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Module-type Triboelectric Nanogenerator for Collecting Various Kinetic Energies

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Abstract

A triboelectric nanogenerator (TENG) can obtain electrical output due to the reciprocal motion between two objects (i.e., rubbing), in which repetitive contact is made. High reliability, stable output, and high reproducibility are important aspects of the electrical output obtained through a TENG as a sensor or generator, thus enabling its meaningful use. Therefore, many researchers fabricated TENGs into individual parts in the form of one module type to obtain high reproducibility and reliability. Since a TENG manufactured as a module type operates as a single device, it is possible to collect kinetic energy and convert it into electrical energy through the interaction between internally configured elements without the need for a separate structure. In addition, it is relatively easy to apply the size to the body, machine tools, and natural environment by simply adjusting the size suitable for use and surrounding environmental conditions. In this paper, the application cases of module-type TENGs are divided into four areas, and the research progress of module-type TENGs in each area is extensively reviewed.

Keywords: Triboelectric effect, Module type, High reproducibility, Wide coverage, Kinetic energy harvesting

1. INTRODUCTION

Carbon emissions and the use of fossil fuels, which are increasing every year, cause global warming that adversely affects the environment [1, 2]. To prevent this, researching and developing new and renewable energy is encouraged while proposing and implementing environmental policies, such as carbon neutrality. Considering this, it is necessary to develop an energy source that is environmentally friendly and can prevent air pollution and environmental destruction. The most actively researched fields are solar power [3, 4] and wind power [5, 6]. Although it is the most efficient method, it is not easy to always maintain its best performance because there are many restrictions depending on the climate or environment. Therefore, it is essential to develop an eco-friendly energy source that is not affected by location or other environmental conditions.

Moreover, with the advent of the 4th industrial revolution, the Internet of Things (IoT) [7, 8], smart factory [9], and artificial intelligence [10, 11] fields have been rapidly developing. Due to the proliferation of smart devices and the development of IoT technology, the importance of data collection is expanding, and sensors are being applied to various environments [12]. However, most sensors require a battery, which is inconvenient since the battery must be replaced before the end of its battery life or the sensor itself must be replaced [13]. If self-generation technology is applied to semi-permanently use the sensor, it is possible to solve the aforementioned problem.

A triboelectric nanogenerator (TENG) is an eco-friendly energy source that can convert kinetic energy into electrical energy based on contact electrification and electrostatic effect. This technology can be applied to various applications due to its advantages, such as high voltage, low cost, high sensitivity, easy fabrication, and wide selection of materials [14, 15]. In real-world situations, countless amounts of energy are wasted. Energy sources in the low frequency range below 10 Hz that occur in nature (i.e., wind power, hydraulic power, and wave power), vibration energy from machine tools, thermal energy from vehicles and automobiles, and even kinetic energy generated while walking are part of the wasted kinetic energy. To collect the wasted kinetic energy, many researchers have designed a structure that can obtain the maximum effect in each situation and select the appropriate materials. This can further improve the performance of the generator and sensor by securing stable output and high reproducibility after fabricating the structure with an optimal parameter design into one TENG module device. In addition, the

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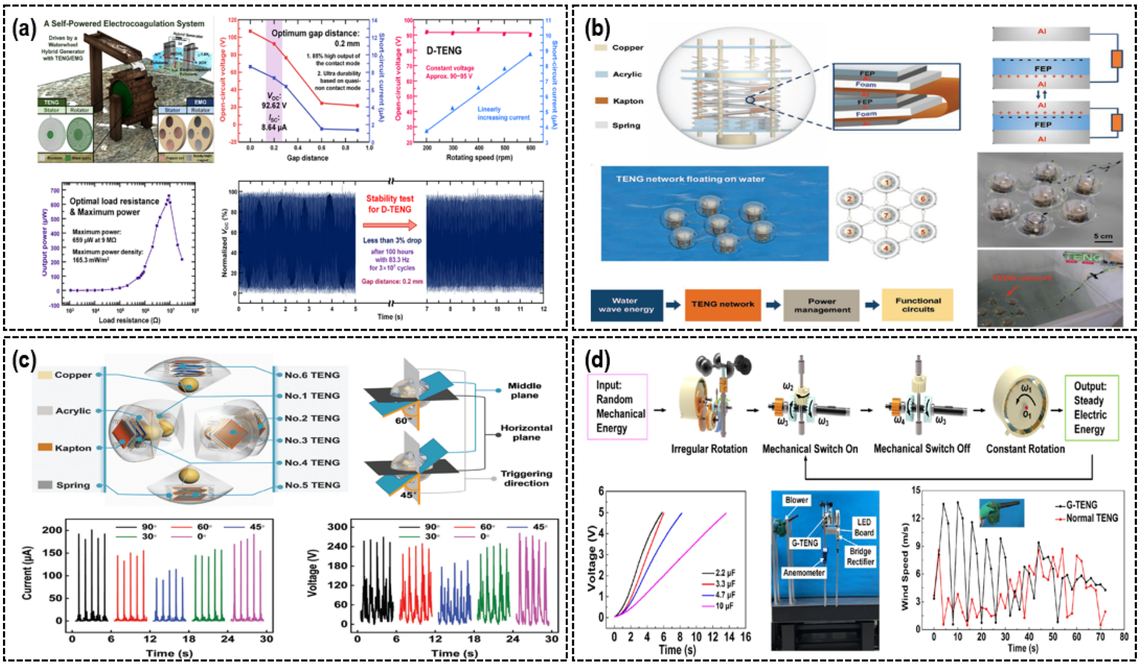

Fig. 1. Module-type TENG application applied to natural environment energy source. (a) A water wheel complex generator using a TENG and an EMG is proposed by fabricating a waterwheel-based structure. Reprinted with permission from Ref.[16]. Copyright (2022) John Wiley & Sons. (b) A multi-spring structure with an integrated power management module (PMM) is proposed to effectively collect the wave force that can be utilized as large-scale blue energy. Reprinted with permission from Ref.[17]. Copyright (2019) John Wiley & Sons. (c) Fabrication of the TENG structure for multi-directional hydraulic energy collection based on a spring multi-layer structure and PMM. Reprinted with permission from Ref.[18]. Copyright (2015) Springer Nature. (d) Energy storage module package and output module for converting wind energy into stable electrical energy. Reprinted with permission from Ref.[19]. Copyright (2021) Elsevier.

module-type TENG can be easily installed by attaching it to the source of kinetic energy. Thus, it can be applied to various applications.

In this study, the application cases of the module-type TENG are divided into four areas, and the research progress is reviewed. The application area is classified into natural environment energy collection [16–19], human body energy collection [20–23], transportation means application [24–27], and structure application [27–30]. Subsequently, examples of application as a generator or as a power source for a sensor are summarized.

2. MODULE-TYPE ENERGY CONVERSION SYSTEM

A hybrid generator with a water wheel structure for collecting rotational energy by combining a disk-type triboelectric nanogenerator (D-TENG) and EMG was reported by Cho, H. at el. (Fig. 1(a)). D-TENG is manufactured based on the printed circuit board (PCB) technology and consists of one rotator and stator. It is manufactured through the process of electrospinning and sintering (PTFE) as negatively charged materials. D-TENG has a water contact angle of 160.5º, allowing smooth operation even at high relative humidity, and has high frequency and high output characteristics. Therefore, it is suitable for converting a low-band frequency generated in the aberration structure into a stable, high-density energy form. It is also reported that it is possible to successfully purify wastewater with a high removal rate of over 95% for 18 h by using a power management module [16]. Xi, L. et al. proposed a spring multilayer structure-based power management module for large-scale blue energy collection by constructing a TENG network (Fig. 1(b)). Electric output can be obtained using the frequency and amplitude of waves, and energy collection efficiency can be improved up to 96 times through the power management module. Moreover, an output performance equivalent to 270 μA and 354 V at a frequency of 1 Hz and an amplitude of 2.5 V can be obtained [17]. Xi, L. et al. reported a water level detection and alarm system by fabricating a spherical TENG based on a spring multilayer structure (Fig. 1(c)). TENG fabricated in a spherical shape is a suitable method for effectively collecting blue energy by collecting multidirectional wave energy. By separating the spring structure

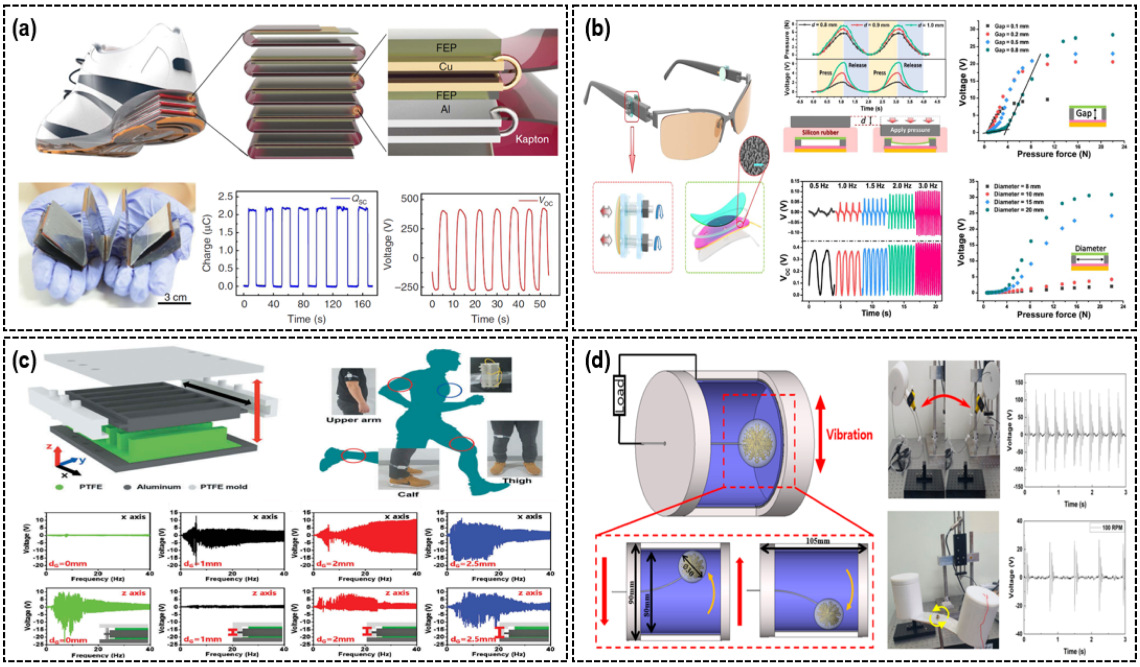

Fig. 2. Modular structure to effectively collect body energy. (a) TENG with a structure that can be inserted into a shoe to collect kinetic energy generated during walking. Reprinted with permission from Ref.[20]. Copyright (2015) Springer Nature. (b) ultra-high sensitivity TENG that can effectively capture motions such as blinking. Reprinted with permission from Ref.[21]. Copyright (2017) AAAS. (c) structure based on hand-held pendulum (HHP) system to collect various kinetic energy generated from human movement including walking, jumping, and running. Reprinted with permission from Ref.[22]. Copyright (2019) Taylor & Francis. (d) module-type TENG structure in which a silicon rubber ball is inserted into the cylinder structure and is a structure for measuring the strength of various physical quantities. Reprinted with permission from Ref.[23]. Copyright (2021) MDPI.

inside the spherical TENG into six parts, it is possible to independently act in each direction; thus, it is possible to grasp the relative positions of the six parts [18]. Wang, Y. et al. reported a gravitational triboelectric nanogenerator (G-TENG) for converting unstable wind energy into stable electrical energy (Fig. 1(d)). G-TENG consists of an energy input module, an energy storage module, and an energy output module. Wind energy is transmitted from the input module to the energy storage module and converted into gravitational potential energy, which is then converted into stable electrical energy. The power can be stably supplied to electronic devices by confirming that the standard deviation (I_{SD}) of the short-circuit current peak is less than 0.31 μA and the fluctuation degree (I_{FD}) reaches 2.3% through the energy conversion module [19].

Human biomechanical energy is characterized by fluctuating amplitude and variable low frequency and is an energy source that can be used as self-driving and auxiliary power sources for wearable devices. Niu, S. et al. proposed a high refresh rate charging power system by configuring TENG and power management module for sustainable operation of mobile electronic devices (Fig. 2(a)).

It is driven in contact and separation mode using Al and FEP films, and a nanostructure was created on the surface to stably improve the output performance. The fabricated TENG was inserted into the sole of the shoe to effectively collect the kinetic energy generated during walking to obtain an output performance of up to 2.2 μC and 700 V_{pp} [20]. Pu, X. et al. reported a TENG-based micro-motion sensor to capture mechanical micro-movements of skin around the eye (Fig. 2(b)). Since the TENG-based micro-motion sensor operates according to the triboelectric phenomenon and the electrostatic induction principle, it has the advantages of ultra-high sensitivity, high stability, easy operation, and low cost. Therefore, it has great potential in the field of mechnosensational HMI, and it can effectively capture the blinking motion with sufficiently high signal level (~750 mV) compared to the electrooculogram approach (~1 mV) [21]. Hwang, H. J. et al. reported a simple hand-held pendulum (HHP) system to effectively collect multidirectional wasted mechanical energy (Fig. 2(c)). The HHP-based TENG system can be attached to the calf of the human body and achieve an RMS power value of 5.28 μW during light running motions. In addition, it was confirmed that the maximum output performance of 6.5 μA and

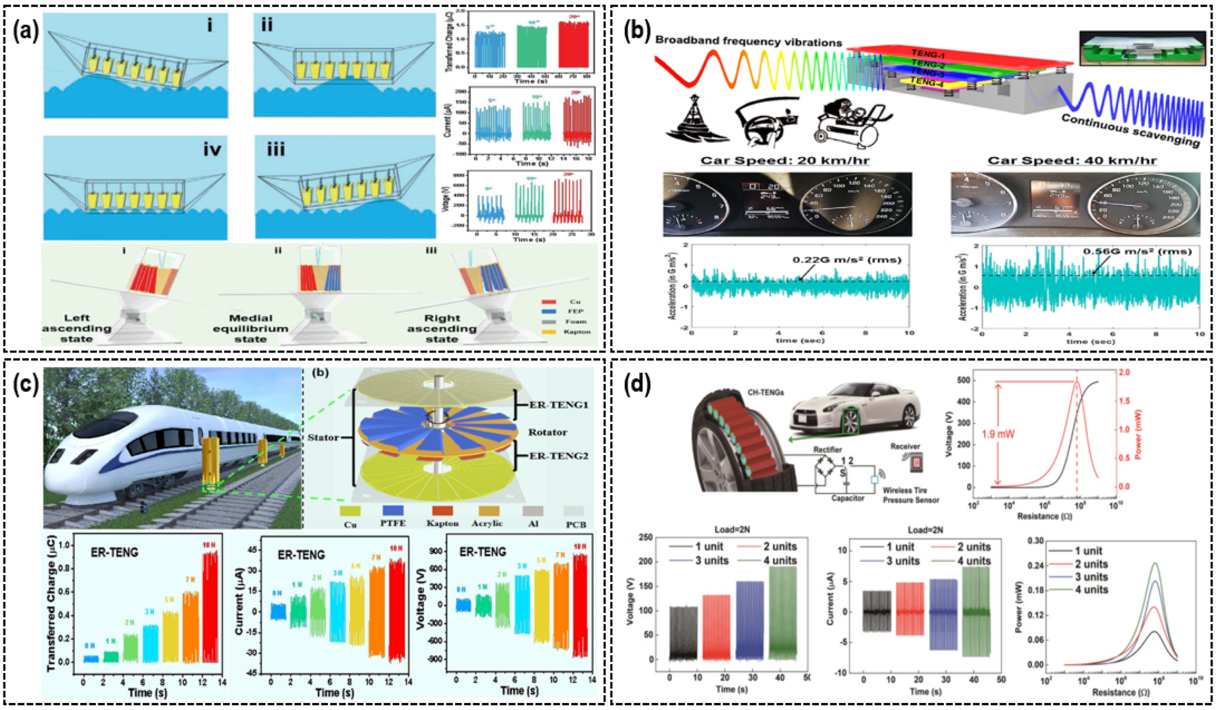

Fig. 3. Module-type TENG application applied to various means of transportation. (a) TENG module with a multi-layer structure of bifilar pendulum applied to ship for wave energy harvesting. Reprinted with permission from Ref.[24]. Copyright (2021) John Wiley & Sons. (b) TENG with a cascade impact structure to effectively collect broadband frequencies generated from the vehicle dashboard part. Reprinted with permission from Ref.[25]. Copyright (2019) AAAS. (c) Wind energy collection system generated by a high-speed moving train using an elastic rotation-based TENG module. Reprinted with permission from Ref.[26]. Copyright (2021) American Chemical Society. (d) Development of a compressible hexagonal TENG array system for harvesting mechanical energy generated from tires. Reprinted with permission from Ref.[27]. Copyright (2018) Elsevier.

116 V can be obtained under the condition of 4-cm bending displacement by configuring the pendulum shape of the cantilever structure [22]. Shin, J. et al. reported a system that can convert kinetic energy into electrical energy in various environments by fabricating a modular TENG system in the form of a silicone rubber ball inserted into a cylinder structure (Fig. 2(d)). An Al film was attached to the inside of the cylinder-shaped structure, and the shape of silicone rubber was classified into four types to analyze the improvement of output performance through an optimal parameter design. In addition, it is possible to easily convert kinetic energy into electrical energy by attaching the module-type TENG to energy sources, such as vibration, rotation, and pendulum motions [23].

Various kinetic energy, such as vibration, rotation, and heat, are wasted energy sources in various transportation means, such as ships, aviation, and automobiles. In addition, since it has a large usable space, it is a suitable application for module-type TENG. Zhang. C. et al. reported a convenient maintenance monitoring system utilizing a ship as an energy collection platform by proposing a bifilar pendulum multilayer structure TENG (BM-TENG) (Fig. 3(a)). In this study, a bifilar pendulum module was constructed to effectively collect changes in the motion of a ship due to the height of the waves. In addition, the output performance of 1.3 μC, 120 μA, and 400 V was confirmed by checking the output performance based on the rotation angle by manufacturing a seesaw-shaped structure to simulate the motion of a ship. The energy harvesting method based on the BM-TENG module can obtain higher efficiency by optimizing the size of the ship, number of modules, and mass of the BP. In addition, it is possible to monitor the operating status of the ship in the marine environment without the need for an external power source. It has been proven to be an effective method [24]. Bhatia, D. et al. reported a cascade impact structure triboelectric nanogenerator (CIT-TENG)-based structure to stably and effectively collect irregular vibration energy generated from a vehicle (Fig. 3(b)). CIT-TENG was separated into four layers and collected individually to effectively collect broadband vibrations from a single source, such as a car dashboard.

The four layers are designed to resonate at the natural frequencies of 8, 24, 32 and 40 Hz, respectively, and analyze the

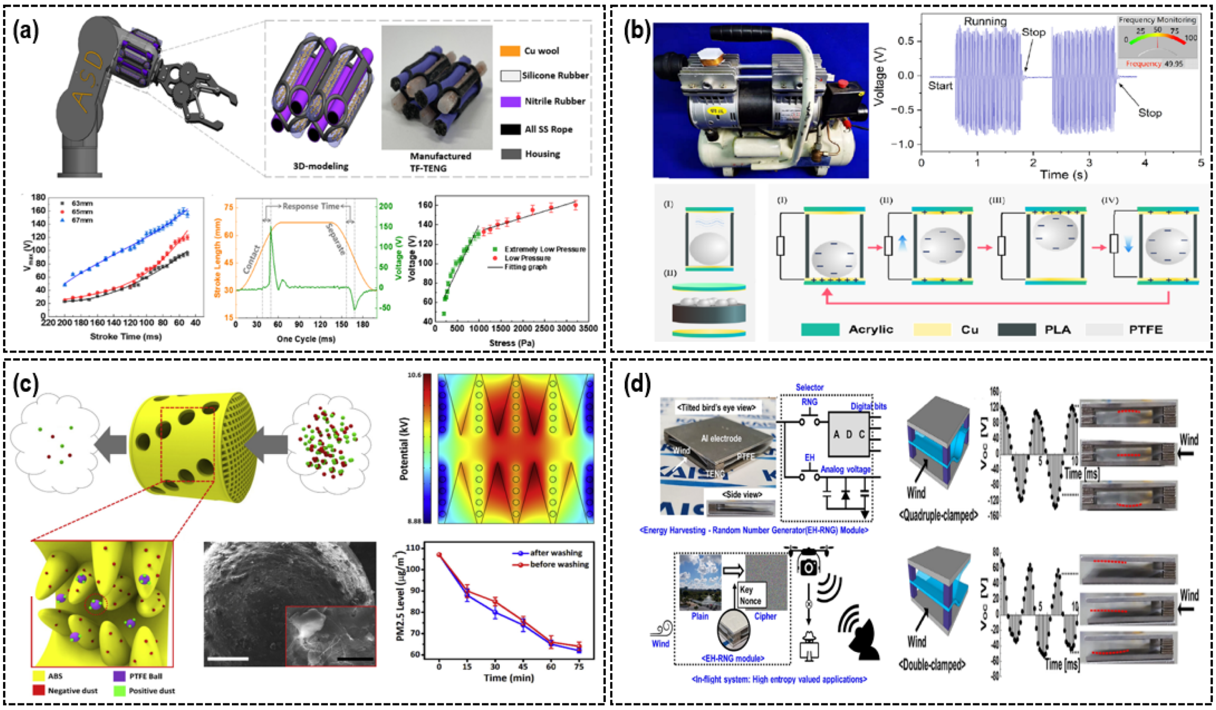

Fig. 4. Proposal of the module-type TENG structure applied to various mechanical devices. (a) 3D structure TENG for two-axis external force collection that can be attached to the robotic-arm as a skin type. Reprinted with permission from Ref.[28]. Copyright (2022) Elsevier. (b) TENG module structure for monitoring and diagnosing working conditions of marine machinery. Reprinted with permission from Ref.[29]. Copyright (2021) MDPI. (c) TENG module with a biomimetic villi structure that can perform the function of its own dust filter. Reprinted with permission from Ref.[30]. Copyright (2019) Elsevier. (d) TENG with a quadruple clamp flip-flop structure to create an encryption application using the characteristics of turbulence generated while flying objects are in motion. Reprinted with permission from Ref.[31]. Copyright (2021) Elsevier.

frequency response based on the input acceleration of approximately 0.2–0.5G m/s^2 and the output generated in each frequency band. The performance was also confirmed. As a result of the measurement, it was confirmed that values of approximately 9.55 V (RMS) and 0.1 μA (RMS) could be obtained at a driving speed of 20 km/h. In addition, an effective energy collection from various vibrational energy sources is possible through the module-type CIT-TENG [25]. Zhang, C. et al. reported an elastic rotational triboelectric nanogenerator (ER-TENG) to effectively collect wind energy generated from high-speed trains (Fig. 3(c)). The wind energy harvesting device module built based on ER-TENG is intended to harvest wind energy generated by high-speed trains and to supply power to related signals and sensing devices. In addition, obtaining an appropriate mechanical contact and reducing the driving force with a low coefficient of friction and low pressure are possible by using a combination of the Kapton film and PTFE. ER-TENG could secure the output performance of 80% or more and the durability even in high-speed rotation tests of more than 250,000 times by designing the optimal material and structure [26]. Guo, T. et al. reported a TENG (CH-TENG) array module with a compressible hexagonal structure for collecting wasted mechanical energy in tires (Fig. 3(d)). The CH-TENG module was fabricated in the form of an array and an optimization test was conducted to increase the energy collection efficiency. Moreover, obtaining the maximum instantaneous power of approximately 1.9 mW from eight unit modules is possible [27].

With the continuous development of IoT sensors, the importance of sensors has been significantly increased. In addition, the number of sensors used in various environments has increased. It is an important problem to solve the power supply of the sensors. Many researchers have conducted various research such that sensors used in different environments can be used for self-generation. Ji, S. et al. reported an emergency stop system for cooperative robots by fabricating a flexible 3D structure module-type TENG (Fig. 4(a)). By repeatedly inserting a cylindrical triboelectric material inside the housing made in the form of a greatly flexible and 3D structure, when contact occurs from the outside, the contact between the inner triboelectric material cores is induced based on the bending motion of the housing and the electrical output performance is improved. Moreover, we demonstrated that the module-type TENG can be composed of an emergency stop sensor and system by making an algorithm that can produce the emergency stop motion of the cooperative robot [28]. Du, T. et al. proposed a cylindrical bouncing ball triboelectric nanogenerator (BB-TENG) for effectively collecting vibration energy of mechanical devices used in ships (Fig. 4(b)). At the vibration frequency of approximately 10–50 Hz, BB-TENG could obtain an output performance of up to 12 V and 0.6 μA. Additionally, it was possible to fabricate a condition monitoring system for intelligent marine machinery using the BB-TENG sensor [29]. Yoon, H.-J. et al. reported a dust particle adsorption system using a TENG module fabricated with a biomimetic villi structure using a 3D printer (Fig. 4(c)).

The surface area of the biomimetic villus structure can effectively increase the contact surface area compared to the planar structure, and high output performance can be improved by using PTFE powder as a negatively charged material [30]. Kim, M.S. et al. reported random number generator (RNG) due to unique turbulent characteristics generated from wind energy by manufacturing TENG using a quadruple clamp flip-flop membrane (Fig. 4(d)). The optimized design of the double and quadruple clamp flip-flop membrane TENG was carried out to produce true random number generator (TRNG), which is one of the basic hardware-based security elements. In addition, after being applied to drones or aircraft, wind energy generated during operation is collected using the TENG module, and the intrinsic turbulence characteristics of wind power are used in reverse to prove that it can be used as an encryption application for information protection [31].

3. CONCLUSIONS

Applying TENG, which has been highlighted for its high energy efficiency among energy harvesting techniques, to more diverse applications by manufacturing it as a module type is possible. In addition, the module-type TENG acts similar to a small device and can be easily installed anywhere that generates kinetic energy. In this study, this study aims to discuss the case of TENG used as a module type by dividing various applications into four areas, such as human body application, natural environment, transportation means, and mechanical device application. Wasted kinetic energy inevitably occurs for all four divided areas. Therefore, various researchers conducted optimal parameter studies to effectively collect wasted kinetic energy, resulting in the significant increase of the energy collection efficiency and the obtained energy was used as a generator or an instrument to detect abnormal signals. Its applicability as a monitoring system for diagnosing devices or working environments is proven. In addition, the use of sensors to measure physical quantities, such as water level, wind speed, temperature, and pressure, using the high sensitivity of TENG were discussed. Moreover, various uses of this technology were also discussed. However, for the commercialization of TENG sensors and monitoring systems, its durability must be improved through a more optimized structural design, and its reliability must be verified in extreme working environments in the future. Therefore, it is important to study a more perfectly packaged module-type TENG to develop a TENG device that has high reliability and can be easily applied to various environments.

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