IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 41, No. 6, December, 2023, pp. 1655-1660
Journal homepage: http://iieta.org/journals/ijht

Modeling of Electricity Generation Using Smart Piezoelectric-Materials

Ouf A. Shams[1], Osama D.H. Abdulrazig[2], Salim M. Sanousy[3], Monaem Elmnifi[4], Lina Jassim[5], Hasan Shakir Majdi[6], Laith Jaafer Habeeb[7*]

[1] Power Mechanics Department, Technical Institute of Anbar, Middle Technical University, Baghdad 10001 Iraq
[2] Department of Mechanical Engineering Faculty of Engineering-Bright Star University, Elbriga 00218, Libya
[3] Department of Materials Engineering, University of Ajdabiya, Elbriga 00218, Libya
[4] Department of Mechanical Engineering, Bright Star University, Elbriga 00218, Libya
[5] Mechanical Engineering Department, Mustansiriyah University, Baghdad 10001, Iraq
[6] Department of Chemical Engineering and Petroleum Industries, Al-Mustaqbal University College, Hillah 51001, Babylon, Iraq
[7] Training and Workshop Center, University of Technology - Iraq, Baghdad 10001, Iraq

Corresponding Author Email: Laith.J.Habeeb@uotechnology.edu.iq

https://doi.org/10.18280/ijht.410629

Received: 4 February 2023
Revised: 15 May 2023
Accepted: 21 May 2023
Available online: 31 December 2023

Keywords:
smart materials, piezoelectric, electricity, energy harvesting

ABSTRACT

This study explores the potential of smart piezoelectric materials as a means of clean electricity generation through the conversion of mechanical stresses into electrical potential. A speed bump module outfitted with these materials serves as the experimental model. The materials are modeled and simulated using COMSOL software, and the output is assessed under a range of load states and other parameters. The findings provide a comparative analysis of various piezoelectric materials and their performance characteristics. The overarching aim is to harvest energy from typically inefficient sources such as footsteps, sound, pressure, and vehicular traffic. The practical implementation of these findings could lead to the reuse of power from the main grid for applications like street lighting and signboards, thereby reducing overall energy consumption and environmental impact. A secondary objective of this research is to evaluate the feasibility of implementing renewable energy systems based on smart materials in Libya. This study thereby contributes to the broader discourse on sustainable energy solutions and demonstrates the untapped potential of smart materials in energy harvesting.

1. INTRODUCTION

In recent decades, the capacity of smart piezoelectric materials to generate electricity has garnered significant attention. Their unique characteristic of producing an electric charge upon the application of mechanical stress or strain presents a promising avenue for the development of innovative energy harvesting systems. Such systems endeavor to convert mechanical vibrations, movements or pressures into usable electrical energy. To comprehend the electricity generation from these materials, a multi-faceted approach is necessitated. Firstly, the properties of the smart piezoelectric material in question must be understood. This includes the piezoelectric coefficient, a crucial determinant of the material's ability to generate an electric charge when strained. Other mechanical and electrical properties of relevance also warrant consideration. Subsequent to this, the analysis of the mechanical stress or strain experienced by the piezoelectric material in its intended application is required. This may entail an examination of the vibration patterns, forces, or pressures to which the material would be subjected. Finite element analysis (FEA) or other mechanical modeling techniques may be employed for simulating and understanding these mechanical factors. The third step involves the development of an electrical circuit model representative of the energy harvesting system. This model typically encompasses the piezoelectric material, conditioning circuits, and an energy storage component, such as a capacitor or battery. The impedance characteristics of the piezoelectric material and the conversion efficiency of the conditioning circuits need to be incorporated into the electrical model. Performance analysis constitutes the fourth step in this process. With the mechanical and electrical models in place, the power output, voltage/current characteristics, and efficiency of the system can be evaluated. This analysis might involve simulations or experiments to validate the model and to comprehend the system's behavior under varying operating conditions. Finally, based on the insights gleaned from the performance analysis, the model can be further refined to optimize the design of the energy harvesting system. This may involve exploring alternate configurations, materials, or operating parameters with the objective of maximizing the system's efficiency and power output. It must be emphasized that the modeling process can vary depending on the specific application and requirements. For instance, modeling electricity generation from piezoelectric materials in a wearable device would involve different considerations compared to a large-scale infrastructure application. In conclusion, modeling electricity generation using smart piezoelectric materials necessitates a comprehensive understanding of the material's properties, an analysis of mechanical stress or strain, the development of electrical circuit models, performance analysis, and the optimization of system design. This iterative process aids in the creation of efficient and effective energy harvesting systems that leverage smart piezoelectric materials.

The phenomenon of piezoelectricity, defined as the ability of certain materials to generate an electric charge in response to applied mechanical stress, has been the subject of extensive research due to its promising applications in electricity generation [1, 2]. The term "piezoelectricity" is derived from the Greek verb "piezein," meaning "to press firmly or squeeze," aptly describing the process whereby mechanical stress leads to electrical charge [1, 2]. This phenomenon was first observed in 1880 by French physicists Jacques and Pierre Curie, who identified the piezoelectric effect in crystals of sugar, quartz, and Rochelle salt [1, 2]. They demonstrated this relationship by measuring the charge produced across electrodes placed on these materials when subjected to mechanical deformation. The inverse effect, whereby electrical charge leads to mechanical deformation, was initially derived mathematically by Lippmann in 1881 and later experimentally confirmed by the Curie brothers [1-3]. Since these initial discoveries, significant advancements have been made in the field of piezoelectric materials and electronics. Notably, Frederick Lack developed a temperature-resistant crystal that facilitated the use of aviation radio, enabling widespread coordinated attacks [4-8]. Simultaneously, in Japan, Issac Koga produced a temperature-stable crystal, marking another significant milestone in the field [4-8]. The first electronic devices to leverage the piezoelectric effect included electronic oscillators, filters, buzzers, and audio transducers, leading to significant advancements in sonar [4-8]. Further discoveries revealed that polymeric materials, such as Poly Vinylidene Fluoride (PVDF), also exhibit piezoelectric characteristics [8-10]. Barium-Titanate ($BaTiO_3$), an early synthetic piezoelectric material, demonstrated superior piezoelectric and thermal properties compared to quartz crystals [8-10]. Despite these advancements, the development of cost-effective, reliable, and environmentally robust actuators remains an active area of research [8-10].

In recent years, piezoelectric smart materials have gained substantial attention due to their capability to convert mechanical energy into electrical energy. This unique property has drawn interest in diverse fields, including energy harvesting and structural health monitoring, in which the potential to generate electricity is being explored [10]. Modeling electricity generation using these smart materials involves leveraging the piezoelectric effect, where an applied mechanical force induces an electric charge on the material's surface. This charge can subsequently be stored or utilized to power electrical devices. The modeling process necessitates the determination of the material's physical properties, such as its piezoelectric constant, modulus of elasticity, and dielectric constant [10]. The applied mechanical force can be modeled using various methods, including finite element analysis or analytical models. The magnitude of electricity generated by the piezoelectric material is contingent on several factors, including but not limited to the magnitude and frequency of the applied force, the size and shape of the material, and the load resistance. As such, the optimization of these parameters is critical for enhancing the efficiency of electricity generation [10].

A number of studies have shed light on the process of exploiting compressive materials for electricity generation. For instance, Chen et al. [11] demonstrated that piezoelectric smart materials can generate energy from human motion, and that the performance can be enhanced with specific materials and technologies [11].

Zou et al. [12] discovered that the use of piezoelectric smart materials in harnessing electricity from vibrations can be efficient, and that the design and performance optimization can augment efficiency and reliability.

Moreover, Maino et al. [13] found that non-resonant mechanical amplification technology can increase power generation efficiency and improve performance in piezoelectric smart material generation. Liu et al. [14] illustrated that piezoelectric smart materials can be employed in various forms and designs for electricity generation, such as the use of composite materials containing cellulose and polyvinylidene fluoride.

Lastly, Izadgoshasb [15] underscored the potential use of piezoelectric smart materials in electricity generation for self-powered wireless sensing systems.

2. PROBLEM STATEMENT

In response to the escalating demand for energy, the escalating costs, and the depletion of natural resources, the exploration of alternative energy production sources has become imperative. These alternatives must align with environmental considerations, economic viability, and broad application potential. One such promising application is energy harvesting, specifically through the utilization of piezoelectric materials [16].

Harvesting the energy of vibrations or motion from moving entities presents a significant area of interest. Such entities include, but are not limited to, pedestrians, vibrating machinery, and vehicular traffic. As these sources of energy are currently untapped and ubiquitous, efficient and cost-effective harnessing of this energy would constitute a substantial stride towards more sustainable and eco-friendly energy production. In light of this, the current project designs a system that generates and harvests energy using a speed bump as a model. This system leverages Piezoelectric Smart materials, experimenting with diverse materials, load states, and formats, thereby testing the feasibility of this application. The aim is to exploit the wasted mechanical energy for various applications, one compelling example being lighting [11-17].

3. METHODOLOGY

3.1 Estimating external force

In the American Classification of Trucks according to "GVWR" [18] and assuming that, the road is designated for the transit the Light and Medium duty trucks (Figure 1), to calculate the Arithmetic Mean of the mass:

- Mean of mass: $\frac{6000+10000+14000+16000+19500+26000}{6} = 15250\ Pounds.$
- External force: 67789.379=70 Kilo Newton approximately. This is affecting a speed bump, specifically on

the Moving substrate, above springs.

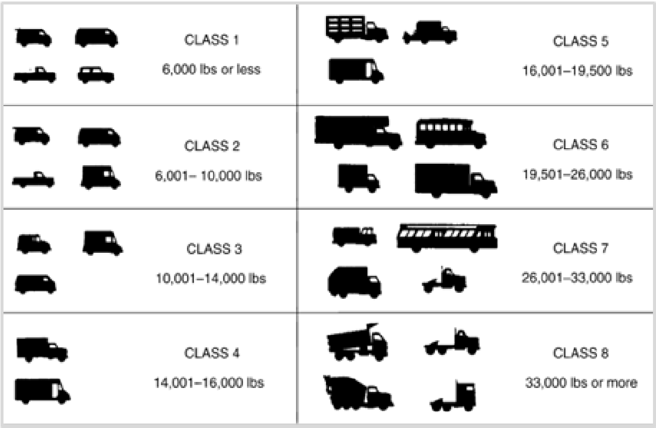

Figure 1. Classification of trucks by (GVW)

3.2 Smart module designing

One of the models were designed is model A. Where the descending segment by effect of external force, causes Impact Load on Edge of the piezo beam (yellow parts), causing an Edge load or Boundary load. In this model, the dimensions of Piezoelectric segment are (Width 0.5_Depth 0.15_Height 0.15 m). In addition, this segment is subject to 4 Different Load States. The dimensions of piezoelectric segment are determined by means of mathematical equations shown by Tabatabaian [19].

The system shown in Figure 2 is for improving energy harvesting and conversion. This design works to withstand different speeds, platforms to accommodate more presence of springs to maintain vibration.

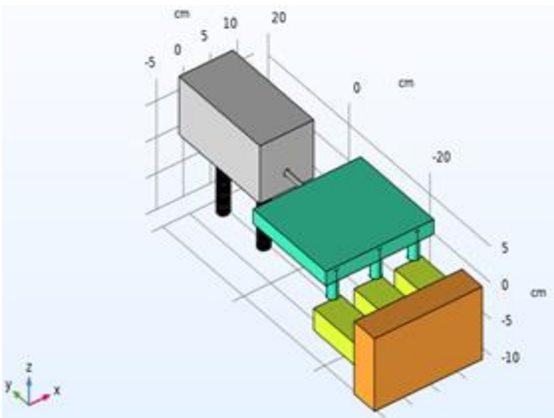

Figure 2. Speed bump model A

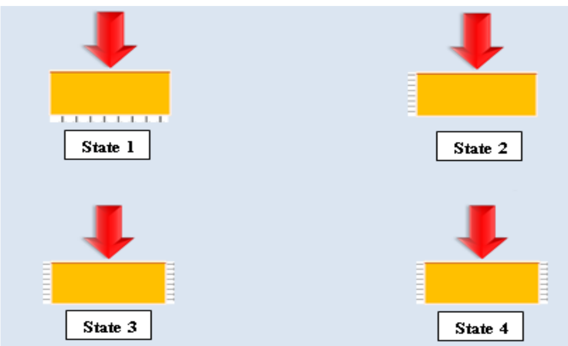

Figure 3. States of loads

State1: Segment is fixed from bottom; load is uniform on surface boundary.

State2: Segment is fixed from one edge; load is uniform on surface boundary.

State3: Segment is fixed from two edges; load is uniform on surface boundary.

State4: Segment is fixed from one edge; load is localized on the other edge.

The basis for selecting the four types of loads is based on the above literature review for the practical experiments (Figure 3). In addition, there are other ways to load the force referred to in the recommendations section.

3.3 Drawing and simulation using COMSOL5.5

A general-purpose simulation program for modeling designs, devices, and processes in all branches of engineering, industry, and scholarly inquiry is called COMSOL Multiphysics®. In addition, that includes all the procedures, including specifying the geometries, material characteristics, and physics that explain certain phenomena, as well as solving and post processing models to get reliable and correct findings. Additionally, create digital twins and simulation programs from models for usage by other design teams, production divisions, test labs, and more. In order to simulate electromagnetics, structural mechanics, acoustics, fluid flow, heat transfer, and chemical engineering, the platform product can be utilized independently or augmented with capability from any combination of add-on modules [20, 21].

Modelling and simulation piezoelectric segment steps using "COMSOL 5.5" starts with select model wizard to creating a new model. Then select 3D space dimensions and select physics "piezoelectricity". After that, select Stationary under Preset Studies and finish. From model builder, select Geometry, select Block, or the required geometry, writing the dimensions, then Build. In a Component node, the Materials node maintains the material attributes for all physics and domains. The content can be chosen and added (PZT-5H). To see the available properties, look at the Material Settings window's Material Contents section. The physics in the simulation employ the properties with green checkmarks. Define the global parameters, such as the applied load or geometries' dimensions. Set the boundary conditions after the geometry and materials have been determined. Select the Intended boundary, one or more, under the Boundaries Fixed, by Physics tab, Boundaries Fixed Constraint. Right-click Solid Mechanics (solid) in the Model Builder and choose Boundary Load, Edge Load, or another choice. The Model Builder sequence is expanded by a Boundary Load (or other) node. Next, decide on the load type, write the value, right-click Electrostatics(es), and then choose Electric Potential. After that, choose the intended boundary. The resolution of the discretized model's finite element mesh is controlled by the mesh parameters. The model is broken up into tiny, geometrically straightforward elements using the finite element method.

4. RESULTS

4.1 Results of load states

Description of the Study Case: Geometry (W 0.5_D 0.15_H 0.15 m), Material (PZT-4D), External Load (-1000 N k), Electric Potential (0 V), Normal Mesh. Piezo Material Lead Zirconate Titanate (PZT-4D) the material characteristics: high dielectric constant; high coupling; high charge sensitivity; high density with a fine grain structure; a high Curie point; and a clean, noise-free frequency response, see Figures 4-7.

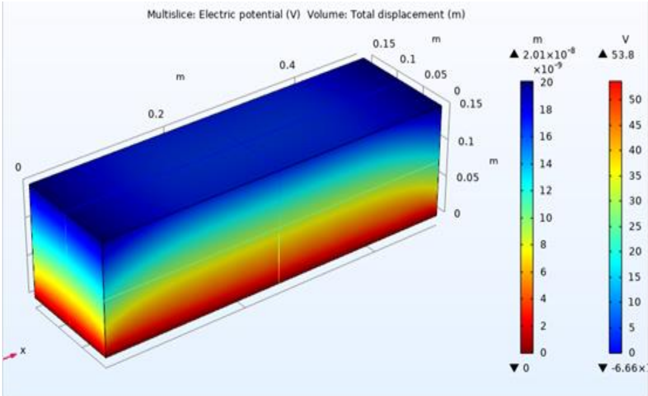

Figure 4. Electric potential and total displacement in state 1

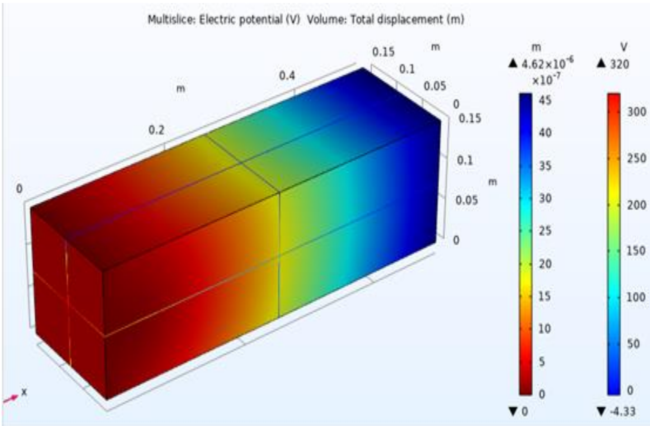

Figure 5. Electric potential and total displacement in state 2

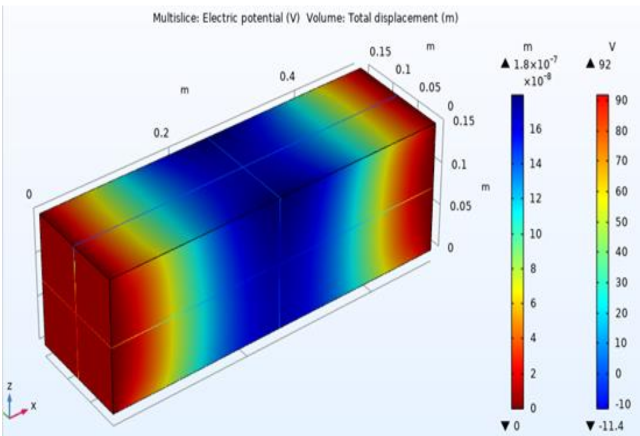

Figure 6. Electric potential and total displacement in state 3

4.2 Results of piezoelectric materials

Ceramic vs. polymeric Piezoelectric material. Description of the Study Case, see Figures 8-11:

- Geometry (W 0.5_ D 0.15 _ H 0.15 m)
- External Load (-1000 N k)
- Electric Potential (0 V)
- Load Type (State 4)

- Finer Mes.

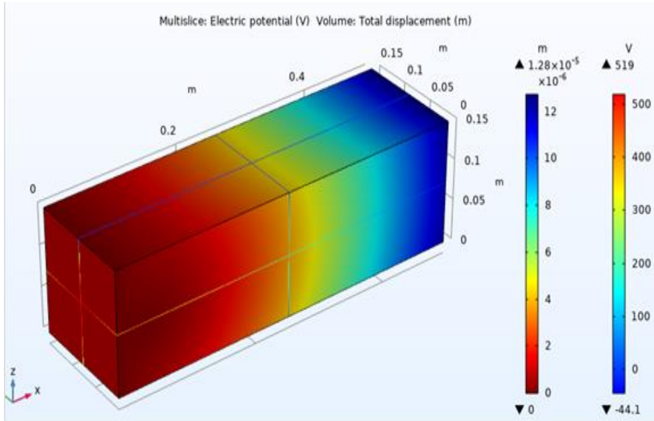

Figure 7. Electric potential and total displacement in state 4

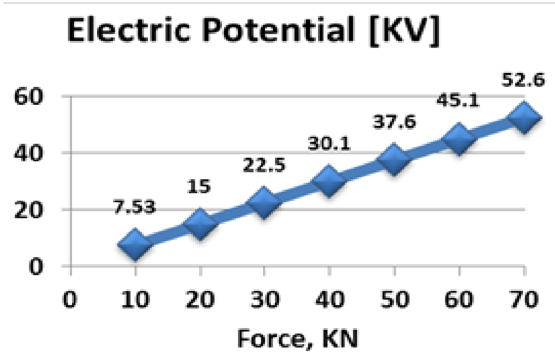

Figure 8. Electric potential result of PZT-2

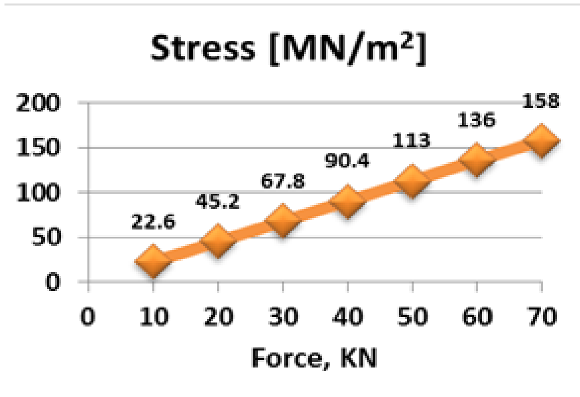

Figure 9. Stress result of PZT-2

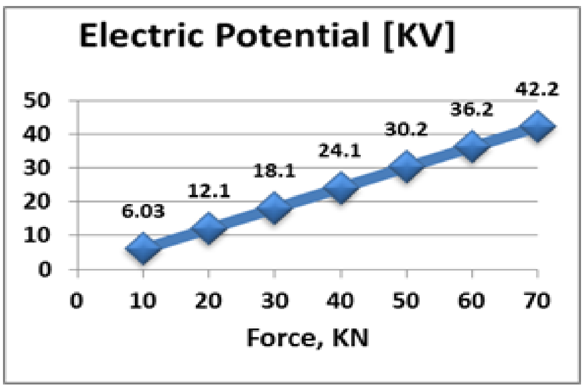

Figure 10. Electric potential result of PVDF

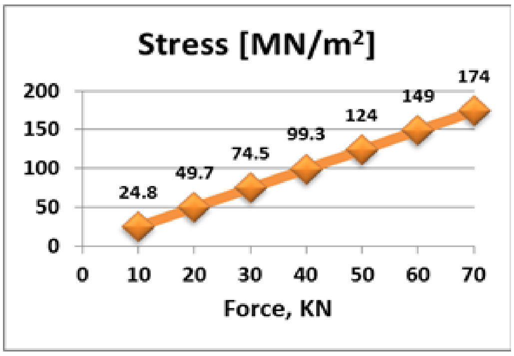

Figure 11. Stress result of PVDF

5. DISCUSSION

Load states: Based on the results, State 4 has the best result, see Figure 12.

State4: was the best because the load was localized, not distributed, and fixing from one-sided gives more flexibility, for produce more E. potential, Max. V [**519 V**].

State2: Was good result, one-sided fixation conferred good E. potential, because it is flexible, Max. V. [**320 V**].

State3: In this case, a curvature occurred, not a deflection. Acceptable but not satisfactory result, Max V. [**92 V**].

State1: Bad result, less flexibility, less stress, less voltage. It is the lowest of the four cases, with the same substance and other conditions. Max. V. [**53.8 V**].

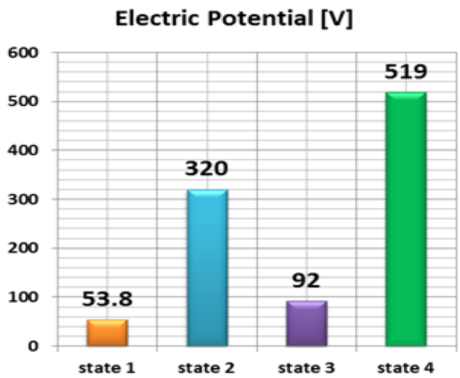

Figure 12. Compare electric potential between load states

Piezoelectric Materials: Best Maximum Electric Potential, see Figure 13, was from **$LiNbO_3$ (54.8), PZT-2(52.6), PZT-7A(52.6), $BaTiO_3$ (48.3), PVDF(42.2)**. In general (PZT) Better in properties, more reliability, more usability and application compatibility. Another thing has been noticed: The difference between (**$BaTiO_3$**) regular material and (**$BaTiO_3$**) Poled material, as (**$BaTiO_3$-Poled**) is better than (**$BaTiO_3$**) when all boundaries had a default electric potential (**0 V**) while the opposite was when it upper boundary (4) only had a default electric potential (**0 V**).

We must choose one of load states, by comparing their results in same case. Based on the results, State 4 has the best result, because it has the highest stress, highest voltage, and highest displacement.

Explanation of the difference between states 4 and 2:

- Distributed loading is more area, thus less stress per unit area.
- The localized load has less area, thus higher stress per unit area.

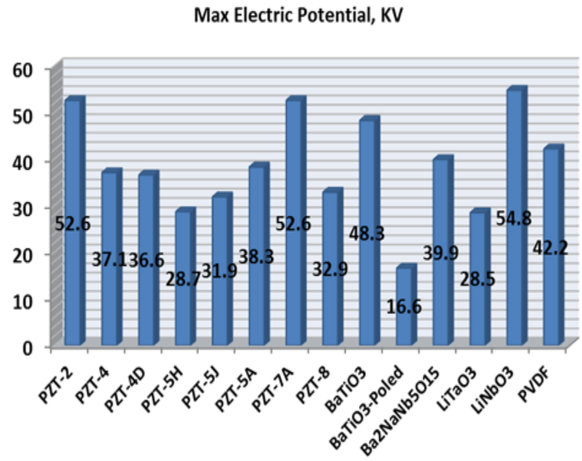

Figure 13. Compare of electric potential

6. CONCLUSIONS AND RECOMMENDATIONS

In this study, COMSOL software was used to drawing, modelling, and simulation of piezoelectric materials. These materials involve in speed bump module, as the energy harvester, to harvest the wasted mechanical energy, and reduce the work on the main network, by providing secondary sources of lighting for instance. 14 materials were exterminated, the maximum value of electric potential (+54.8 KV) for one piezoelectric segment (Subject to increase). Also concluded from this study that:

1. PZT, $LiNbO_3$, $BaTiO_3$, and PVDF are the best materials.
2. Beam deflection is better than bending it.
3. Better fixing of the segment on one side than from the bottom.
4. Localized force is better than uniform force.
5. The less restrictive the material, the more produced.
6. The more flexibility the material, the more produced.
7. Load state, segment shape, area under stress and dimensions greatly affect the results.

Future research plan is as follows:

- Attention to all mechanical calculations and choosing realistic spring designs.
- Ensure the choices of materials involved in designing the speed bump model (moving parts).
- Ensure that the speed bump dimensions comply with local and standard specifications.
- Design of electrical circuits required to collect and store this energy.
- Create a study similar to this, to collect energy at airports or footpaths.
- Expanding the field of research in piezoelectric materials and thermoelectric materials.
- Study of piezoelectric composite materials (ceramic - polymeric).
- Attempt to search for piezoelectric polymeric-composites from which to make a tire of vehicles.
- Application of such a study to piezoelectric nano-materials.

ACKNOWLEDGMENT

The authors would like to thanks Al-Mustaqbal University College for the assistance in completing this work.

REFERENCES

[1] Bengisu, M. (2001). Engineering Ceramics. Berlin: Springer International Publishing.

[2] Bohidar, S., Kumar, D., Mishra, P., Sharma, R. (2015). Smart materials for future. International Journal of Advance Research in Science and Engineering, 4(2): 365-372.

[3] Committee on Review of DOE's Office of Heavy Vehicle Technologies. (2000). Review of the U.S. Department of Energy's Heavy Vehicle Technologies Program. Washington: National Academy Press.

[4] Leo, D. (2007). Engineering Analysis of Smart Material Systems. Blacksburg: Virginia Polytechnic Institute & State University.

[5] Safari, A., Akdogan, E. (2008). Piezoelectric and Acoustic Materials for Transducer Applications. Springer International Publishing.

[6] Schwartz, M. (2002). Encyclopedia of smart materials. A Wiley-Interscience Publication.

[7] Sharapov, V. (2011). Piezoceramic Sensors: Microtechnology and MEMS. Springer International Publishing.

[8] Varadan, V., Vinoy, K., Gopalakrishnan, S.I. (2006). Smart Material Systems and MEMS Design and Development Methodologies. Chichester: John Wiley & Sons Ltd.

[9] Varadan, V., Vinoy, K., Gopalakrishnan, S. (2006). Smart Material Systems and MEMS Design and Development Methodologies. Chichester: John Wiley & Sons Ltd.

[10] Kamila, S. (2013). Introduction, classification and applications of smart materials: an overview. American Journal of Applied Sciences, 10(8): 876.-880.

[11] Chen, J., Bao, B., Liu, J., Wu, Y., Wang, Q. (2022). Piezoelectric energy harvester featuring a magnetic chaotic pendulum. Energy Conversion and Management, 269: 116155. https://doi.org/10.1016/j.enconman.2022.116155

[12] Zou, D., Liu, G., Rao, Z., Cao, J., Liao, W.H. (2022). Design of a high-performance piecewise bi-stable piezoelectric energy harvester. Energy, 241: 122514. https://doi.org/10.1016/j.energy.2021.122514

[13] Maino, C., Misul, D., Musa, A., Spessa, E. (2021). Optimal mesh discretization of the dynamic programming for hybrid electric vehicles. Applied Energy, 292: 116920. https://doi.org/10.1016/j.apenergy.2021.116920

[14] Liu, D., Li, C.S., Malik, O.P. (2021). Nonlinear modeling and multi-scale damping characteristics of hydro-turbine regulation systems under complex variable hydraulic and electrical network structures. Applied Energy, 293: 116949. https://doi.org/10.1016/j.apenergy.2021.116949

[15] Izadgoshasb, I. (2021). Piezoelectric energy harvesting towards self-powered internet of things (IoT) sensors in smart cities. Sensors, 21(24): 8332. https://doi.org/10.3390/s21248332

[16] Shackelford, J. (2015). Introduction to Materials Science for Engineers. Davis: University of California.

[17] Akhras, G. (1999). Advanced composites for smart structures. In Proceedings, ICCM-12, 12th International Conference on Composite Materials, Paris, pp. 5-9.

[18] Pryor, R.W. (2021). Multiphysics Modeling Using COMSOL 5 and MATLAB. Mercury Learning and Information.

[19] Tabatabaian, M. (2015) COMSOL5 for Engineers. (Multiphysics Modeling) Illustrated Edition. Mercury Learning and Information.

[20] Salim, S.M., Abdulrazig, O.D. (2020). Using smart-piezoelectric materials to generate electricity. Bright Star Journal for Scientist Research, 1: 0-1.

[21] Elmnifi, M., Moria, H., Elbreki, A.M., Abdulrazig, O.D. (2021). Possibilities study of using hybrid solar collectors in northeastern libya residential home. International Journal of Renewable Energy Research (IJRER), 11(2): 654-661.