Portable device for water-sloshing-based electricity generation based on charge separation and accumulation

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Abstract

Hydropower generation is a well-known electricity generation technique that employs Faraday’s law and hydraulic turbines. Recently, a triboelectrification-based electricity generation device, employing water as the triboelectric material (W-TEG) was developed. In addition to the enhancement of the electrical output performance through the operation mechanism, the characteristics of the W-TEG must be examined at the design level to facilitate its portable application. Therefore, in this work, we developed a portable water-sloshing-based electricity generator (PS-EG) that can produce a high electric output and achieved its closed-loop circuit design and quantitative analysis for portable applications. The proposed PS-EG produced peak open-circuit voltage ($V_{OC}$) and closed-circuit current ($I_{CC}$) of up to 484 V and 4.1 mA, respectively, when subjected to vibrations of 2 Hz. The proposed PS-EG can be effectively utilized as an auxiliary power source for small electronics and sensors.
**Introduction**

Water, which covers 70% of the Earth’s surface and serves as a promising alternative energy source, can be used in electric power generation. Hydropower generation, in which the dynamic energy of falling or flowing water is converted to electricity, is a widely employed electricity generation technique that applies Faraday’s law to hydraulic turbines. With the advancement of the Internet of things, which relies on small/thin electronics or self-powered sensors, researchers are attempting to ensure a balance between the portability and electrical output of energy harvesters. Furthermore, various energy harvesters that use the electrokinetic effect (Duffin and Saykally, 2008, Koranlou et al., 2019) or triboelectrification (Kim et al., 2018a, Zhu et al., 2012, Fan et al., 2012, He et al., 2017, Kim et al., 2019) techniques have been developed to generate the electric power necessary to power small electronics. Among such devices, triboelectrification-based electricity generators, which are made of lightweight materials and can produce a high electrical output, have demonstrated potential to function as auxiliary power sources of small electronic devices or self-powered sensors (Wang, 2017, Chung et al., 2019, Hwang et al., 2019, Meng et al., 2013, Kim et al., 2019). Existing works on water-based triboelectric generators (W-TEGs) involved the use of water hydraulics to induce solid–solid contact (Zhang et al., 2020b, Kim et al., 2018b, Xu et al., 2019) and the electrical aspects of water (Lee et al., 2016, Chung et al., 2018, Lin et al., 2014, Jang et al., 2020, Cho et al., 2019, (Helseth, 2020, Helseth and Guo, 2015, Helseth and Guo, 2016) to exploit liquid–solid contact. However, owing to the mechanism of triboelectrification, solid–solid contact generators are highly vulnerable to wear failure and humidity (Mule et al., 2019, Nguyen and Yang, 2013). Consequently, it is desirable to develop W-TEGs with liquid–solid contact to ensure an extended lifespan and constant electrical output in humid environments.
The key challenges for the practical implementation of liquid–solid contact W-TEGs in portable applications are to enhance the electrical output performance and realize a portable design. Recently, the electrical output performance of W-TEGs was considerably improved from the nanowatt to microwatt scale by inducing direct contact between the water and a conductive material (Xu et al., 2020, Zhang et al., 2020a, Chung et al., Under Review). Although the development of a working mechanism to realize a high electrical output is in progress, the characteristics of W-TEGs must be examined at the design level to ensure their suitability for portable applications. In this regard, W-TEGs with a closed-loop circuit are preferable, as no additional circuit for the electrical ground is required, and the device is more efficient than single electrode generators (Meng and Chen, 2020). In addition, because a high electrical output is generated only when water in motion contacts the conductive material, the relationship between the water motion and electrical characteristics must be quantitatively analyzed. Therefore, it is desirable to realize an extensive design and analysis of liquid–solid contact W-TEGs.

To this end, in this work, through a closed-loop circuit design and quantitative analyses, we developed a water-sloshing-based electricity generator (PS-EG) that can produce a high electric output. The PS-EG is composed of a dielectric container (perfluoroalkoxy alkane, PFA) containing water, a central electrode, and an outer electrode. When mechanical input is applied to the container, charge separation and accumulation occur owing to the self-ionization of water under the electric field induced by the negative surface charge of the PFA container. The dynamic motion of water, which induces the charge separation and accumulation, can be categorized as wall impact, wave motion, or water-droplet-related motion. Considering these mechanical movements, quantitative analyses were performed on the optimized device design, based on the location of the outer electrode and amount of water, examining the peak and root mean square (RMS) output. The proposed PS-EG could power
120 LEDs continuously during walking or running activities and demonstrated promising potential for implementation in everyday applications.

**Result and discussion**

The PS-EG consists of four basic components: a dielectric container, two electrodes, and water (Figure 1a). PFA was used as the dielectric material because the associated negative surface charges can induce a strong electric field owing to its high electron affinity. The central electrode was electrically connected to the outer electrode in a closed-loop circuit. In general, when a container vibrates vertically, the water inside the container no longer remains stationary. The movement of water inside a container is often termed as “sloshing motion” (Hashimoto and Sudo, 1988, Ibrahim et al., 2001). During this movement, charge separation and accumulation occur in the water owing to the self-ionization of water. In particular, water naturally undergoes self-ionization and produces negative (hydroxide ion, OH\(^-\)) and positive charges (hydrogen ion, H\(^+\) / hydronium ion, H\(_3\)O\(^+\)) (Pitzer, 1982). Owing to the mechanical movement of the water in the PFA container, the electric field of the container leads to the separation and accumulation of the charges. When water with the accumulated charge contacts the central electrode, electricity is generated according to the water behavior. When a vertical excitation of 6 Hz is continuously applied by a vibration tester to the container, the water behavior, although irregular and complex, can be divided into three types (Chung et al., Under Review): wall impact, wave motion, and water-droplet-related motion. First, when water impacts a wall of the container and moves along the negative wall surface, net positive charges of water are induced, forming an electrical double layer, which consists of a stern layer and diffuse layer. The stern layer is an immobile region in which the positive ions of water adhere to the negative surface of the PFA. Even if the water continues to slide against the PFA surface, the stern layer remains immobile. In the mobile diffuse layer, which is
present next to the stern layer, positive or negative ions can move freely, and the positive ions are attracted by the strong negative surface charges of the PFA. Until the Debye length, at which the negative surface charges of the PFA are fully screened by the ions and water molecules, is reached, the water exhibits a net positive charge (Figure S1). Therefore, as the water impacts and propagates on the wall surface of the PFA, the positive charges of water are continuously induced and accumulated. When these accumulated positive charges contact the central electrode, a distinctively high electrical peak is generated. Second, when the water in the middle of the container oscillates longitudinally in a wave motion, negative charges are accumulated owing to the high positive charge concentration of the water near the PFA wall surface. Simultaneously, positive charges are induced at the central electrode, owing to the negative surface charge of the PFA. When the water at the center of the container rises and contacts the central electrode, a negative peak output is generated (Chung et al., Under Review). Third, water droplets may be separated from the bulk water surface during the wall impact and wave motions. These water droplet fragments exhibit either a positive or negative charge according to the Poisson model (Wiederschein et al., 2015). Thus, when a water droplet contacts the electrodes, positive and negative peak outputs are produced. Notably, the electrical output from the wall impact and water-droplet-related motion is higher than that corresponding to the wave motion. Moreover, because the water movement in the PS-EG involved substantial wall impacts and droplets contacting the central electrode, the high electrical output of the PS-EG can be attributed primarily to these behaviors.

Figures 1b and c show the peak open-circuit voltage ($V_{oc}$) and closed-circuit current ($I_{cc}$) at a vertical input frequency of 6 Hz, respectively. The maximum $V_{oc}$ and $I_{cc}$ were 440 V and 8.4 mA, respectively. Total amount of transferred charges between the electrodes also can be calculated by integrating peak current in Figure 1c. The total charges transferred between the electrodes for 30 seconds is 0.39 mC. Moreover, the voltage and current pertaining to various
external load resistances were measured and converted into RMS voltage ($V_{RMS}$) and current ($I_{RMS}$) values, as follows.

$$V_{RMS} = \sqrt{\frac{\int V(t)^2 dt}{T}}, \quad I_{RMS} = \sqrt{\frac{\int I(t)^2 dt}{T}}$$

where $V(t)$, $I(t)$, and $T$ denote the measured peak voltage, peak current output, and measurement period, respectively.

In general, the RMS value is a quantitative indicator and does not reflect the peak output value, and the waveform generated by the PS-EG is an extremely sharp peak. Therefore, it is necessary to examine the RMS output to evaluate the suitability of the device for use as an auxiliary power source for small electronics. The converted $V_{RMS}$ and $I_{RMS}$ values of the PS-EG at various external load resistances are shown in Figure 1d. With the increase in the external load resistance, the RMS voltage and current increase and decrease, respectively. Figure 1e shows the average power plot obtained by multiplying the $V_{RMS}$ and $I_{RMS}$ values at each external load resistance. It can be noted that the PS-EG generates a maximum average power of 2.69 µW at an external load resistance of 50 MΩ.

Figure 2a shows the electrical output of the PS-EG, measured at different positions of the outer electrode ($h_1$–$h_4$). In general, for the PS-EG to be utilized in portable applications, a dual electrode configuration must be used to eliminate the requirement of an electrical ground; moreover, a single electrode is usually less efficient than a dual electrode (Meng and Chen, 2020). As the PS-EG is cylindrical and exhibits vertical motion, the electrode on the outer surface of the dielectric container can be adjusted. When vertical excitation of 6 Hz is applied to the PS-EG through a vibration tester, the water inside the container exhibits three types of dynamic behaviors and contacts each electrode.

Figures 2b and c show the average peak voltage and $V_{RMS}$ output of the PS-EG at different
outer electrode locations (h₁–h₄), and Figure S3 shows the voltage vs. time plots corresponding to these locations. The outer electrode locations are equally spaced; specifically, h₁ to h₄ are located from the bottom to the top of the container at equal intervals. The plots indicate that both the average peak voltage and \( V_{RMS} \) exhibit similar tendencies. When the outer electrode is located at h₁, the lowest average peak voltage output and RMS voltage output are 61 V and 3.3 V, respectively. The average peak voltage and \( V_{RMS} \) increase as the position of the outer electrode shifts to the top, that is, from h₂ to h₄. The highest average peak voltage and RMS voltage (204 V and 13.8 V, respectively) occur when the outer electrode is located at h₄.

As mentioned previously, the main behaviors of water that produce a high electrical output are the wall impact and water-droplet-related motion. Considering the amount of water in motion, wall impact is the water movement that most notably affects the electrical output of the PS-EG. When the PFA container is excited vertically, the water starts to slosh inside the container, and wall impact motion occurs. When water propagates to the top of the PFA container, the water mass appears triangular owing to the influence of gravity (Figure 2d, S4). Owing to this phenomenon, when two electrodes are located at high and low positions, the contact area (\( A_1 \) and \( A_2 \), respectively) between the PFA and water is larger on the electrode that is placed lower (\( A_1 < A_2 \)). In the contact area, the surface charge of the PFA is screened by the ions and molecules of water, owing to which the electrode behind the PFA (outer electrode) exhibits a lower induced charge. Because the measured output of the PS-EG is mainly based on the electrical potential difference between the two electrodes when water contacts the central electrode, the generated output is expected to decrease when a larger amount of surface charge of the PFA is screened by the water.

Furthermore, Figure S5a shows the average peak voltage and \( V_{RMS} \) output of the PS-EG
for different center electrode length of 1, 2, 3, 4, 5 cm. The voltage versus time plot corresponding to these lengths is shown in Figure S5b. Center electrode length of over 5 cm, which reaches water surface of 150 ml, is not considered. When the center electrode is 1 cm, the lowest average peak voltage of 93.6 V and RMS voltage of 6.1 V are generated. The average peak voltage and $V_{RMS}$ increase as the length of center electrode increase from 1 cm to 5 cm. The highest average peak voltage of 177.5 V and RMS voltage of 13.2 V are produced when center electrode is 5 cm. It is because that water with accumulated charges is more likely to contact the center electrode as the center electrode length increases. Figure S6a represent the average peak voltage and RMS voltage output of the PS-EG at PFA thickness of 1T (0.55 mm) and 2T (0.1 mm). Figure S6b shows the voltage vs. time plot corresponding to these thicknesses. When the PFA thickness is 1T, average peak voltage of 125.1 V and RMS voltage of 10.2 V are generated. The PS-EG with thickness of 2T also produced average peak voltage of 144.8 V and RMS voltage of 10.7 V, comparable to those for 1T. As a result, it is expected that PFA thickness does not significantly affect electrical performance of the PS-EG.

Figure 3a shows a schematic of the PS-EG pertaining to different amounts of water inside the PFA container (water volume of 50, 100, 150, 200, and 250 mL). When a vertical vibration is applied to the PS-EG, the water inside the container exhibits different mechanical movements depending on the water volume. Figures 3b and c show the average peak voltage and $V_{RMS}$ output of the PS-EG for different values of the water volume (50–250 mL). The $V_{OC}$ vs. time plot for each value of the water volume is shown in Figure S7. When the volume of water is 150 mL, which is the volume corresponding to the midline of the PFA container, the highest peak voltage of 189 V and $V_{RMS}$ of 14 V are generated. The volume of 50 mL corresponds to the smallest peak voltage of 61 V and $V_{RMS}$ of 2.9 V. The peak voltage and $V_{RMS}$ corresponding to the volume of 250 mL are also small, 69 V and 6.2 V, respectively,
comparable to those for the volume of 50 mL.

In general, water with accumulated charge generates electricity when it contacts the central electrode; therefore, the main factors influencing the charge accumulation inside the water are the PFA surface and disruption of the water surface (Wiederschein et al., 2015, Shewchuk and Iribarne, 1971, Lenard, 1892). In other words, for water to have a higher accumulated charge, the water must contact and propagate more on the PFA surface and must have sufficient space to exhibit mechanical movement. Specifically, the PS-EG can produce a higher output when both these factors are satisfied. Figure 3d shows high-speed camera photographs of the water behavior for volumes of 50, 150, and 250 mL (Supplementary Videos 1–3), which correspond to the volume of water that is below, exactly at, and above the midline of the PFA container, respectively. As shown in Figure 3d-i, although a volume of 50 mL (below midline of PFA container) means that the water has sufficient free space to move, owing to the limited volume, the contact area between the PFA and water is smaller than that for the water volume of 150 mL. When the water volume is 150 mL, the water has sufficient space to move, and the contact area is larger than that when the volume is 50 mL, which increases the charge separation and charge accumulation, thereby leading to the generation of a high electrical output (Figure 3d-ii). As shown in Figure 3d-iii, when the water volume is 250 mL, (above the midline of the PFA container), the water does not have sufficient space to move or contact the PFA. These results indicate that the largest electrical output is generated when the water level is near the midline of the dielectric container.

The proposed PS-EG can be applied directly in everyday applications. Figure 4a shows a schematic of the PS-EG as a self-powered water bottle with a straw, consisting of a PFA bottle containing water, an outer electrode, and electrode-coated straw as the central electrode. When the water bottle is swung owing to hand or body motion, the water inside the bottle
exhibits sloshing movement and contacts the central electrode. During daily walking or running activities, the PS-EG can power 120 LEDs attached on the forearm, through a full-wave bridge rectifier, as shown in Figure 4b. The details of the rectification circuit are shown in Figure S8. Supplementary Videos 4 and 5 show that the 120 LEDs are continuously lit when the device is shaken by the hand and during running motion, in which the PS-EG is subjected to vibrations with a frequency of 2 Hz. Figures 4c and d show the detailed peak open-circuit voltage ($V_{OC}$) and peak closed-circuit current ($I_{CC}$) plots under a manual vibration input frequency of 2 Hz, respectively. A maximum peak $V_{OC}$ and peak $I_{CC}$ of 484 V and 4.1 mA are produced, respectively. Moreover, the PS-EG can charge energy storage units, such as capacitors. To demonstrate the charging capability, a commercial capacitor with different load capacitances is charged using the PS-EG. Figure 4e shows the charging plot of the PS-EG for 22, 33, and 47 μF capacitances for 200 s, during manual shaking with a frequency of 2 Hz. Figure S9 presents the details of the charging circuit, in which the capacitor is connected to a full-wave bridge rectifier. Furthermore, the PS-EG can charge 330 μF capacitor and power portable digital clock temperature-humidity meter by charging a capacitor. Figure S10 shows detailed charging circuit and the photograph powering portable digital clock temperature-humidity meter. Supplementary Videos 6 shows that the PS-EG can power digital clock temperature-humidity meter after 40 minutes charging. The proposed PS-EG can be effectively integrated in various applications in everyday life. For example, the water-bottle-type PS-EG can serve as a portable self-powered safety lamp as well as an auxiliary power source for small electronics such as a safety tracking device while an individual is climbing a mountain or walking and running at night. As shown in Figure S11, even after 24 hours of operation, the PS-EG has shown consistent output.

Conclusions
We developed a PS-EG that can generate a high electrical output through water movement. The device has a simple design involving a dielectric container containing water and two electrodes. When water sloshes inside the dielectric container, the water ions are separated, leading to accumulated charge. As the water with the accumulated charge contacts the central electrode, a distinctly high electrical output is generated. The electrical output of the PS-EG corresponding to different electrode positions and water volumes inside the container was measured, and it was noted that the highest output was generated when the electrode was located at the top of the dielectric container, with the water volume corresponding to the midline of the container. The proposed PS-EG produced a peak $V_{oc}$ and $I_{cc}$ of up to 484 V and 4.1 mA, respectively, when subjected to vibrations of 2 Hz. The proposed PS-EG can be utilized as an auxiliary power source for small electronics and sensors.

**Limitation of Study**

The PS-EG device developed in this study can be utilized as effective mechanical energy harvester. However, the electrical output of the device can be further improved when solid material with greater surface charge compared to PFA is used. In addition, the PS-EG developed in this article mainly focus on utilizing water as liquid material, but the concept of PS-EG has potential be utilized in other liquids as well. In the future studies can explore the influence of using different solid/liquid materials to increase the electrical output utilizing current generator design.

**Resource Availability**

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Material Availability

Materials used in the study are commercially available.

Data and code availability

This study did not generate computer code. All data and analytical methods are available in the main text or in Supplemental information section.

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Author Contribution

J.C. and D.H. designed experiments and wrote the manuscript. J.C., D.H. and K.C. performed experiments. J.C., D.H., and K.C. analyzed the data. Z.L., J.H. and S.L provided expertise and feedback.

Declaration of Interests

The authors declare no competing interests.
Reference


dynamics.


drop energy by a sequential contact- electrification and electrostatic- induction process. 

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Figure. 1. Schematic and electrical performance of portable water-sloshing-based electric power generator (PS-EG). (a) Schematic illustration of PS-EG. (b) $V_{OC}$ and (C) $I_{CC}$ performance of PS-EG. Root-mean-square (RMS) (d) voltage, current, and (e) power performance of PS-EG.
Figure 2. Electrical performance of the PS-EG, for different locations of the electrode. 
(a) Schematic illustration of different locations of electrode on PS-EG. (b) Average peak voltage, and (C) RMS voltage depending on different locations of electrode. (d) Illustration on water movement depending on different location of electrode.
Figure 3. Electrical performance of the PS-EG for different values of the water volume. (A) Schematic of the water level pertaining to the volume of water inside the container. (B) Average peak voltage and (C) RMS voltage of the PS-EG for different values of the water volume. (D) Photograph of water sloshing inside the PFA container for a water volume of (i) 50 mL, (ii) 150 mL, (iii) 250 mL.
Figure 4. Schematic and electrical performance of commercial cup-type PS-EG, for different values of the water volume. (A) Schematic of the PS-EG designed as a commercial cup. (B) PS-EG powering 120 LEDs during walking and running activities. (C) $V_{OC}$ and (D) $I_{CC}$ output when vibration with a frequency of 2 Hz is applied to the PS-EG. (E) PS-EG charging a commercial capacitor.
Supplementary Videos

Supplementary Video 1. Water sloshing movement when 50 mL of water is inside the container. Related to Figure 3.

Supplementary Video 2. Water sloshing movement when 150 mL of water is inside the container. Related to Figure 3.

Supplementary Video 3. Water sloshing movement when 250 mL of water is inside the container. Related to Figure 3.

Supplementary Video 4. 120 LEDs continuously lit when the PS-EG is shaken by the hand. Related to Figure 4.

Supplementary Video 5. 120 LEDs continuously lit by PS-EG during running motion. Related to Figure 4.

Supplementary Video 6. Digital clock temperature-humidity meter powered by PS-EG after 40 minutes charging. Related to Figure 4.
- Portable electric generator utilizing water sloshing motion is proposed.
- Quantitative analysis for optimized water generator design.
- Power generation through walking and running motion.