

Article

Influencing Factors of Electrical Output in Droplets Triboelectric Nanogenerator

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Abstract

The Droplets Triboelectric Nanogenerator (DTENG) possess distinctive merits in harvesting ambient hydropower into usable electricity. Nevertheless, droplet spreading, contact separation behavior, and dynamic interfacial interactions on insulating film surfaces are extremely sensitive to external environmental factors, giving rise to complicated nonlinear output characteristics. Herein, this work reports a droplet-driven TENG based on fluorinated ethylene propylene (FEP) thin films. We systematically explore how electrode geometry, droplet falling height, substrate inclination angle, and droplet flow rate modulate electrical output performance, and further clarify the fluid-triboelectric electron transfer between droplet hydrodynamic evolution and electric signal generation. Notably, we identify the retraction current during droplet recession, a signal largely neglected in previous solid–liquid TENG research, which complements the fundamental mechanism of interfacial charge transfer. This work not only provides a systematic experimental basis for understanding the working mechanism of DTENG, but also lays a theoretical and practical foundation for developing efficient and controllable water energy collection and self-powered sensor systems.

Keywords: triboelectric nanogenerator; droplets dynamics; solid–liquid contact; water energy harvesting; electrical output characteristic

1. Introduction

TENGs have a novel micro energy collection and signal sensing technology based on the triboelectric effect and electrostatic induction [1]. It was first proposed by Professor Wang Zhonglin's team at Georgia Institute of Technology in 2012 [2,3]. This technology generates charge transfer through material interface contact separation or sliding friction, and induces current between electrodes to achieve the conversion of mechanical energy to electrical energy. It has the advantages of simple structure, low manufacturing cost, high output power, and strong environmental adaptability. In recent years, TENGs have made significant progress in structural design, material research and development, and performance optimization, gradually applied in multiple fields such as wearable electronics [4–7], environmental monitoring [8–10], intelligent healthcare [11–13], micro robots [14–18], and intelligent transportation [19–21]. Especially in low-power self-powering systems and wireless sensor network applications, TENGs have become the preferred technological solution for micro energy harvesting and self-driving sensors due to their characteristics of



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no external power supply, strong environmental adaptability, and high energy recovery efficiency [22–24].

Solid–liquid mode TENGs have become one of the key research directions in recent years due to their ability to directly utilize the widely existing solid–liquid contact/separation behaviors in nature, such as water droplet impact and water flow friction, for energy conversion [25,26]. The solid–liquid mode TENGs achieve charge transfer and electrical energy output through dynamic contact between solid electrodes and liquids (conductors, semiconductors, or electrolytes) [27–29]. Its core advantage lies in its efficient capture capability for low-frequency, low-amplitude fluid mechanical energy. Compared with traditional electromagnetic power generation technologies, this mode does not require complex mechanical structures and has the characteristics of lightweight, low-cost, and flexible adaptation, which can meet the self-power supply needs of wearable devices, IoT nodes, ocean monitoring equipment and other scenarios [30–34]. At present, researchers have significantly improved the output performance and environmental adaptability of devices by regulating the surface morphology of solids, optimizing the dielectric properties of liquids, and designing electrode structures.

Zuankai Wang 2020 invented a device to harvest energy from impinging water droplets and developed a new mode to enhance the surface charge density by several orders of magnitude by connecting one end of the wire to an aluminum electrode on the of FEP film and the other end to the Indium Tin Oxide electrode sticking to the polytetrafluoroethylene film back [35]. Subsequently, Zhonglin Wang investigated the contributions of each functional group to the contact electrification between several polymer films and the same water drop, with results showing that the unsaturated groups can enhance stronger electronic capability than the saturated groups [36]. TENGs based on solid–liquid mode have developed liquid interface recognition and self-driven droplet manipulation [37,38]. Nevertheless, most previous studies focusing on droplet-based TENGs mainly concentrated on the electrical response during the droplet impact and spreading stages. The dynamic characteristics and generation mechanisms of current produced during droplet retraction have long been overlooked, and there is a lack of in-depth research on the full-cycle coupling between droplet spreading–retraction dynamics and triboelectric effects. Additionally, the comprehensive regulation rules of multiple operating parameters for DTENG still need further systematic exploration, which limits the further miniaturization, intellectualization and industrialization of this technology.

This study focuses on the expansion and contraction process of droplets on FEP–aluminum electrode composite structures, and systematically explores the influence of multiple parameters such as electrode size, droplets incidence height, film inclination angle, and flow rate on the electrical output performance. Firstly, from the perspective of fluid dynamics, when a water droplet falls from a certain height and impacts a flat plate, it exhibits a typical transient process of “rapid broadening surface tension contraction oscillation stabilization”. During this process, the dynamic changes in the contact area of the droplets directly determine the distribution of frictional charges at the solid–liquid interface, thereby coupling the electron transfer behavior between the back electrode and the front electrode. In terms of electrode structure regulation, increasing the width of the front electrode (3–18 mm) will significantly reduce the electrical output, manifested as a decrease in voltage from 40 V to 5 V and a decrease in current from 2 μA to 0.5 μA . An excessively wide electrode causes power output dispersion and an increase in equivalent capacitance, thereby weakening the potential difference and transient power output rate. In terms of droplets kinetic energy regulation, under the condition of maintaining an electrode width of 3 mm, the drop height of the droplets was increased from 5 cm to 25 cm, the output voltage was increased from 10 V to 40 V, and the current was increased from 0.8 μA to 2.5 μA , showing a significantly

enhanced energy conversion effect. However, as the height further increased to 30 cm, the voltage and current remained constant. In terms of regulating operating parameters, the inclination angle and water droplet flow rate of FEP film have a sensitive impact on output performance. When the inclination angle increases from 15° to 60° , the voltage drops from 60 V to 45 V, while the current remains basically unchanged. On the other hand, when the inclination angle is maintained at 45° and the water droplet's velocity increases from 20 to 40 revolutions per minute (rpm), there is a slight increase in both voltage and current; but when the flow rate further increases to 50 rpm, the output actually decreases. Distinct from prior DTENG studies that only focus on droplet impact and spreading behavior, this work innovatively focuses on the retraction current, and reveals the full-cycle electron transfer between droplet spreading–retraction dynamics and solid–liquid triboelectric effects. We also clarify the quantitative regulation laws of multiple key parameters, including electrode size, droplet height, substrate inclination and flow velocity. The findings provide a solid theoretical and experimental basis for the structural design and practical application of droplet-based triboelectric nanogenerators.

2. Result and Discussion

2.1. Experimental Setup

Construction of solid–liquid mode TENG: To prepare TENG, we chose FEP thin film (5 cm in length, 5 cm in width, and 0.1 mm in thickness, with no additional surface modification before use) with strong electron harvesting ability at the solid contact surface. FEP features high tribonegativity and hydrophobicity to generate and retain triboelectric charges. Its good dielectric property and chemical stability guarantee steady output in liquid–solid environments. In order to process the induction electrode on the back of FEP, we directly pasted the aluminum electrode onto the FEP film. The area of aluminum is equal to the area of FEP film, with a thickness of 0.06 mm, with no additional surface modification before use. In order to construct the upper electrode on TENG, we assembled aluminum electrodes of different sizes onto FEP film. Finally, connect the manufactured TENG device with wires and fix it on an acrylic flat plate.

The droplets are generated by a self-made peristaltic pump, and the flow rate can be manually adjusted. The short-circuit current and open circuit voltage are checked using Keithley 6514 electrostatic meter (Keithley Instruments, Incorporated, Solon, OH, USA). The dynamic morphological evolution of droplets during impact, spreading and retraction was recorded by a Xiaomi mobile phone (Xiaomi Communications Company Limited, Beijing, China). The obtained videos were processed frame by frame using OpenCV 4.12 software to extract key morphological information for subsequent analysis. A commercial peristaltic pump was adopted to generate droplets, and its flow rate could be adjusted manually.

2.2. Dynamic Characteristics of DTENG

When water droplets fall freely from a height of about 25 cm and collide with a horizontal Fluorinated Ethylene Propylene (FEP) flat surface and transverse aluminum electrodes, their dynamic process exhibits a typical “expansion contraction” two-stage characteristic. As shown in Figure 1a(i,ii), water droplets gain a certain amount of kinetic energy under the action of gravity. At the moment when the water droplets contact the FEP substrate plate and transverse aluminum electrodes, kinetic energy will be rapidly converted into radial momentum, causing the droplets to spread rapidly in the radial direction (Figure 1a(iii)). At this point, the droplet's shape transitions from an approximately spherical shape to a thin liquid film structure, with clear liquid rings appearing at the edge of the liquid film, and the spreading diameter reaching its peak in a short period of time. This stage is mainly

driven by inertial forces, resulting in a sharp decrease in the thickness of the liquid film and a significant increase in the interfacial energy of the droplets.

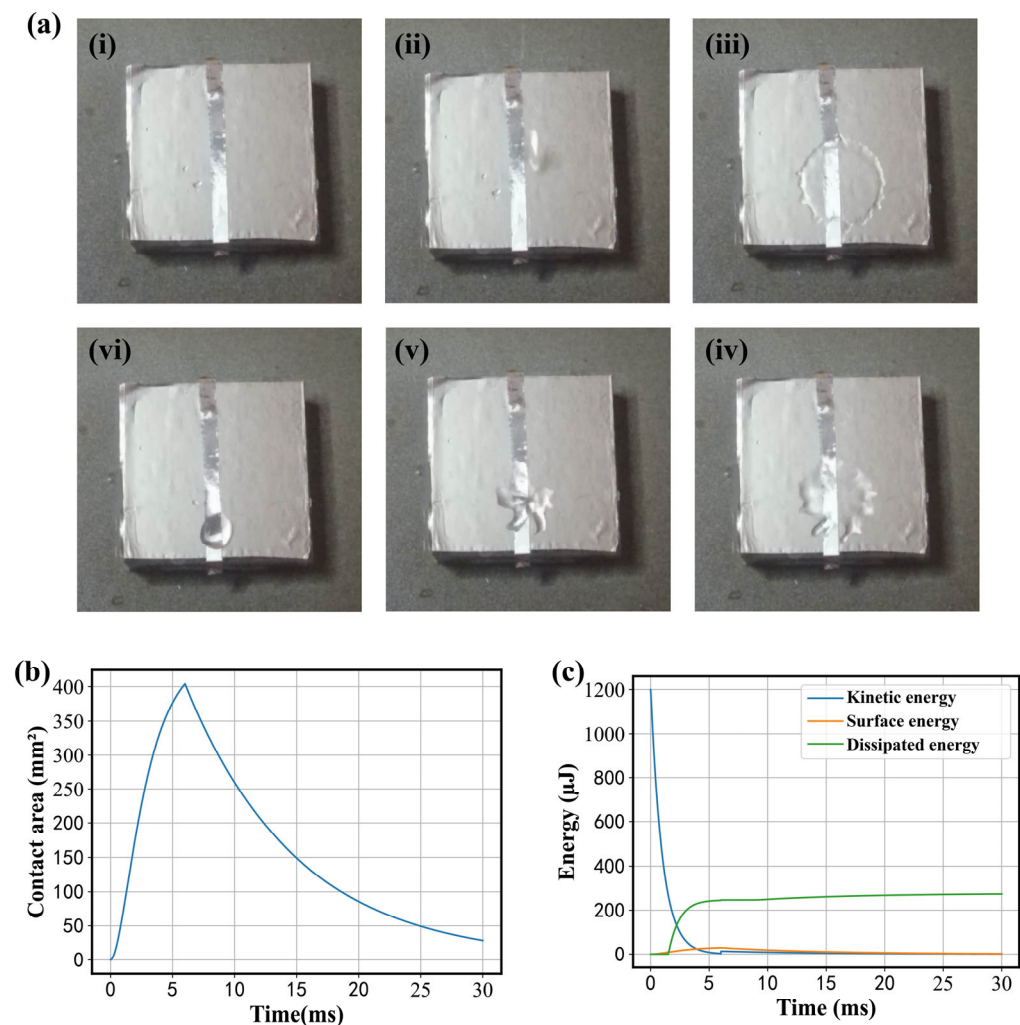


Figure 1. The motion trajectory and dynamic modeling of water droplets in DTENG. (a) Photo taken of droplets impinging on FEP surface. (i) Static initial phase; (ii) Free descent phase of water droplet; (iii) Lateral spreading phase of liquid droplet; (iv) Gradual shrinkage phase of water droplet; (v) Fully contracted phase of water droplet; (vi) Interfacial sliding phase of water droplet. (b) Droplets oscillation trajectory on FEP surface. (c) Energy Conversion of droplets.

After reaching the maximum spreading diameter, the movement of the droplet enters the retraction stage. Due to the effect of surface tension, the edge of the liquid film is strongly driven by contraction, and the liquid begins to flow back from the outer edge to the center. At this point, the droplet's shape gradually shrinks from a flattened state, the thickness of the liquid ring increases, and the central area bulges, showing a trend of the liquid film recovering towards a spherical shape (Figure 1a(iv)). Due to the ideal smoothness and moderate wettability of the flat surface, there may be some amplitude oscillation during the droplet's retraction process (Figure 1a(iv)). The liquid film ultimately tends towards the equilibrium state in a stationary state, which is a stable spherical droplet (Figure 1a(vi)). The detailed movement process of the relevant water droplets can be seen in Video S1. This time-resolved process clearly characterizes the dynamic law of “inertial-driven diffusion surface tension contraction viscous dissipation stability” after the droplets impacts the flat plate. The entire process of changing the diameter of water droplets can be

described as follows, and the detailed derivation process can be found in the supporting data (Note S1 and Table S1, Supplementary Materials).

$$R(t) \approx at \quad (0 \leq t \leq t_1) \quad (1)$$

$$R(t) \approx R_{\max} \cdot \exp(-\beta t) \quad (t_1 \leq t \leq t_2) \quad (2)$$

$$A(t) = \pi R(t)^2 \quad (3)$$

where A is a constant obtained based on the maximum radius, $\beta \sim \sqrt{\frac{\gamma}{\rho R_0^3}}$ is shrinkage rate factor.

As shown in Figure 1b, at 0–6 ms, the kinetic energy of the droplet rapidly transforms radially into a spreading motion. The lower part of the droplet is obstructed, while the upper inertia causes the liquid to expand outward from the center, forming a thin liquid film. At 6 ms, the droplet's diameter reaches its maximum value, and the circular protrusion at the edge of the liquid film is most prominent, with the droplet's shape resembling a thin disk. Starting from 6 ms, the outer edge of the liquid film generates a contraction driving force under surface tension, and the liquid begins to flow back from the edge to the center. The liquid ring gradually thickens, and the radial velocity of the liquid film changes from outward expansion to inward contraction. Once it reaches 30 ms, the droplet eventually remains as a stable spherical crown-shaped droplet with an equilibrium diameter smaller than the maximum expansion diameter. At this point, the system energy reaches its minimum, inertia and interfacial tension reach dynamic equilibrium, and the motion process terminates. As depicted in Figure 1c, this “diffusion retraction” process reflects the competitive relationship between droplet's kinetic energy, surface energy, and viscous dissipation. The diffusion stage is dominated by inertia, while the retraction stage is dominated by surface tension, and the entire process is accompanied by a certain amount of energy dissipation, manifested as the final equilibrium diameter of the droplets being smaller than the maximum diffusion diameter.

2.3. Working Mechanism and Equivalent Circuit Model of DTENG

When a water droplet drops from a height of 25 cm onto the surface of a FEP film with a size of 5 cm × 5 cm, the droplet first contacts the aluminum electrode strip (width 3 mm, length 5 cm) covering the front of the film. At this point, as FEP belongs to strongly negatively charged materials, under the frictional electric effect of solid–liquid contact, the surface of FEP film tends to acquire negative charges, while water droplets maintain positive charges, thus forming a stable power output distribution at the solid–liquid interface. A layer of aluminum electrode of the same size is attached to the back of the FEP film to form electrode 2. Due to the separation of positive and negative charges between the FEP surface and water droplets, an equivalent electric field is generated inside the system, driving electron migration between A2 and the front electrode (A1). The complete movement process of water droplets impacting the FEP tablet can be seen in Video S2. This process undergoes dynamic changes with the evolution of the droplet's morphology and can be divided into the following stages.

As shown in Figure 2a(i), during the free fall of water droplets, they also come into contact with the FEP film and aluminum electrode 1. At this point, an equivalent circuit is formed and the entire circuit is in a disconnected state because there is no electrostatic induction process (Figure 2b(i)). When the droplets contact the surface of A1 and FEP film, the droplets spread rapidly. The widening of the liquid film rapidly increases the contact area between water and FEP, enhances the interface friction electrification effect, and more negative charges accumulate on the FEP surface. At this point, the system needs to maintain electrical neutrality, and the electrons driving A2 flow through an

external circuit to A1, forming a transient current (Figure 2a(ii)). This process corresponds to the electron transport during the droplets broadening stage, forming a closed circuit (Figure 2b(ii)). The positive charge stored in the capacitor $C_{D/F}$ begins to release, while other capacitors in the circuit ($C_{D/A1}$, $C_{F/A2}$) are also charged. When the droplet reaches its maximum spreading diameter, the contact area reaches its peak and the interface charge distribution is basically stable. Macroscopically, electrons continuously flow from A2 to A1, increasing the ground current output. As the droplets shrink under surface tension, the liquid–solid contact area decreases and the exposed area on the FEP surface increases. Due to changes in the distribution of induced charges at the interface, the direction of the system potential reverses, driving electrons to flow back from A1 to A2 (Figure 2a(iii)). This process corresponds to the reversal of current direction during the droplets' retraction stage. According to Kirchhoff's laws of voltage and current, the entire process of continuous contact between water droplets, FEP film, and electrode can be described as the following differential equation. The detailed derivation process can be found in the supporting data (Note S2 and Table S2, Supplementary Materials)

$$\frac{Q_0 - q(t)}{C_{D/F}(t)} - \frac{dq(t)}{dt} R_D - \frac{q(t)}{C_{D/A1}(t)} - U_{R_L}(t) - \frac{q(t)}{C_{F/A2}(t)} = 0 \quad (4)$$

$$\frac{dq(t)}{dt} - \frac{U_{R_L}(t)}{R_L} = 0 \quad (5)$$

$$C_{D/F}(t) = \frac{\varepsilon_D S_{FEP}(t)}{d_{EDL}} \quad (6)$$

$$C_{D/A1}(t) = \frac{\varepsilon_D S_{A1}(t)}{d_{EDL}} \quad (7)$$

$$C_{F/A2}(t) = \frac{\varepsilon_F S_{FEP}(t)}{d_{FEP}} \quad (8)$$

where Q_0 represents the accumulated positive charge of $C_{D/F}$ when the droplets contact A1, $q(t)$ represents the amount of charge transferred in the circuit, U_{R_L} represents the voltage across the load, and ε_D and ε_F represent the capacitance of the droplets and FEP, respectively. In addition, $S_{FEP}(t)$ and $S_{A1}(t)$ represent the contact area between the droplets and the surfaces of FEP and A1. d_{EDL} represents the thickness of the double layer, and d_{FEP} represents the thickness of FEP.

When the droplets return to a stable spherical shape, the current in the external circuit has decayed to zero, and the system reaches equilibrium (Figure 2a(iv)). At this point, even if the water droplets are still in contact with the aluminum electrode, the circuit still does not conduct because the essence of capacitors is to conduct AC and resist DC. The numerical changes in open circuit voltage and short-circuit current at 2 s in Figure 2c,d illustrate the operation process of the entire water droplets from the beginning of falling to leaving the FEP substrate plate. In summary, the expansion and contraction process of droplets on the FEP–aluminum electrode composite structure is not only a typical fluid dynamics process, but also an electrical process of frictional charge induction potential difference drive electron back and forth migration. The experimental trends shown in Figure 2c,d are highly consistent with our theoretical inferences and the findings reported in journal articles [35].

In further structural optimization experiments, as exhibited in Figure 2e, we adjusted the width of the front aluminum electrode to investigate the effect of electrode geometry on output performance. As in Figure 2f,g, when the front aluminum electrode is widened from 3 mm to 18 mm, the experimental results show that the output voltage sharply decreases from about 40 V to 5 V, while the output current decreases from about 2 μ A to 0.5 μ A.

This significant attenuation phenomenon indicates that the increase in electrode width has adverse effects on the effective induction of interface charges and the driving capability of external circuits. The reasons can be attributed to the following aspects: Firstly, as the electrode width increases, the contact area between the droplets and the electrode changes from local concentration to large-scale distribution during the expansion and contraction process, resulting in the dilution of the contribution of power output density per unit area and the weakening of the power output induction effect. Secondly, the wide electrode makes the charge distribution more uniform, significantly reducing the potential difference in the system and directly causing a decrease in the output voltage amplitude. Once again, the expansion of the electrode area increases the equivalent capacitance, which limits the voltage output under the same amount of charge and also limits the efficiency of transient charge transfer, resulting in a decrease in output current. In summary, the geometric dimensions of electrodes play a crucial role in the energy conversion process of solid–liquid TENG. Narrow electrodes can maintain high power output; the wide electrode causes charge dispersion and voltage collapse, ultimately leading to dual attenuation of output voltage and current. The experimental results emphasize the importance of optimizing electrode width design and provide experimental basis for the performance regulation of subsequent devices.

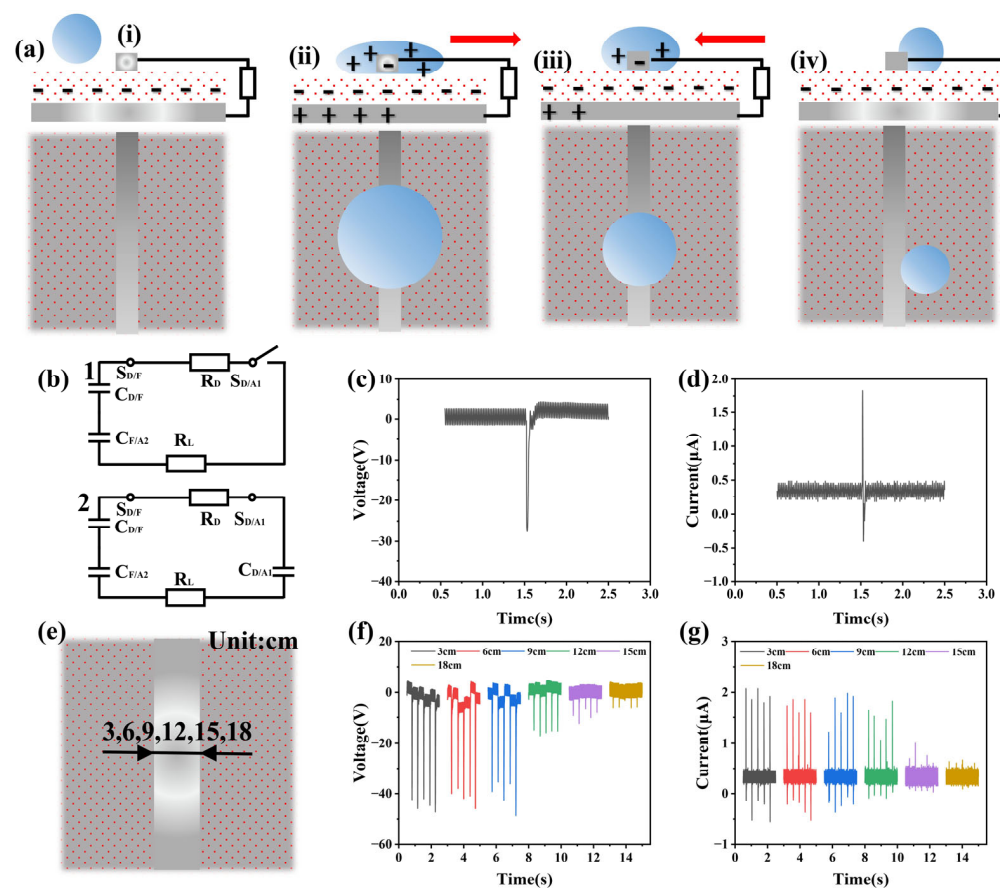


Figure 2. Verification of TENG universality. (a) Working mechanism of the TENG. (i) A configuration that the water droplet has no interfacial contact with the Al electrode coated on FEP film; (ii) The interfacial contact state under the fully spread morphology of water droplet on the Al electrode and FEP film; (iii) The contact morphology formed when water droplet contracts tightly on top of the Al electrode and FEP film; (iv) The motion for water droplet to roll off the Al electrode and FEP film. (b) Establishment of DTENG equivalent circuit. (c,d) The voltage and current signal characteristics of droplets based on TENG. (e) Schematic diagram of electrode size as a variable. (f,g) The voltage and current output at different electrode sizes.

2.4. Research on the Output Law of DTENG

The DTENG is driven by a variable speed peristaltic pump to quantitatively study the electrical output, as displayed in Figure S1. When comparing the output characteristics of different electrode and dielectric structure modes, this study further reveals the significant influence of material interface and electrode layout on the performance of water droplets TENG. As shown in Figure 3a,b, in the single electrode mode, where only a single layer of aluminum electrode is used, when water droplets directly drip onto the metal surface, a corresponding equivalent circuit is formed. Despite limited interface charge transfer, due to extremely low charge separation efficiency, the output voltage is only about 1 V and the current is nanoampere level, as depicted in Figure 3c,d, with almost no effective energy harvesting capability. In double-layer mode, when the bottom layer is an aluminum electrode and the top layer is an FEP film, and the water droplets directly contacts the FEP surface, the output voltage and current are both zero. This result indicates that without an effective charge collection path, a simple insulation layer interface cannot achieve charge induction and transfer, and the system is in an “open circuit” state, unable to form an effective current loop. The bottom layer is an aluminum electrode, the middle is an FEP dielectric layer, and the top is a transverse aluminum electrode with a width of 2 cm. During testing, water droplets are placed on the FEP surface next to the top electrode to form mode 3. This mode is actually the same as mode 4, producing a maximum voltage of 70 V and a maximum current of 35 μ A. Again, by introducing the optimization mode 4 mentioned earlier in this article, which combines the bottom aluminum electrode with the upper FEP film, when water droplets drip onto the interface of the FEP film, stable voltage and current output is achieved through solid–liquid contact charge transfer and inductive coupling with the lower electrode, exhibiting good frictional energy conversion characteristics.

Finally, in the fifth mode, an equally sized aluminum electrode was further covered on top of the FEP film, and water droplets were dropped onto the surface of the upper electrode. The experimental results also showed zero voltage and current. This is due to the failure to excite effective frictional charges when water droplets come into direct contact with metal, and the upper metal electrode blocks the direct interaction between water droplets and FEP, resulting in complete system failure. As posted in Figure 3e, the comparative experiments of different structural modes fully demonstrate that the interaction between FEP and the droplet’s interface is the core of frictional charge generation, while the induction and charge collection of the lower aluminum electrode are necessary conditions for energy output.

When further exploring the energy conversion characteristics of the droplet and FEP film–aluminum electrode composite structure, we designed a front aluminum electrode with a length of 2 cm and a width of 3 mm, while keeping the bottom 5 cm $\times$ 5 cm FEP film and the back aluminum electrode of the same size unchanged, to systematically study the output behavior of droplets in contact with the electrode during the expansion and contraction process. The experimental results showed significant differences among the three typical cases. As shown in Figure 4a, when water droplets fall onto the FEP film, they only come into contact with the front aluminum electrode after completing the complete widening and retraction process. As depicted in Figure 4b,c, the output voltage of this far case is only about 3 V, and the current is also very weak. This phenomenon may be due to the extremely short storage time of the charges generated by the droplets during the diffusion stage during the separation process from the FEP interface. By the time the droplets finally contact the aluminum electrode, the interface charges have significantly decreased, resulting in a significant weakening of the charge induction effect and almost disappearance of the output signal. Secondly, when the water droplets come into contact with the front aluminum electrode during the expansion process, the output voltage reaches about 100 V and the current is about 25 μ A, which is much higher than other modes. At

this time, the droplets are still in the high-speed distribution stage, with a rapid increase in contact area, high interface charge concentration, and large transient potential difference, which enables the most sufficient electron transfer between the back electrode and the front electrode, thereby achieving maximum energy conversion efficiency. The third scenario is when water droplets directly drip onto the FEP film and front electrode, which is the classic mode mentioned earlier in this article, with an output voltage of about 40 V and a current of about 2 μA . Compared to the second mode, the interface charge induced effect is partially weakened, resulting in a lower output amplitude than in the case of contact during the expansion process.

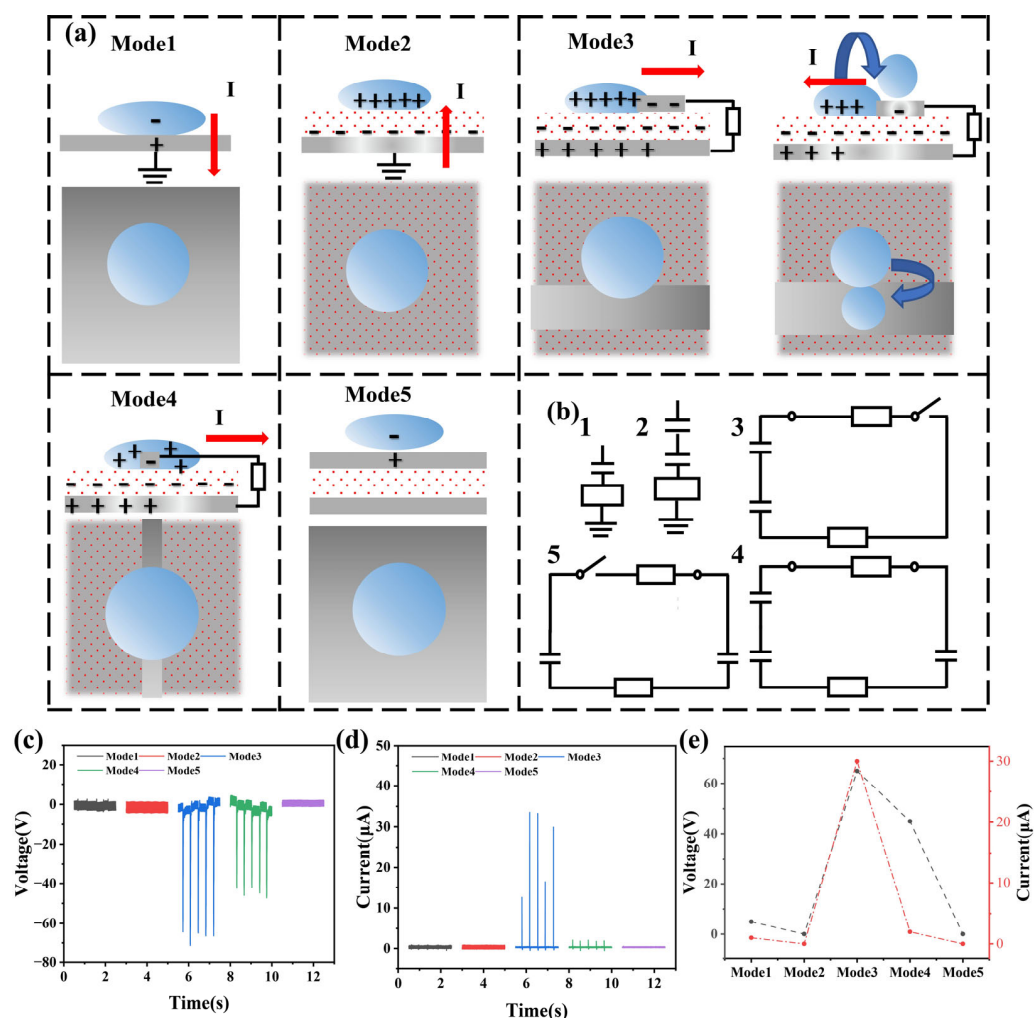


Figure 3. Research on the output characteristics of TENG under mode changes. (a) Schematic diagrams of different modes. (b) Establishment of DTENG equivalent circuits for different modes. (c,d) The voltage and current signal of five modes designed in this work. (e) Comparison of electrical output of five modes.

We introduce the mode of horizontal electrodes here. As shown in Figure S2a, there are also three situations. The situation in the first two schools is the same as the classic model in this article. The third scenario is when the water droplets fall next to the electrode during close, so that the expansion and contraction process of the water droplets occur as much as possible above the aluminum electrode. Figure S2b,c shows the voltage and current changes in the transverse electrode in these three situations. Comparing the two structures, as exhibited in Figure 4d, the vertical electrode ground voltage is greater than the horizontal electrode ground voltage. This is attributed to the reduction in capacitance caused by the

limited contact area, which enhances the transient potential difference. Figure 4e illustrates the magnitude of the ground current during the expansion process of the water droplets, and the output current of the two structures is almost the same. Figure 4f shows the magnitude of the ground current during the retraction process of water droplets. It was found that in the closed state, the current value of the longitudinal electrode was slightly larger than that of the transverse electrode, which further validates the theory proposed in this paper. From the comprehensive analysis of the three modes, it can be seen that the temporal contact between the droplets and the electrode during the diffusion stage has a decisive impact on the accumulation of frictional charges and transient potential difference. During the process of high kinetic energy broadening, water droplets can fully excite interface charge transfer upon contact with electrodes, significantly improving voltage and current output. After the droplet completes its expansion and contraction, it contacts the electrode. Due to the limited time for the stored charge in the droplet and the significant decrease in its movement speed, the energy collection efficiency is significantly reduced. This result reveals the electron transfer between the dynamic behavior of droplets and electrode layout in the droplet–film–electrode system, providing experimental evidence for optimizing the structural design and operating conditions of water droplet-driven TENG. All data in Figure 4d–f were obtained from at least 10 repeated independent experiments, with standard deviations represented by error bars in the corresponding figures to verify the reproducibility of the experiments. And for the position, the farther away the DTENG's output signal is, the less it will be.

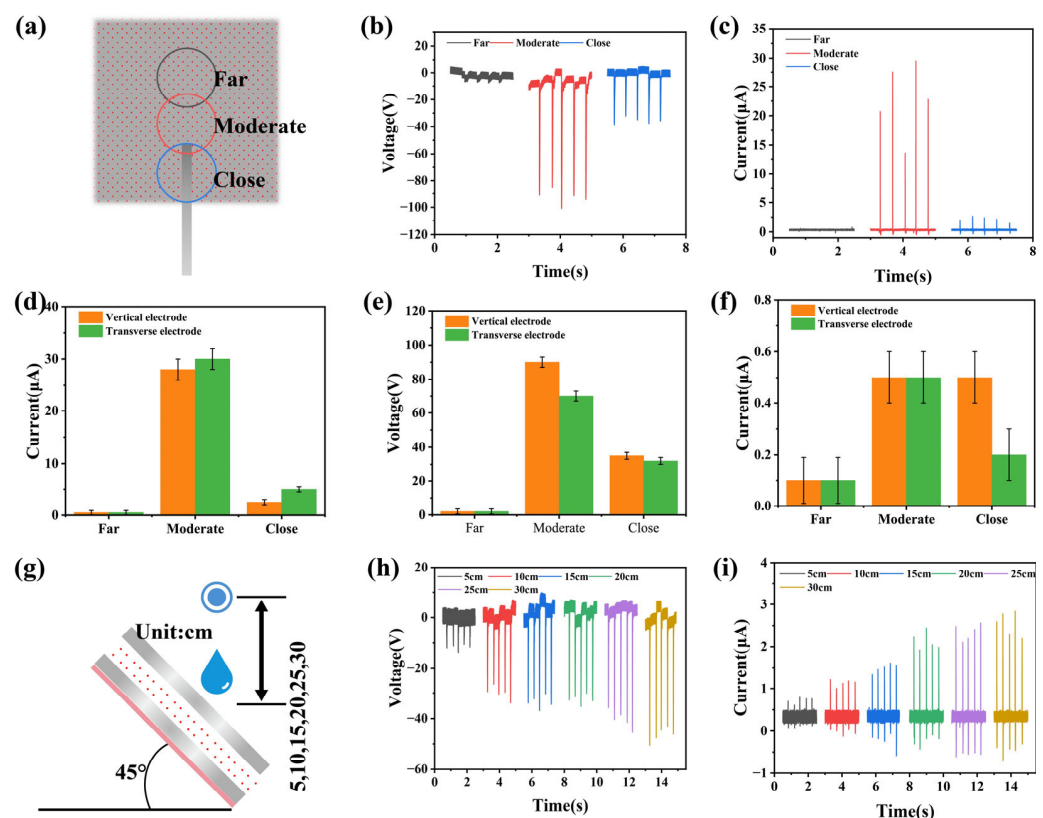


Figure 4. Verification of the influence of water droplets' impact behavior on the output of TENG electricity. (a) Schematic diagram of the landing point of water droplets as a variable. (b,c) The voltage and current output at different landing points of water droplets. (d) Comparison of device output voltage under horizontal and vertical electrode conditions. (e,f) The influence of horizontal and vertical electrodes on the output current of the device under the diffusion and contraction states of water droplets. (g) Schematic diagram of the starting height of water droplets as a variable. (h,i) The voltage and current output at different water droplets velocities.

In order to further investigate the effect of incident kinetic energy on output performance, as shown in Figure 4g, we systematically examined the relationship between water droplets' drop height and electrical output while keeping the front electrode width constant at 3 mm. As displayed in Figure 4h,i, when the falling height increases from 5 cm to 25 cm, the output voltage continues to rise from about 10 V to 40 V, while the output current significantly increases from about 0.80 μ A to 2.5 μ A. This process reflects the greater kinetic energy of droplets at higher falling heights, effectively enhancing the contact separation dynamics between droplets and FEP films, thereby expanding the interface transient contact area and improving charge transfer efficiency, thus achieving synchronous enhancement of voltage and current. However, as the falling height further increased from 25 cm to 30 cm, the output voltage and current no longer showed significant changes and remained at levels of approximately 40 V and 2.5 μ A, respectively. The main reason is that the expansion contraction process of the droplets have reached the limit state in geometry and fluid dynamics: as the falling height increases to a certain threshold, the maximum spreading area that the droplets can achieve after impact tends to saturate, and the effective contact area provided by the FEP surface does not increase anymore. Therefore, even if the input kinetic energy is further increased, the degree of interface charge separation and induced potential difference remain stable, resulting in no further increase in electrical output. The experimental results reveal a nonlinear saturation relationship between the incident kinetic energy of water droplets and the output performance of the device: in the low to medium height range, the output performance increases with height; after exceeding the critical height, the maximum diffusion area of the droplets is limited by geometric boundary conditions, and the output performance enters a saturation plateau. This law provides important reference for the application of TENGs in droplets energy harvesting, indicating that rational regulation of droplets kinetic energy while avoiding ineffective energy input is the key to achieving efficient device operation.

In order to investigate the comprehensive effects of incident angle and flow velocity on the output performance of the device, as shown in Figure 5a, we first studied the tilt angle effect of FEP film under conditions of constant falling height (25 cm). Figure 5b,c shows that when the tilt angle increases from 15° to 60°, the output voltage decreases from 60 V to 45 V, while the output current remains basically unchanged. This indicates that as the tilt angle increases the actual spreading area of the droplets on the film surface slightly decreases, resulting in a decrease in the number of induced charges at the interface and a significant decrease in voltage output, while the current is not significantly affected. This phenomenon reveals a high dependence of the contact area between droplets and solid surfaces on voltage sensitivity.

Under the condition of maintaining the inclination angle and height unchanged, as depicted in Figure 5d, we further investigated the effect of water droplets velocity. Figure 5e,f show that when the flow rate increased from 20 rpm to 40 rpm, both voltage and current showed a slight upward trend. This is mainly attributed to the increase in droplet frequency, which leads to an increase in the number of contact separation cycles per unit time, thereby enhancing the efficiency of charge accumulation and release. However, as the flow rate continued to increase to 50 rpm, the output voltage and current actually decreased. The reason for this abnormal phenomenon is that when the frequency of water droplets is too high, the previous droplet has not yet completed the expansion contraction and retraction process, and the latter droplet has already reached the surface, resulting in overlapping and interference in the expansion contraction processes of the droplets, and the interface contact behavior is no longer complete, thereby weakening the frictional electrification effect and charge induction effect. Figure 5g illustrates the relationship between different flow velocities and voltage at angles of 15°, 30°, 45°, and 60°. When

reaching 50 rpm, the voltage decreases relatively. Meanwhile, Figure 5h displays the relationship between different flow velocities and the current in the diffusion state of water droplets at angles of 15° , 30° , 45° , and 60° . Figure 5i exhibits the relationship between different flow velocities and the current in the water droplets retraction state at angles of 15° , 30° , 45° , and 60° . The current also shows a decreasing state at 50 rpm for each angle. The change in FEP plate angle will affect the impact behavior characteristics of water droplets, but only slightly (Figure S3). In summary, the tilt angle of the thin film and the droplet flow rate have a dual regulatory effect on the output performance of the TENG. The tilt angle mainly affects the voltage sensitivity by changing the contact area, while the flow rate has an optimal range, resulting in insufficient energy conversion at low frequencies and weakened performance due to scaling interference at high frequencies. This result provides experimental evidence for the geometric and operational optimization of droplet-driven energy harvesters. All data in Figure 5g–i were obtained from at least 10 repeated independent experiments, with standard deviations represented by error bars in the corresponding figures to verify the reproducibility of the experiments.

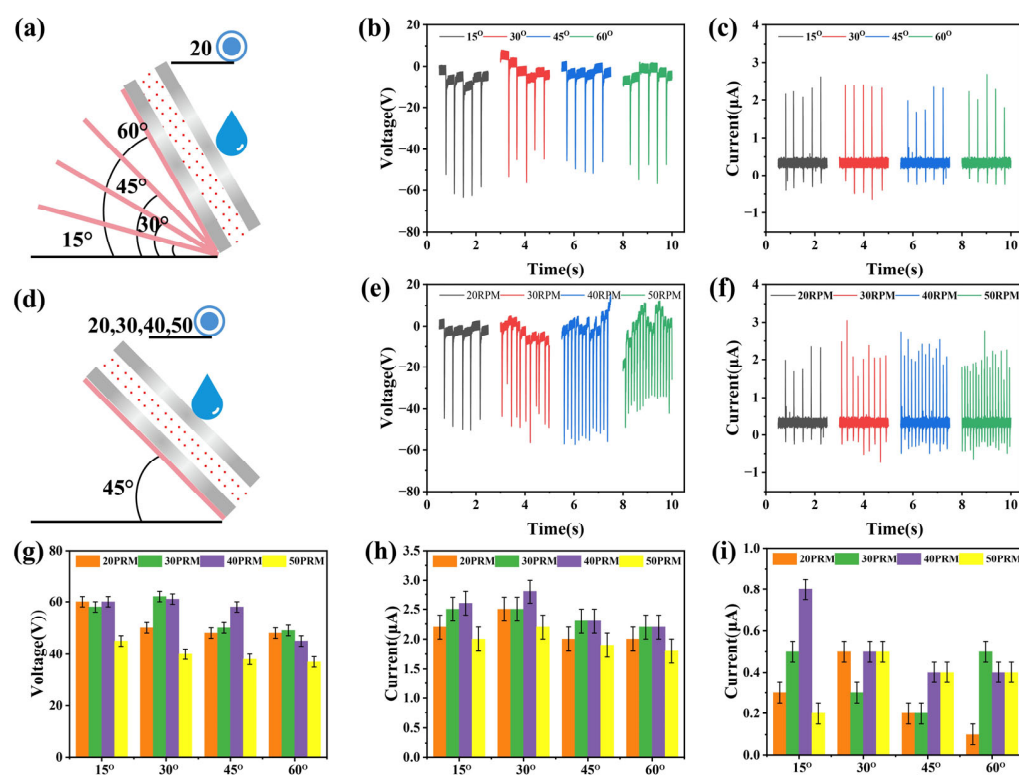


Figure 5. Research on the influence of external factors such as water flow velocity and water droplets' impact behaviors on electrical output. (a) Schematic diagram of FEP film angle as a variable. (b,c) The voltage and current output at different FEP film angles. (d) Schematic diagram of water droplet velocity as a variable. (e,f) The voltage and current output at different water droplet velocities. (g) Comparison of the correlation between fluid flow velocity and device voltage output at different inclination angles. (h,i) The influence of different inclination angles and flow velocities on the output current of the device under water droplet diffusion and contraction states.

We carried out fatigue tests by continuously dripping water droplets from a height of 30 cm onto the FEP film and attached aluminum electrode of a dry DTENG device. Figure S4a records the evolution of open-circuit voltage as the dry FEP surface gradually becomes wet. The voltage rises from an initial value of ~ 40 V to approximately 70 V, which demonstrates that retained electrons on the FEP surface contribute positively to the electrical output of the DTENG. Correspondingly, a slight upward trend in short-circuit

current can be observed in Figure S4b. In addition, slight device vibration occasionally shifts the droplet impact position to the edge of the aluminum electrode, leading to sporadic sharp current spikes. After continuous water rinsing for 3 min, both voltage and current signals stabilize at constant levels, verifying the reliable operational stability of the device.

Review articles and original research papers have systematically compared the merits and drawbacks of diverse working modes for solid–liquid TENG [39,40]. Table 1 summarizes the output performance of solid–liquid TENG with different working modes. For the solid–liquid single electrode mode, the electrical output is extremely low, with open-circuit voltage only at the millivolt level. The solid–liquid independent layer mode delivers stable and favorable voltage signals, yet its short-circuit current remains relatively weak. By contrast, the solid–liquid contact shrinkage mode achieves outstanding performance in both voltage and current outputs. Distinct from most existing literature, this work focuses on a rarely discussed issue: we discovered the unique retraction current generated during droplet shrinkage, which constitutes the core novelty of our study.

Table 1. Output performance comparison of various solid–liquid TENG modes.

Mode	Test Substance	Output Voltage	Output Current	Output Charge	References
Independent layer	Liquid column	160 V	3 μ A	60 nC	[25]
Single electrode	Droplet	180 mV	(-)	(-)	[30]
Contact shrinkage	Droplet	150 V	260 μ A	50 nC	[35]
Contact shrinkage	Droplet	100 V	16 μ A	(-)	[41]
Independent layer	Liquid column	120 V	0.25 μ A	50 nC	[42]
Contact shrinkage	Droplet	550 V	4.5 mA	30 nC	[43]
Contact shrinkage	Droplet	38 V	45 μ A	30 nC	[44]
Contact shrinkage	Droplet	60 V	2.5/0.6 μ A	(-)	This article

3. Conclusions

In this work, a DENG constructed with a 5 cm $\times$ 5 cm FEP film and asymmetric aluminum electrodes is systematically studied under varied structural and hydrodynamic conditions. The experimental results reveal that electrode geometry, droplet falling height, substrate inclination angle, and droplet flow rate jointly govern the charge transfer efficiency and overall electrical output performance. Of particular note, we discovered and systematically analyzed the retraction current generated during droplet recession, a phenomenon largely overlooked in previous studies. Reducing the electrode width from 18 mm to 3 mm yields prominent enhancements in both open-circuit voltage and short-circuit current, which verifies that narrow electrodes facilitate concentrated local surface charge density. Comparative tests of diverse solid–liquid TENG operation modes confirm that the solid–liquid interfacial contact electrification between FEP and water droplets serves as the fundamental source of triboelectric charges; whereas, electrostatic induction from the underlying aluminum electrode is an indispensable prerequisite for extractable electric output. The uncovered electron transfer linked to rational electrode layout offers solid experimental guidance for the structural optimization of droplet-based TENG. Moreover, the output voltage and current rise with increasing droplet falling height until a critical threshold of 25 cm; a further height increase triggers contact area saturation and restrains performance improvement. Substrate inclination experiments demonstrate that larger tilt angles shrink the effective spreading area of impinging droplets, leading to declined voltage outputs while the current remains relatively stable. Varied flow rate tests further suggest that a moderate flow rate benefits efficient energy harvesting, whereas an excessively high flow rate disturbs droplet spreading–retraction dynamics and suppresses effective charge transfer. Collectively, these results elaborate the intricate coupling between

droplet hydrodynamic behavior and electrode geometric configuration, which dominates the energy conversion efficiency of droplet TENG devices. This study not only delivers practical experimental guidance for electrode and system architecture optimization, but also establishes a fundamental physical framework for designing high-efficiency water-driven energy harvesting equipment.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/sym18071107/s1>, Video S1. The motion characteristics of droplets on fluorinated ethylene propylene (FEP) and transverse aluminum electrodes; Video S2. The motion characteristics of droplets on FEP and horizontal aluminum electrodes; Note S1. The relationship between water droplet contact area and time; Table S1. Description of the process of water droplet impact on a flat plate used in this work; Note S2. The derivation process of circuit equations; Table S2. The descriptions of circuit elements used in this work; Figure S1. Variable speed peristaltic pump in the experiment; Figure S2. Verification of the influence of water droplet impact behavior on the output of TENG electricity. (a) Schematic diagram of the landing point of water droplets as a variable. (b,c) The voltage and current output at different landing points of water droplets; Figure S3. Study on the influence of external factors such as flow velocity and droplet impact behavior on electrical output. (a–c) The relationship between output and droplet velocity, where the tilt angle of the solid interface (15°) and droplet height (25 cm) are fixed. (d–f) The relationship between output and droplet velocity, where the tilt angle of the solid interface (30°) and droplet height (25 cm) are fixed. (g–i) The relationship between output and droplet velocity, where the tilt angle of the solid interface (60°) and droplet height (25 cm) are fixed; Figure S4. Cyclic durability tests of the DTENG: (a) Output voltage of the DTENG from dry to wetted state; (b) Output current of the DTENG from dry to wetted state.

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