material is the most important part of the energy harvester. When it is exposed to mechanical vibrations or stress, the ions in the material move about, creating a net electric charge because of the dipole moment of the unit cell. This occurrence creates an electric potential across the material. This review paper presents a comprehensive examination of piezoelectric energy harvesters (PEHs). Furthermore, the essential concept of piezoelectric materials, together with its modeling for many applications, is carefully elucidated. Next, a list of prior research that looked into PEH's additional uses is given, taking into account the technical details and methods used. A conversation has been presented as a critical evaluation of contemporary difficulties in this domain. Consequently, this evaluation might serve as a guidance for academics intending to use PEHs for their research.

Keywords: piezoelectric energy harvester; piezoelectric materials; smart materials; energy harvesting; modeling

INTRODUCTION

The Energy Harvesting Systems

The usage of electronic gadgets has expanded quickly and will keep growing quickly as technology becomes better. Batteries or electrical outlets are regularly used to power electronic devices. The more we utilize nonrenewable energy sources like batteries, the more pollution we create and the more likely we are to have serious energy crises. When batteries are thrown away, they have a big effect on the environment. They also don't last as long as electrical equipment. This is a serious concern these days since they need to be charged and replaced often, may be hard to get to, or can mess with the production cycle. For example, in an industrial setting, changing the batteries in nodes with sensors on machines that keep an eye on the manufacturing process generates downtime, waste that slows down output, delays, and higher maintenance expenses. Think about the costs of replacing batteries in hard-to-reach places, like the middle of the ocean or in devices that are implanted in the body. Energy harvesters are seen to be one of the best technologies for getting around problems caused by batteries since they are small, powerful, versatile, and can communicate with little power.

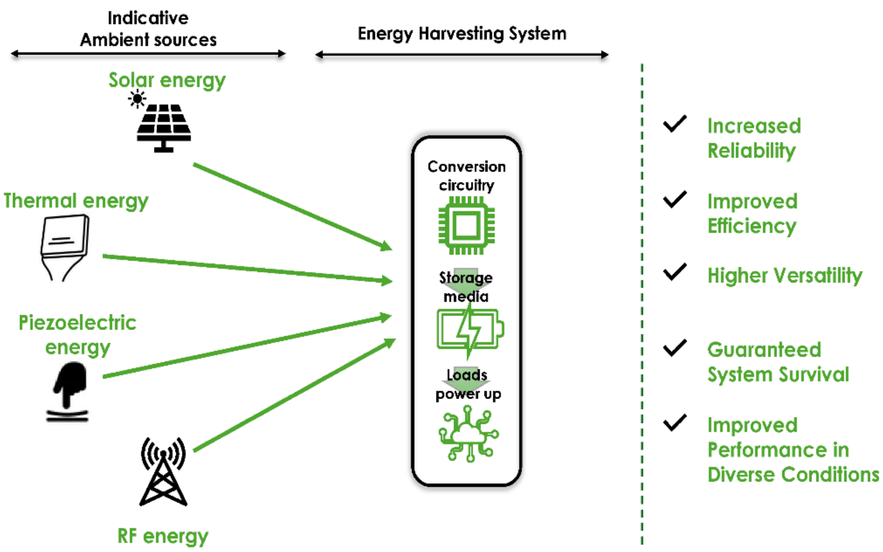

Figure:1 Energy Harvesting Systems

Energy harvesting is the process of collecting and changing ambient energy from the environment into electrical energy that may be used. Energy harvesters or energy scavengers are devices designed for this purpose. They let people rely less on traditional power sources like batteries and grid electricity. These systems are especially useful in places that are hard to get to or far away, where it is hard to change or fix the batteries. Energy harvesters come in a broad range of sizes and levels of sophistication. Some are small enough to power sensors, while others are big enough to produce a lot of electricity. The kind of energy source and the conversion technology used have a big effect on how well they work. As contemporary electronics, particularly in areas like the Internet of Things (IoT), wireless communication, and biomedical engineering, move forward quickly, energy harvesting technologies are becoming more and more vital for devices to work on their own and in a way that is good for the environment.

Sources and Types of Energy Harvesting Technologies

Depending on the needs of the application, energy harvesting systems may use several types of ambient energy sources. Some common sources include mechanical energy, thermal energy, solar radiation, and even biological activities. Mechanical energy is one of the most common types of energy since it is present in daily activities like moving people, vibrating things, and moving structures. There are several sorts of nanogenerators, such as piezoelectric nanogenerators (PENG), triboelectric nanogenerators (TENG), pyroelectric nanogenerators (PYNG), thermoelectric generators, and solar cells. These types are based on how they change energy. Each kind works on a different physical premise and has its own benefits. Thermoelectric systems, for example, turn temperature differences into electricity, while piezoelectric devices turn mechanical stress into electrical impulses. The choice of a certain technology relies on things like how much energy is available, the weather, and how well the output should work.

Mechanical Energy Harvesting and Piezoelectric Principle

One of the most promising ways to collect energy is via mechanical energy harvesting, which takes use of the fact that mechanical vibrations and motions are common in the environment. Most systems that are made to collect mechanical energy use electromagnetic, electrostatic, or piezoelectric principles. Piezoelectric technology has gotten a lot of interest since it is both efficient and flexible. Piezoelectricity is the interaction of electrical and mechanical characteristics in certain crystalline and ceramic materials. When these materials are put under mechanical stress, they create an electric charge because to internal polarization. This special feature makes piezoelectric devices very good at turning vibrations, pressure, and strain into electrical energy. This idea is employed a lot in sensors, actuators, and micro-electromechanical systems (MEMS), which makes it an important part of contemporary energy harvesting technologies.

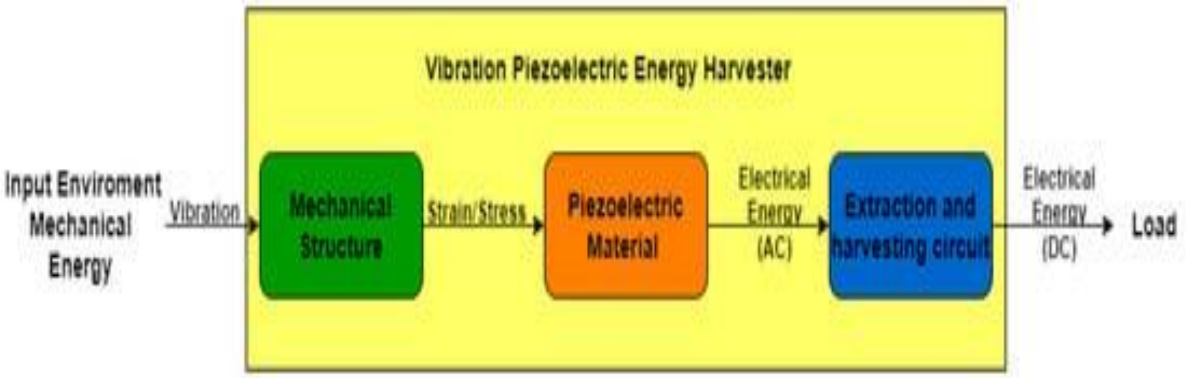

Figure:2 Architecture of the vibration energy harvesting chain from source to use

Advantages and Design Considerations of Piezoelectric Harvesters

There are several good things about employing piezoelectric energy harvesters instead of other kinds of energy-gathering devices. They are compact, light, and may be employed in small electronic systems. They also last a long time, are extremely dependable, and are responsive to low-frequency mechanical stimulation. Certain kinds of devices are more affected by variations in temperature and humidity than piezoelectric devices. But for them to work, a few crucial aspects have to be right, such the properties of the piezoelectric material, the frequency and amplitude of the mechanical vibrations, and how efficiently the electrical circuit gathers and stores energy. You need to create your system the right way, including the architecture of the structure and the circuits that manage energy, in order to get the most out of it. You need to know these things to make energy-harvesting devices that perform successfully in the real world.

This research focuses on the investigation of piezoelectric energy harvesting technologies and their applications in contemporary systems. It looks at the basic ideas of piezoelectricity and sorts piezoelectric materials into groups depending on where they come from, how they are made, and how they work. The research also looks at several structural designs utilized in piezoelectric vibration energy harvesters, from traditional ones to new ones. Another essential topic is the function of electronic interface circuits, which are in charge of effectively getting, conditioning, and storing the electrical energy that is generated. This study attempts to provide a full picture of piezoelectric energy harvesting devices and their promise for future technological progress by bringing together material science, structural design, and circuit optimization.

Theory of motion energy harvesting

Most motion energy-harvesting systems include a proof mass that may move in relation to the frame of the device. You may change energy by putting an outside force directly on the proof mass or the frame. There are pictures of the two sorts of devices. Using the device frame as a reference for motion, the force speeds up the proof mass in the first scenario, which does work that can be turned into electrical energy. The force speeds up the frame in the second scenario, which makes an inertial force act on the evidence mass in relation to the frame. This inertial force's work is employed to change energy from one form to another.

OBJECTIVE

1. 1. To research and discuss the fundamental laws and features of thermoelectric and piezoelectric materials utilized in energy harvesting systems, focusing on energy conversion and efficiency.
2. 2. To test thermoelectric and piezoelectric materials in sensors, wearable devices, and renewable energy systems and compare their performance.

METHODOLOGY

This study employs a qualitative review-based methodology to do a thorough examination of prior research concerning piezoelectric energy harvesters (PEHs) and their applications. The relevant literature was gathered from credible academic sources, including peer-reviewed journals, conference proceedings, and scholarly publications generated during the last thirty years. The sources were chosen because they were important to piezoelectric materials, energy collection techniques, and engineering uses. The collected articles were meticulously examined to comprehend the fundamental concepts of piezoelectricity. Some of these ideas were about the properties of the materials, the ways that energy is changed, and the ways that models are made. We also looked at a variety of alternative designs and setups for piezoelectric energy harvesters, focusing on how well they work, how efficient they are, and how they may be used in real-world systems.

The method also includes a comparative analysis of other studies to find common patterns, changes, and boundaries in the field. A lot of technical details were looked at closely, such as the choice of materials, the structure's architecture, and how to get the most power out of the electrical system. The report also looks at the several ways that academics have utilized models to predict and enhance the performance of PEH materials. While doing a thorough review of the current literature, we noticed a number of problems and holes in the research. Some of these problems and gaps were worries about poor power generation, constraints on materials, and environmental rules. This all-encompassing approach not only guarantees a well-structured understanding of the current status of piezoelectric energy harvesting, but it also establishes a foundation for future research and advancement in this domain.

RESULT AND DISCUSSION

Piezoelectric Constitutive Equation

The constitutive equations of the PZT property posit that the total strain in the transducer is the aggregate of the mechanical strain resulting from mechanical stress and the controlled actuation strain generated by the applied electric voltage.

The direct piezoelectric effect occurs when piezoelectric materials may create an electric field while they are under mechanical stress. This characteristic of piezoelectric materials is used to produce electrical energy under applied strain. The inverse piezoelectric effect is the opposite of the direct piezoelectric effect. In this case, mechanical strain is caused by the electric field. These effects are very much affected by how the crystal is oriented in relation to the strain or electric field. In many circumstances, a strong piezoelectric effect may be seen in one direction. The poling axis, or the direction of polarization, is parallel to the z-axis. The conventional way to write piezoelectric notation is to use subscripts 1, 2, and 3 for the x, y, and z axes. The electrical behavior of piezoelectric materials is described by Hooke's law, which is shown as.

$$D = \varepsilon E$$

D is the electric polarization, ε is the permittivity, and E is the intensity of the electric field that is applied. Hooke's Law says that to characterize a system:

$$S = sT$$

S is the strain, s is the compliance, and T is the stress. The following relationships are obtained by combining equations (1) and (2):

$$\begin{cases} \{D\} = [d^t]\{T\} + [\varepsilon^t]\{E\} \\ \{S\} = [s^E]\{T\} + [d]\{E\} \end{cases}$$

where [d] is the matrix of direct piezoelectric coefficients, $[d^t]$The matrix that shows the converse piezoelectric effect is E (the electric field vector), T (the stress vector), and t (the transposition matrix).

A simpler way to explain the direct and inverse piezoelectric action is shown in.

$$D = dT + \varepsilon E$$

$$S = sT + dE$$

The constitutive equation represents the direct piezoelectric effect,

$$D = dT + \varepsilon E$$

D is the electric polarization (C/m2), d is the piezoelectric coefficient matrix, T is the stress vector (N/m2), ε is the electrical permittivity matrix (F/m), and E is the electric field vector (V/m). polarization orientation of the piezoelectric material.

The given indices also show the projected orientations of mechanical strain and an electric field in a piezoelectric material. For instance, if a piezoelectric material is in d31 mode, it means that stress on axis 1 causes the output to be perceived across the material on axis 3. The electrical output here is proportional to the coefficient d31, which is why it is called d31 mode. Equation shows that the amount of charge that the piezoelectric material generates is directly related to the amount of stress that is put on it. Because of this, the PEHs are designed to work best under a certain amount of mechanical force. The performance of PEH's [30] is based on the transducer's mechanical-electrical conversion efficiency E%, which can be found by

$$E_{\%} = \frac{P_{out}}{P_{in}} \times 100$$

where P_{out} is the electrical output power, defined as,

$$P_{out} = v_p i_p$$

and P_{in} is the mechanical input power, defined as,

$$P_{in} = Fv$$

where v_p is the total voltage produced between the transducer's electrodes, ip is the current provided by the piezoelectric transducer, F is the external mechanical force, and v is the object's speed.

Types of Piezoelectric Material Configurations

Piezoelectric materials transducers come in these forms: The cantilever beam structure is the most prevalent for PEHs. They may have one or more layers, which are called unimorph and bimorph (Figure 3a and b). This is because they can handle a lot of mechanical strain during vibration and are easy to build. The basic bending modes of a cantilever have a resonance frequency that is substantially lower than that of the piezoelectric element's other vibration modes. Most PEHs employ this setup because it has these benefits. Figure 3a depicts a cantilever made of a thin layer of piezoelectric ceramics that is glued to a non-piezoelectric layer (typically a metal that acts as a conductor for the charge that is created) and has one end fixed so that the structure may bend. The structure is called a "unimorph" because it only has one active layer, which is the piezoelectric layer. 3b, two thin layers of piezoelectric ceramic are glued together on the same metal sheet to make a cantilever that gets the most power out of the unit.

This setup is called a "bimorph" structure since it has two active levels. The bimorph shape doubles the energy capacity of PEH without adding much to the unit volume. Because of this, bimorph piezoelectric cantilevers are more often utilized in PEH experiments.

In the "31 mode," the "3" stands for the direction of the polarization of the piezoelectric layer and the "1" stands for the direction of the stress, which is mostly in the planar direction of the cantilever. The "31 mode" employs the d31 piezoelectric charge constant. In the 31 modes, stress is not applied along the polar axis of piezoelectric material; hence, d31 is always less than d33 for a given material. In this case, a piezoelectric layer may be used in the "d33" mode to produce more energy. An interdigitated electrode design has an array of thin positive and negative electrodes on the surface of the piezoelectric sheet. When the sheet is being poled, these interdigitated electrodes make the electric field apply sideways instead of up and down, which is how it is usually done. So, when the sheet bends, the stress direction is parallel to the piezoelectric's poled direction. This lets you use the principal piezoelectric charge constant, d33. You may figure out the resonance frequency of a simply supported cantilever beam by.

fr = 2n 12 rmwEI (9) v2

π L

E is Young's modulus, *I*is the moment of inertia, *L* is the length, w is the width of the cantilever, and m is the mass per unit length of the cantilever beam.v_n= 1.875 Is the mass per unit length of the cantilever beam the eigenvalue for the basic vibration mode

To change the resonant frequency to match the frequency of the environment, which is normally below 100 Hz (Figure 3d), a seismic mass is frequently added to the free end of the cantilever. You may use the seismic mass to get an idea of what equation looks like.

$$f_r = \frac{v_n'^2}{2\pi} \frac{1}{L^2} \sqrt{\frac{K}{m_e + \Delta m}}$$

where $v'^2_n = v^2_n \sqrt{0.236/3}$, m_e = 0.236mwL is the effective mass of the cantilever, Δm is the seismic mass, and K is the effective spring constant of the cantilever.

The amount of energy a cantilever can produce relies mostly on its seismic mass and the amount of piezoelectric material that is placed under mechanical stress. When a cantilever bends, the tension that is caused is greatest toward the end that is clamped. The strain is highest at the end that is clamped and becomes lower as you go away from the clamp. So, the part of the piezoelectric layer that isn't strained doesn't help generate power. Theoretical and experimental study has revealed that a tapered or triangular cantilever shape creates a constant strain level over the length of the cantilever. This is why tapered piezoelectric cantilevers are typically employed to make the cantilever smaller and lighter.

The circular diaphragm construction has a thin disk-shaped piezoelectric layer that is connected to a metal shim that is mounted on the edges of the clamping ring. To make the power output better and the performance better at low frequencies, a proof mass is added to the middle of the diaphragm demonstrates cymbal transducers that are employed in situations where there are strong impact forces. Usually, it has a piezoelectric ceramic disc in the middle and a metal (steel) end cap on either side. Steel is stronger than brass and aluminum, which means that the transducer can handle a lot of weight Stack piezoelectric transducers are made up of many piezoelectric layers stacked on top of each other. The layers are layered such that their poling direction matches the force exerted (Figure 6). These transducers are employed in situations when greater pressure is needed.

each setup compares, along with its pros and cons. It illustrates that each form of setup has its own advantages, which make them good for a lot of different uses. But it should also be emphasized that it could not be useful in other situations. So, the limits should be looked at before they are used.

DISCUSSION

Todaro et al. did a thorough evaluation of thin piezoelectric films based on MEMS energy harvesters. They spoke about the techniques and methods used by the harvester. The authors proposed that for the extraction of energy from environmental vibrations, these harvesters have to be small and economical. A comprehensive examination of nanostructured polymer-based piezoelectric and triboelectric materials was conducted. These materials were light, flexible, safe for living things, devoid of lead, and cheap. It was shown how several factors, such nanoconfinement, surface polarization, growth parameters, self-poling, and device assembly, affect the performance of PEH. Piezoelectric materials are employed in many various ways, each with its own unique aeronautical, automotive, and medicinal properties. This review category may help researchers have a better picture of the many aspects of piezoelectric material research, especially at the beginning of their work.

As wireless technologies, wearable gadgets, implants, and the internet of things grew, so did the demand for self-powered systems. Batteries don't always work in hard-to-reach places, and their power is limited. So, the answer is to employ systems that run on their own. Using piezoelectric actuators to collect mechanical energy is one technique to power these kinds of devices. But piezoelectric actuator-based energy harvesters have certain problems: they produce low voltage and low power, and they require extra circuitry to straighten out the voltage, get the most power, and keep the voltage at its highest level. There is a lot of room for study on how to choose the right piezoelectric material, set up the transducer, and create a piezoelectric energy harvester that works best for a certain use. The current literature delineates the incremental development of piezoelectric actuators in energy harvesting. Energy harvesting is one of the areas in which these actuators have been employed more and more, as seen by the large number of studies done on them. The majority of prior studies concerning the dynamic responses of piezoelectric coupled systems under open-circuit electrical boundary conditions were conducted using finite element models.

Abuzaid et al. have employed piezoelectric material to stop damage from spreading in aircraft structures. The concepts were formulated to generate compressive and tensile stress around the damaged region, in conjunction with the width of the piezoelectric actuator. The authors asserted that raising the piezoelectric voltage would lead to a reduction in fracture metrics, including the stress intensity factor and stress concentration factor. However, the voltage increase in their research was restricted to 150 V owing to voltage limitations. Piezoelectric actuators can fix or manage damaged aeronautical structures, but they can only handle a certain amount of voltage. So, in these instances, the PEHs may be used to raise the voltage range and lower the fracture parameters to make constructions stronger.

CONCLUSION

The current study indicates that piezoelectric energy harvesters (PEHs) are an efficient and promising technology for the conversion of mechanical energy into electrical energy via the direct piezoelectric action. These systems have garnered considerable interest in recent years, especially in the development of self-sustaining and eco-friendly electronic products. There are a number of important elements that affect how well piezoelectric energy harvesters work. These include the choice of materials, the way they are built, the mechanical limits, and the effectiveness of the electrical circuitry that goes with them. New research has led to new ways of designing and using systems that are meant to boost energy production and system dependability. However, there are still certain problems, such as poor power generation and reliance on the environment. This report offers a thorough summary of current research, emphasizing significant trends, methods, and obstacles in the domain of piezoelectric energy harvesting. The categorization and analysis provided provide significant insights into many application domains and structural designs, functioning as a beneficial framework for researchers and engineers. It also stresses the necessity for ongoing innovation to get around present problems and make the system work better. This study enhances the comprehension of piezoelectric energy harvesters and facilitates future research initiatives focused on creating efficient, application-specific energy harvesting systems.

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