Paper ID: MS-05

Review on Shape Memory Alloy Substrate with Thermoelectric and Piezoelectric Behavior for Thermo-Pezo-electric Generation Unit

Robiul Islam Rubel[1], Md. Washim Akram[1], Md. Hasan Ali[1], Md. Abu Jafor[1], Sk. Suzauddin Yusuf[1]
[1]*Facauly of Mechanical and Production Engineering, Bangladesh Army University of Science and Technology, Saidpur 5310, Bangladesh*
E-mail: rubel.ruet10@gmail.com

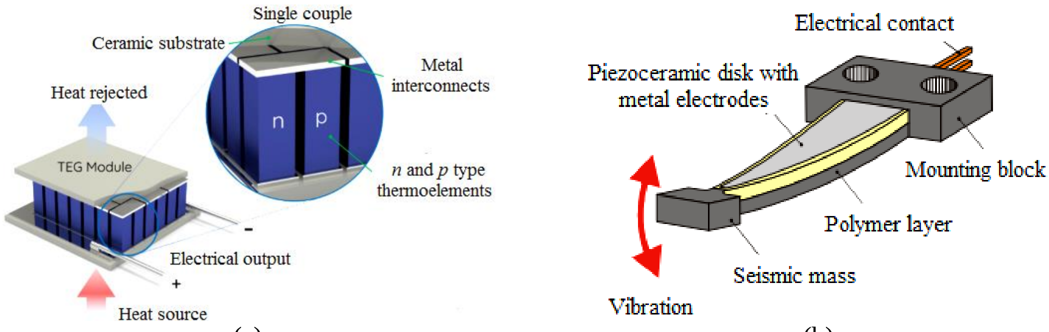
Abstract

A Thermo-Pezo-Electric Generation (TPEG) unit has evolved to achieve electrical energy using the waste heat exhausted in nature and vibration of an object. In TPEG, thermoelectric (TE) and piezoelectric (PE) substrate are beneath continuous deformation in multi-direction, twisting, impact, vibration when capturing heat energy from the engine or moving object in the non-planar surface. Thus endures permanent deformation, chipping or formation of micro-cracks in brittle TE and PE substrate or their laminates. This consequences intimate attachment failure between the TPEG body to waste heat source, substrate, and coatings materials. Additionally, the substrate reached its fatigue limit with narrow durability. To overcome the problem, flexible shape memory alloy (SMA) having both TE and PE effect may be incorporated to achieve stable power and durable TPEG unit. It will not only contribute to robust and fatigue-free harvesting materials but also for the industrial revolution in waste heat and vibration. This study reviews the prospect of SMA as energy harvesting portable TPEG devices.

Keywords: Thermo-Pezo-electric Generation Unit, Shape Memory Alloy, Thermoelectric and Piezoelectric materials, Energy Harvesting.

1. Introduction

The concept of energy harvesting was confined within the solar energy, wind energy, wave energy etc. for a long time. When the economy of energy uses come forward, energy harvesting turns its concept from the action to take profit of the non-used ambient energy surrounds us and to convert it into usable mechanical or electrical energy [1, 2, 3]. R. A. Kishore et al. [4], N. Punith et al. [5], and Dr. T. Hendricks [6] reviewed a lot of researches on PE, TE, Magneto-Electric and SMA for low-grade energy harvesting to explain its future prospects. Their study covered industrial, automobile, and domestic sectors. The harvesting devices are now classified into three major categories. First one is thermal energy harvesting by Thermoelectric (TE) materials called Thermo-electric generator (TEG). A thermoelectric generator (TEG), which convert waste heat into electricity, is one of the most promising energy harvesting devices for today and tomorrow [7]. New TEG material and TEG device have opened up the possibility of many new applications, particularly those involving the utilization of waste heat [8]. Since the thermoelectric generator (TEG) is highly dependent on the thermoelectric material, research on improving the performance of the thermoelectric material is continuing. Even hydroelectric power plant has incorporated with TEG [9, 10].



(a) (b)

Fig 1. The basic principle of (a) TEG and (b) PEG unit.

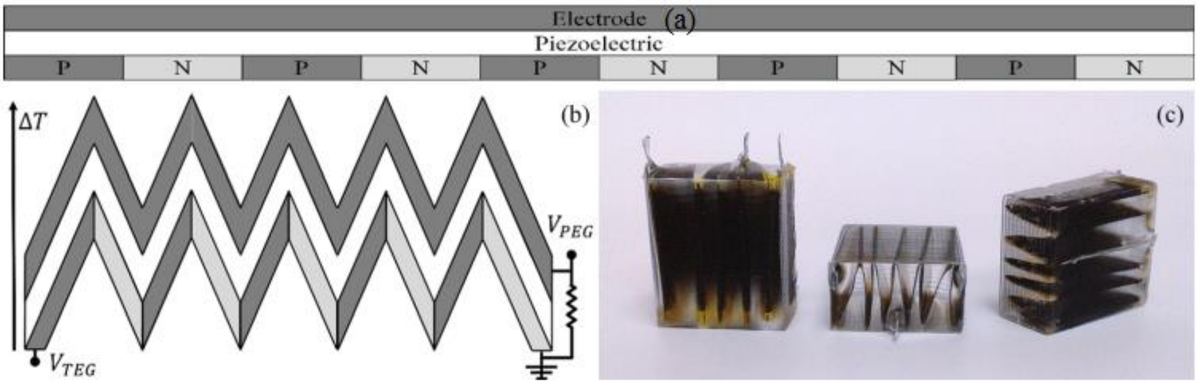


Fig. 2. The TE-PE combination/hybrid device [11].

The second category is vibration/motion energy harvesting by Piezoelectric (PE) materials called Piezoelectric generator (PEG). It recovers energy from mechanical movements to electrical energy via a piezo substrate [12]. The last and the modern development is heat and vibration energy harvesting simultaneously by TE-PE material combination called hybrid energy harvesting device. Researchers are continuously introducing a new class of hybrid TE-PE substrate. The principle is based on laminated layers of TE and PE materials. One layer of PE substrate is attached with one/multi-layer of PE substrate and vice versa. The lamination of PE-TE layers is performed mechanically. Since the combination has a different prospect of energy harvesting, they become isolated during application under vibration and heat. Thus the overall hybrid device fails. S. Sojan et al. [13], and F. Yildiz [14] reviewed TEG devices and its future prospect based on TE and PE materials. They described a group of devices, source of energy that can be harvested, and potential of the application. But nothing new about the problem described above.

However, some researcher has proposed an intellectual solution regarding this problem. If the material is developed that comply with TE and PE behavior, then can be used for hybrid energy harvesting without making the laminated/layered substrate. This will overcome the mechanical failure of separate TE-PE uses. The best choice of such materials again introduced a series of new materials, composites/alloys and so on. The best composites thought about is Shape Memory Alloy (SMA). A lot of research is ongoing on SMA for a heat engine and power plant [15]. SMA is based on the physical principle of motion is due to a phase transition, between an austenitic phase and a martensitic phase which have such properties [16]. SMA has sophisticated mechanical properties like fatigue, fracture, and strength by its shape regaining nature. They can be made with good thermal conductivity and mechanical properties than conventional TE or PE substrates.

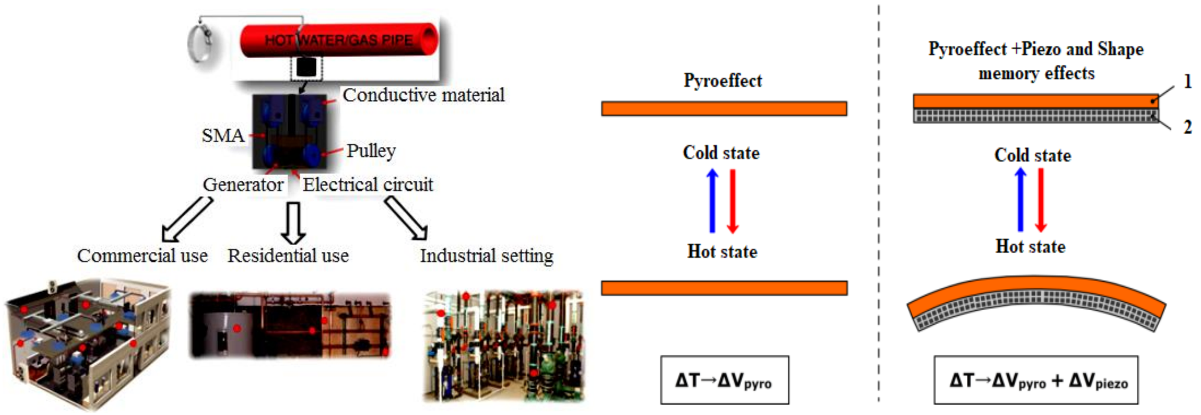
In developing SMA materials, research must be focused on improving the figure of merit ($zT = \frac{S^2}{\rho\kappa}T$). Where, representation is Seebeck coefficient S, the electrical resistivity ρ, and the thermal conductivity κ with T as absolute temperature. Therefore, SMA materials have been using in the industry for numerous applications. Besides this, due to good elastic property, SMA has also used as laminated/layered form separately with TE and PE. Such works are found very common in the last decay. For example, Figure 3 shows the modeling of piezo-SMA composite. Though integration of piezoelectricity with SMA is a comparatively newest attempt. Some experimental studies have been carried out for actuator, energy, environment, aerodynamics, sensing, and many other technical problem solutions [17, 18]. D. Zakharov et al. [19] are first to a laminated hybrid composite consisting of Ti-Ni-Cu shape memory alloy (SMA) and macro fiber composite (MFC) piezoelectric for thermal energy conversion. Y. Liu [20] and J. J. Zhu [21] develop micro-model and physical unit using SMA to demonstrate energy harvesting from waste heat of heat engine. The works were based on the mechanical properties of shape memory alloy to recover the applied stress-strain called constrained recovery. Extensive work has been done to characterize SMA qualitatively through theoretical models for power generation [22].

Constrained together with Piezo to form a hybrid composite

Heating with M-A transformation (constrained recovery)

Cooling with A-M transformation

Fig. 3. Modeling of piezo-SMA composite [2].



(a) (b)

Fig. 4. (a) Typical TE-SMA energy harvesting system [23]; (b) Principle of proposed enhancement of pyroelectric material performance. 1-pyro/piezo-electric layer, 2-SMA layer with SME pre-determined at the temperature range of interest [24].

A. Oudich [25] present an analytical model to analysis the bending of a bimorph beam comprising of piezoelectric (PE) material and shape memory alloy (SMA) thin layers to extract thermal to electrical energy. Many researchers are trying to use SMA in wire form to extract stress energy from aero-foil blade during air flow around it. Many conceptual SMA based energy harvesting system is under consideration. Such as by D. Avirovik et al. [22] discussed an imaginary TE-SMA harvesting plant presented by Fig. 4(a). H. Radousky's [26] group is first to introduce the idea of harvesting mechanical and thermal energy by SMA. Few types of research also attempt to measure the performance of pyro-electric materials has been shown by Fig. 4(b). The main drawbacks of the above works are the use of PE/TE materials with SMA forming multilayered/laminated substrate again. That makes energy harvesting unit heavy, and bulky. Thus inapplicable in thermal condition having loads, vibration, impact, twisting etc. Thus an attempt may be made to develop such a TPEG unit using SMA materials which itself a TE and PE substrate.

2. Results and Discussion

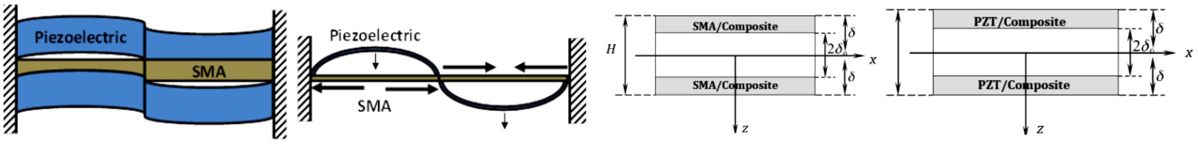
The review has found out a large volume of researches on TE, PE materials, SMA, TE-SMA, PE-SMA, PE-TE-SMA combination. However, the TPEG unit based on the single-use of SMA is not tried yet. SMA has widely used as thermoelectric materials. For example NiTi, Cu-Ni-Ti SMA has wide uses as TE substrate. Though SMA as PE is closely rare.

Common properties of TE and PE materials

Thermoelectric (TE) materials are fabricated materials whose structure works on p-n junction principle, and function mimics Seebeck effect to convert waste heat into electrical energy [8]. The most commonly studied TE materials are semimetals and doped semiconductors. The suitable metals for TE substrate must have very low electrical resistance, Seebeck effect *(S)*, and high thermal conductivity *(k)* [27]. On the other side, the figure of merit *(ZT)* too small for metals but high for semiconductor. At the same time, the semiconductor should show adequate *S*. The target heat source may be considering around 400^{o}-700^{o}C for both *p*-type and *n*-type. Traditionally, inorganic compounds like bismuth telluride [28] and lead telluride are used for their high-performance TE substrate, but they are brittle [29]. Early research on organic TE materials focused on conjugated polymers including polypyrrole, polythiophene, and polyaniline in spite of their relatively low electrical conductivity. Piezoelectric substances (PE) have been largely used as mechanisms to convert motion, vibration, or deformation into electrical energy [30]. But there is a crack problem in piezoelectric material due to mechanical loading [31, 32]. All the employed materials should have good mechanical properties, readily available and inexpensive raw materials, and environmentally friendly.

TE-SMA combination unit

Several alloy and composites, polymer have TE properties as well as SMA properties. H. S. S. Chang et al. [24] proposed an energy harvesting device based on TE laminated composite plate composed of a pyroelectric and non-pyroelectric substrate. The suspension of the substrate is assembled by SMA. A similar model is fabricated by O. C. Namli et al. [22], where the SMA/TE substrate worked under fluctuating temperature. A model satisfies rigidity of fluctuating condition than J. S. Gosliga et al. [33] model. H. S. Kim et al. [34] assembled a linear TEG using TE Cu-aluminum nitride substrate to get power. Graphene, epoxy etc. is very uncommon as SMA. Recently, Y. Wang et al. [35] study the responsiveness of Graphene/Hydro-Epoxy as TEG.



(a) (b)

Fig. 5. (a) Schematic of hybrid SMA/PE (Piezoceramic lead zirconate titanate) (b) Composite for energy harvesting [36].

PE-SMA combination unit

J. S. Gosliga et al. [33] and G.A. Lebedev et al. [37] develop a model of a hybrid device combining PE and SMA effects for vibration energy harvesting. The group simulated the electrical energy predicted by the FE model for the vibration of 494 Hz. Model is reported as to vibrate with the source when harvesting energy. S. B. Choia et al. [36] work on the electro-mechanical characteristics of PE-SMA composite beam. The authors consider a cantilever beam consists of equal thick PE and SMA layer. Typically, a similar approach has adapted by G. Y. Bagdasaryan et al. [38]. The significant difference in their work is the consideration of tensile force. Usually, the layered composite/bimorph has modeled and tested under bending conditions. Energy harvesting composites and hybrid SMA has been shown in Fig. 5.

TE-PE-SMA combination unit

D. S. Montgomery [11] presented an idea of flexible TE and PE materials into a single device structure to overcome several prohibitive issues facing the combination of generators while optimizing the performance of the combined power output. The research group used a PE film as a top electrode and an alternating *n*-type and *p*-type TE substrate as the bottom electrode. They folded the TE-PE combination at *p-n* type junctions to allow for a thermal gradient to be established across the thickness of the device. TE voltage was measured between the opposite sides of the bottom electrode and the PE voltage was measured between the top and bottom electrode. Figure 2 shows the TE-PE combination device. E. Gusarova [39] has worked broadly on the hybridization of smarts materials to form composites for TEG application. The author has only considered piezoelectric shape memory alloy. A lot of fabrication techniques presented in that work. Table 1 presents a list of smart materials with thermo-electric and piezoelectric characteristics.

Table 1. Comparative study of different TE, PE, SMA combination system.

Ref.	Combination	Compositions	Remarks
[8]	TE-SMA	Polyvinylidene fluoride-TiNiCu	Design to develop thermal energy at elevated temperature and characterized by Wiedemann-Franz law.
[40]	TE-SMA	Ni-Ti (Flexinol)	Electricity shows linearly with displacement and current during the heating and cooling cycle respectively.
[41]	TE-SMA	Cu-Ni-Ti	Thermal hysteresis behavior becomes weaker upon substitution of up to 7.5% Cu doped Ti-Ni alloy evident in the Seebeck coefficient.
[42]	PE-TE-Magnetic	ZnO	ZnO piezoelectric Timoshenko beam on elastic Pasternak foundation is analytically investigated under magneto-electro-thermo-mechanical loadings
[43]	PE-SMA	(NiTi) Nitinol	The design concept of SMA-PE, Dynamical modeling of SMA-PE unit was developed and experimentally validated
[44]	PE-SMA	Macro fiber composite-TiNiCu	The TiNiCu ribbon was glued onto the macro fiber composite with cyanoacrylate glue. Hybrid layered of composites workable in low to the high-temperature range.
[45]	PE-TE-SMA	Polyvinylidene fluoride- TiNiCu	Design to harvest small and quasi-static temperature variations along with PE and SMA effect.
[46]	PE-TE-Pyroelectric	ZnO nanowires	The numerical model developed to predicted performance of piezoelectric and piezotronic nanodevices with pyroelectric effect.

Proposed TPEG unit fabrication methodology

TE-SMA and PE-SMA combination has formed and applied randomly. In a few cases, SMA with piezoelectric behavior has combined with TE materials. The fabrication of this combination has studied carefully to retrieve a proposed fabrication method for SMA with TE and PE properties. Initially, SMA with both TE properties and PE properties need to fabricate by consecutive matrix formation from the different substrate. Simulation techniques based on the composition ratio and the lattice structure of materials may be employed to obtain the physical properties of SMA accordingly. The simulation must address the problem of fracture for PE-TE substrate in vibrating, rotating of deformation condition. The fabrication model will be based on composition. Then the subsequent mechanical properties have to determine. Post-treatment may require to ensure proper mechanical properties. Later, a suitable TPEG prototype construction may be carried out by the developed matrix. This may also include fabricating corrosion resistance films/coatings. This hypothesis must translate into the conceptual design with a buildable unit. The unit will undergo surface properties, porosity, wear preventive coatings, fatigue, robustness, etc. and other industrial assessment. After fabricating subsystem parts and complete assembly, the unit must treat for practical application and analysis of the model applicability through experiment. Afterward TPEG performance data collection, TE-PE combine property improvements and adjust composition and processing for best performance are required. A low-cost synthesis or production method for batches TPEG module production will be proposed to consider.

3. Conclusions

TE materials are heavy and brittle in nature. They have low bending or deforming tendency. On the other hand, PE is also less elastic materials. Moreover, there is a difficulty of laminating TE materials with PE materials. This problem is also acute in TE-SMA, PE-SMA, as well as TE-PE-SMA laminates that limit feasibility in many waste heat recovery applications involving transportation and non-planar surfaces. Chipping or formation of micro-cracks; in brittle TE, PE materials are a common phenomenon. Even a high-quality crack-free film of material and even distinct layer formation technique cannot surplus the difficulty. Moreover, energy harvesting device losses the weight to power performance especially for mobile and space applications. Form this motivation; high specific power and flexibility/conformability are desirable for TEG materials by developing SMA combining the TE and PE nature. The research has a significant outcome in the field of waste heat energy recovering at low cost at a versatile condition of motion/vibration. A new suitable substrate from shape memory alloy in TPEG unit will overcome the fatigue problem, and prolong the durability of TPEG in the hazardous application. The previous work of using TE-PE materials composites laminates provided significant output. In addition, the SMA with TE and PE materials composites also tried for thermo-mechanical power production and noted with a noble prospect. Thus, the anticipated project is an integration of electronic systems and mechanical system from a single source with flexibility and robustness. The successful completion of the work will draw a conclusion of smart SMA of PE and TE behavior. That consequence in high-density power from fracture free thin single substrate durable TPEG devices.

4. References

[1] E. Trioux, “Piezoelectric micro-generators for energy harvesting applications.” Université Grenoble Alpes, 2015.

[2] H. S. Kim, J.-H. Kim, and J. Kim, “A review of piezoelectric energy harvesting based on vibration,” *Int. J. Precis. Eng. Manuf.*, vol. 12, no. 6, pp. 1129–1141, 2011.

[3] O. Ando Junior, N. Calderon, and S. de Souza, “Characterization of a thermoelectric generator (TEG) system for waste heat recovery,” *Energies*, vol. 11, no. 6, p. 1555, 2018.

[4] R. Kishore and S. Priya, “A review on low-grade thermal energy harvesting: materials, methods and devices,” *Materials (Basel).*, vol. 11, no. 8, p. 1433, 2018.

[5] B. Orr, A. Akbarzadeh, M. Mochizuki, and R. Singh, “A review of car waste heat recovery systems utilizing thermoelectric generators and heat pipes,” *Appl. Therm. Eng.*, vol. 101, pp. 490–495, 2016.

[6] T. Hendricks and W. T. Choate, “Engineering scoping study of thermoelectric generator systems for industrial waste heat recovery,” Pacific Northwest National Lab. (PNNL), Richland, WA (United States), 2006.

[7] K. Wang, S. Strandman, and X. X. Zhu, “A mini review: Shape memory polymers for biomedical applications,” *Front. Chem. Sci. Eng.*, vol. 11, no. 2, pp. 143–153, 2017.

[8] H. J. Goldsmid, “Towards Improved Thermoelectric Generator Materials,” *J. Electron. Mater.*, vol. 46, no. 5, pp. 2599–2603, 2017.

[9] G. S. Nolas, J. Poon, and M. Kanatzidis, “Recent developments in bulk thermoelectric materials,” *MRS Bull.*, vol. 31, no. 3, pp. 199–205, 2006.

[10] J. M. Jani, M. Leary, A. Subic, and M. A. Gibson, “A review of shape memory alloy research, applications and opportunities,” *Mater. Des.*, vol. 56, pp. 1078–1113, 2014.

[11] D. S. Montgomery, C. A. Hewitt, and D. L. Carroll, “Hybrid thermoelectric piezoelectric generator,” *Appl. Phys. Lett.*, vol. 108, no. 26, p. 263901, 2016.

[12] H. R. Nayan, Power Generation Using Piezoelectric Material, Journal of Material Sciences & Engineering, 2015, 4:3, 1000171. DOI: 10.4172/2169-0022.1000171.

[13] F. Yildiz, “Potential Ambient Energy-Harvesting Sources and Techniques.,” *J. Technol. Stud.*, vol. 35, no. 1, pp. 40–48, 2009.

[14] S. Sojan and R. K. Kulkarni, “A Comprehensive Review of energy harvesting techniques and its potential applications,” *Int. J. Comput. Appl.*, vol. 139, no. 3, pp. 14–19, 2016.

[15] K. A. K. Raju, T. J. Reddy, G. Madhu, and V. Veenavatsalya, “Developing Power by Shape Memory Alloy SMA Heat Engine,” *Int. J. Eng. Sci.*, vol. 5334, 2017.

[16] J. Abadie, N. Chaillet, and C. Lexcellent, “An integrated shape memory alloy micro-actuator controlled by thermoelectric effect,” *Sensors Actuators A Phys.*, vol. 99, no. 3, pp. 297–303, 2002.

[17] M. Bodaghi, A. R. Damanpack, and W. H. Liao, "Triple shape memory polymers by 4D printing," *Smart Mater. Struct.*, vol. 27, no. 6, p. 65010, 2018.

[18] Y. Liu, H. Du, L. Liu, and J. Leng, "Shape memory polymers and their composites in aerospace applications: a review," *Smart Mater. Struct.*, vol. 23, no. 2, p. 23001, 2014.

[19] D. Zakharov *et al.*, "Thermal energy conversion by coupled shape memory and piezoelectric effects," *J. Micromechanics Microengineering*, vol. 22, no. 9, p. 94005, 2012.

[20] Y. Liu, "The work production of shape memory alloy," *Smart Mater. Struct.*, vol. 13, no. 3, p. 552, 2004.

[21] J. J. Zhu, N. G. Liang, K. M. Liew, and W. M. Huang, "Energy conversion in shape memory alloy heat engine part I: Theory," *J. Intell. Mater. Syst. Struct.*, vol. 12, no. 2, pp. 127–132, 2001.

[22] O. C. Namli and M. Taya, "Design of piezo-SMA composite for thermal energy harvester under fluctuating temperature," *J. Appl. Mech.*, vol. 78, no. 3, p. 31001, 2011.

[23] D. Avirovik, R. A. Kishore, D. Vuckovic, and S. Priya, Miniature Shape Memory Alloy Heat Engine for Powering Wireless Sensor Nodes, Book Name: Energy Harvesting and Systems, Chapter: Materials, Mechanisms, Circuits and Storage, Editor-in-Chief: Michael Lublow. Published Online: 2014-01-24.

[24] H. H. S. Chang and Z. Huang, "Laminate composites with enhanced pyroelectric effects for energy harvesting," *Smart Mater. Struct.*, vol. 19, no. 6, p. 65018, 2010.

[25] A. Oudich and F. Thiebaud, "A two-way shape memory alloy-piezoelectric bimorph for thermal energy harvesting," *Mech. Mater.*, vol. 102, pp. 1–6, 2016.

[26] H. Radousky *et al.*, "Harvesting Mechanical and Thermal Energy by Combining ZnO Nanowires and NiTi Shape Memory Alloy," *Adv. Nanomater. Techologies Energy Sect.*, vol. 1, no. LLNL-JRNL-725102, 2017.

[27] Z. Yang *et al.*, "Improved thermoelectric generator performance using high temperature thermoelectric materials," 2017.

[28] H. Goldsmid, "Bismuth telluride and its alloys as materials for thermoelectric generation," *Materials (Basel).*, vol. 7, no. 4, pp. 2577–2592, 2014.

[29] M. Orrill and S. LeBlanc, "Printed thermoelectric materials and devices: Fabrication techniques, advantages, and challenges," *J. Appl. Polym. Sci.*, vol. 134, no. 3, 2017.

[30] D. Motter, J. V. Lavarda, F. A. Dias, and S. da Silva, "Vibration energy harvesting using piezoelectric transducer and non-controlled rectifiers circuits," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 34, no. SPE, pp. 378–385, 2012.

[31] A. Toprak and O. Tigli, "Piezoelectric energy harvesting: State-of-the-art and challenges," *Appl. Phys. Rev.*, vol. 1, no. 3, p. 31104, 2014.

[32] F. Yang and I. Kao, "Crack problem in piezoelectric materials: general anti-plane mechanical loading," *Mech. Mater.*, vol. 31, no. 6, pp. 395–406, 1999.

[33] J. S. Gosliga and O. A. Ganilova, "Energy Harvesting based on the Hybridisation of two Smart Materials," in *Proceedings of EACS 2016*, 2016.

[34] Hee Seok Kim, Takashi Itoh, Tsutomu Iida, Minoru Taya, Keiko Kikuchi, Design of linear shaped thermoelectric generator and self-integration using shape memory alloy, Materials Science and Engineering B 183 (2014) 61–68.

[35] Yongkun Wang, Wenchao Tian, Jianqiang Xie, and Yan Liu, Thermoelectric Responsive Shape Memory Graphene/Hydro-Epoxy Composites for Actuators, Micromachines, 2016, 7, 145.

[36] S. B. Choia, Y. K. Park, and T. Fukuda, "A proof-of-concept investigation on active vibration control of hybrid smart structures," *Mechatronics*, vol. 8, no. 6, pp. 673–689, 1998.

[37] G. A. Lebedev *et al.*, "Thermal energy harvesting using shape memory/piezoelectric composites," in *2011 16th International Solid-State Sensors, Actuators and Microsystems Conference*, 2011, pp. 669–670.

[38] G. Y. Bagdasaryan, A. D. Hasanyan, and D. J. Hasanyan, "Dynamic bimorph thermo-piezoelectric benders with arbitrary support location. part i: application to energy harvesting-analytical derivations," *Mech. Proc. Natl. Acad. Sci. Armen.*, vol. 69, no. 1, pp. 25–38, 2016.

[39] E. Gusarova, "Flexible devices for energy harvesting based on printed organic piezoelectric P (VDF-TrFE) materials." 2015.

[40] H. N. Bhargaw, M. Ahmed, and P. Sinha, "Thermo-electric behaviour of NiTi shape memory alloy," *Trans. Nonferrous Met. Soc. China*, vol. 23, no. 8, pp. 2329–2335, 2013.

[41] A. Bhattacharyya and D. C. Lagoudas, "Thermoelectric shape memory alloy actuators and the issue of thermomechanical coupling," *Le J. Phys. IV*, vol. 7, no. C5, pp. C5-673, 1997.

[42] B. Ramachandran, R. C. Tang, P. C. Chang, Y. K. Kuo, C. Chien, and S. K. Wu, "Cu-substitution effect on thermoelectric properties of the TiNi-based shape memory alloys," *J. Appl. Phys.*, vol. 113, no. 20, p. 203702, 2013.

[43] M. Mohammadimehr, S. A. M. Managheb, and S. Alimirzaei, "Nonlocal buckling and vibration analysis of triple-walled ZnO piezoelectric timoshenko nano-beam subjected to magneto-electro-thermo-mechanical loadings," *Mech. Adv. Compos. Struct.*, vol. 2, no. 2, pp. 113–126, 2015.

[44] T. Todorov, N. Nikolov, G. Todorov, and Y. Ralev, "Modelling and Investigation of a Hybrid Thermal Energy Harvester," in *MATEC Web of Conferences*, 2018, vol. 148, p. 12002.

[45] B. Gusarov, L. Gimeno, E. Gusarova, B. Viala, S. Boisseau, and O. Cugat, "Flexible composite thermal energy harvester using piezoelectric PVDF polymer and shape memory alloy," in *2015 Transducers-2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*, 2015, pp. 722–725.

[46] R. Araneo, F. Bini, A. Rinaldi, A. Notargiacomo, M. Pea, and S. Celozzi, "Thermal-electric model for piezoelectric ZnO nanowires," *Nanotechnology*, vol. 26, no. 26, p. 265402, 2015.