On the force and energy conversion in triboelectric nanogenerators

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ABSTRACT

Triboelectric Nanogenerator (TENG) has been a burgeoning focus as a powerful mechanical energy harvester, with advantages of high-efficiency, cost-effective and easy-scalable. Recently, intensive efforts have been focused on how to improve the performance such as the power output and the efficiency of TENG, which demands further understandings on the force and energy conversion. This paper presents a thorough model and methods to illustrate the force and energy of TENG, which will greatly help researchers to understand the energy conversion from mechanical energy to electrical energy. Through two demonstrated methods, the electrostatic force, which represents the minimum-required input force to drive TENG, is calculated. In addition, the corresponding input mechanical energy was simulated, and the single-cycle energy conversion efficiency was derived for various TENG modes. The model is further demonstrated by analyzing energy conversion in a rotational TENG, which can reveal its performance in practical situations. The proposed model provides a novel perspective to understand the mechanism of energy conversion, and serve as an essential approach to optimize TENG’s performance for practical applications.

1. Introduction

With the rapid development of our modern society, the demand for energy is continuously increasing for applications in the Internet of Things, smart buildings, and the big data [1–5]. Powering these widely-distributed small devices required in these applications through cables becomes a difficult task due to the huge technical difficulties and costs. At the same time, it is also troublesome to use batteries considering the limited lifetime and the needs of maintenance. To address the issue of the power supply, energy-harvesting technologies have been developed in recent years [6]. In the ambient environment, the mechanical energies such as vibrations, body motions, airflows, and water waves are abundant to harvest. To harvest mechanical energy, the triboelectric nanogenerator (TENG), as an emerging energy harvester, has shown advantages such as easy fabrication, lightweight, simple, low-cost and effective [7–10]. The fundamental mechanism of TENG is based on the displacement current in Maxwell’s Equations, as achieved through contact electrification and electrostatic induction [11]. In the past a few years, scientists have been dedicated to improving the output performance and the efficiency through both the advanced structural designs and the optimized materials/surfaces [12–15]. With these worldwide efforts, TENG has shown the potentials for broad applications with predicted market size of US$480 million in 2028 [16].

Recently, in order to understand the basic working principle of TENG and optimize the output performance, scientists have developed theoretical models and metrics for TENG. Niu et al. firstly proposed theoretical models for each TENG mode and demonstrated the methods for modeling the output performance [17], which were furtherly developed and completed in recent years [18–20]. By using the developed theoretical models, Zi et al. proposed the figure-of-merits as standards for quantitatively evaluating TENG’s performance, and developed methods to achieve the maximized energy output [21,22]. There are also some other standards established while considering the practical situations during energy output [23,24]. To some extent, these studies provide us understandings on TENG’s output performance. However, in these research, only the electrical output is evaluated, while the mechanical input force is still elusive, even though scientists have acknowledged that the forces play an important role to improve the charge density and output performance of TENG [25,26]. Considering that a complete energy conversion process starts from the mechanical energy input and ends with the electrical energy output, a more comprehensive model including both input and output energies is urgently required to understand the energy conversion in TENG. Such a model has practical meanings in optimizing TENG designs toward high-output.
high-efficiency, and broadband energy harvesting. In comparison with the counterparts, such models have been established and widely applied for piezoelectric and electromagnetic energy harvesters [27–30], which demonstrated capabilities to understand the energy flows, and guide the advanced design of the devices with boosted performance.

At the same time, efficiency has been considered as not only a critical metric for development and optimization of TENGs, but also a potential standard to compare TENG with other power generation methods (e.g., solar panels, thermal energy harvesters, piezoelectric energy harvesters, etc.). Currently, we still do not have a complete theoretical model to evaluate the energy conversion efficiency of TENG, which obstructs the further development and industrialization of TENG technology. To quantitatively evaluate the efficiency, it is critical to understand the energy conversion flows and establish a theoretical model for the input force and mechanical energy.

Here, we proposed a theoretical model to calculate the minimum-required input force, and evaluated the energy conversion process and efficiency of TENGs. The meaning of the minimum-required input force is significant, since it represents the force that can enable effective energy conversion inside TENG, in other words, it determines how much energy output we may obtain from TENG. We used the integral of the input force \( F \) on the displacement \( x \) to represent the energy input, forming an \( F-x \) plot, in analog to the temperature-entropy plot in the heat engine. The cyclical \( F-x \) plots for different TENG modes are derived and simulated, which can reflect both the mechanical energy input and electrical energy output for each cycle. Therefore, the single-cycle energy efficiencies can be easily calculated and compared between TENGs with different modes and displacements. This model was used to understand the behavior of a rotational TENG as driven by the wind through the mechanical-to-electrical energy conversion. The establishment of the model for the force and energy in TENG will greatly improve our understandings on the energy conversion process, and facilitate the optimization of the TENG technology on its performance in practical applications.

2. Results

2.1. Energy flow analysis and the force-displacement plot

Fig. 1 proposed a complete energy flow in a TENG. The mechanical energy was firstly captured by TENG \( (E_{\text{in}}) \), and then it was converted into internal electrostatic energy \( (E_{\text{es}}) \) through electrostatic induction. Finally, the electrostatic energy was released through external loads as the electrical output \( (E_{\text{out}}) \). It should be noticed that this energy flow ignored a step of transferring mechanical energy from the environment (“excitation”) into the energy harvester.

To establish a model for TENG based on the proposed energy flow, analysis tools are required for both input and output energies. For the output energy per cycle, the voltage-charge \( (V-Q) \) plot has been proposed and widely applied in related studies [17,21], which is based on the following equation:

\[
E_{\text{out}} = \int V dQ
\]  

(1)

Here \( V \) and \( Q \) are the voltage drop and the charge transfer between two electrodes. For the input energy, we have the following equation from the definition:

\[
E_{\text{in}} = W = \int F dx
\]  

(2)

where \( F \) is the input force required to drive the TENG, which is used to make work \( W \), and \( x \) is the displacement. Eq. (2) indicates that the encircled area in \( F-x \) plot equals to the mechanical energy input per cycle. Therefore, we may use it to visualize the mechanical energy input. The upper part of Fig. 1 illustrates the \( F-x \) plot and \( V-Q \) plot in a TENG according to the cycle of the maximized energy output with infinite resistance (CMEO) [21]. This cycle includes four steps: step 1, the relative displacement of triboelectric layers increases from \( x = 0 \) to \( x = x_{\text{max}} \) at the open-circuit condition; step 2, the switch is turned on, enabling charge transfer from one electrode to another one, and then it is turned off. The amount of transferred charge is recorded as short-circuit charge transfer \( Q_{\text{SC}} \); step 3, the displacement of triboelectric layers decreases relatively from \( x = x_{\text{max}} \) to \( x = 0 \) at the open-circuit; step 4, the switch is turned on, enabling charge flow back to the previous electrode, and then it is turned off.

It is worth noting that in the input force \( F \), the electrostatic force \( F_{\text{es}} \) plays an important role, which determines energy conversion amount during the mechanical-to-electrostatic energy conversion. The other forces that may exist, including conservative forces (spring force, elastic force, gravity, etc.) and dissipative forces (damping force, friction, air resistance, etc.), are all related to other energy conversion processes. To reveal and understand the energy conversion that is directly related to the electricity generation, we can define an ideal condition, in which the other forces are all ignored, and thus the input force equals to electrostatic force but opposites in the direction. Besides, the charge density variation induced by the repeated contact-electrification may
also influence the input and output energy of TENG, however here, we only consider the ideal condition when the charge density is a fixed steady-state amount. Studies under this ideal condition are very important to build electromechanical models for TENG in the future.

Apparently, these two plots of TENG are very similar to the temperature-entropy (T-S) plot for heat energy input and the pressure-volume (P-V) plot for mechanical energy output in the heat engine, as shown in the lower part of Fig. 1. It is notable that the net energy input (the pink area in the T-S plot) must equal to the energy output (the yellow area in the P-V plot) under the ideal Carnot cycle, without considering energy dissipation during operation. Similarly, while considering TENG working in the ideal condition, the net energy input (the yellow area in the F-x plot) will also equal to the energy output (the green area in the V-Q plot).

At the same time, the T-S plot for the heat engine also reflects the overall energy input (the pink area plus shaded area in T-S plot) during the process. The energy dissipation as denoted as the shaded area is due to the heat energy waste while contacting the low-temperature reservoir. Similarly, the energy dissipation in TENG is related to the negative work made by the input force from status 3 to status 4 in the F-x plot, which is usually wasted as the heat energy.

2.2. Theoretical model of input force and efficiency

Here, two methods are used to reveal the minimum-required input force to overcome the electrostatic force, while operating a TENG under an ideal condition. One is through the direct derivation of the force equations (Method 1), and the other one is through numerical calculations (Method 2). Both methods are based on the total electrostatic energy \( E_{es} \), which can be expressed as:

\[
E_{es} = \frac{1}{2} \sum q_i \Phi_i
\]  

(3)

Here \( q_i \) and \( \Phi_i \) denote the charge amount and corresponding electric potential in each part of TENG, respectively. To simplify the calculation, one electrode is usually chosen as a reference point (\( \Phi = 0 \)). This \( E_{es} \) can be derived as a function of \( Q \) and \( x \).

By assuming the energy conservation, the variation of the \( E_{es} \) comes from two factors: one is the work made by the input force \( F \) which can overcome electrostatic force \( E_{es} \) and increase \( E_{es} \); the other is the electrical output, which decreases \( E_{es} \). Therefore, the variation of the \( E_{es} \) can be written as:

\[
\Delta E_{es} = \int Fdx - \int VdQ
\]  

(4)

In Method 1, we can directly derive the minimum-required input force \( F \) as equals to the partial differential of \( E_{es} \) over \( x \); which is also the opposite of \( F_5 \):

\[
F = \frac{\partial E_{es}}{\partial x} = -F_5
\]  

(5)

By using this method, the minimum-required input force \( F \) for different modes of TENGs can be derived. The derivation steps and results are given in the Supporting Information Note 2.

In the Method 2, by fully differentiating both sides of the Eq. (4) over \( dx \), we can get:

\[
\frac{dE_{es}}{dx} = F - V \frac{dQ}{dx} = F - \frac{VdQ/dt}{dx/dt} = F - P_{out}/v
\]  

(6)

where \( P_{out} \) is the power output, \( v \) is the velocity of electrode. Therefore, the minimum-required input force \( F \) to drive TENG is:

\[
F = \frac{P_{out}}{v} + \frac{dE_{es}}{dx}
\]  

(7)

It is worth noting that both methods are equivalent, as demonstrated in Supporting Information Note 3. Each of these two methods has its own advantage in the specific situation. In general, results directly calculated by the derived equation in Method 1 are more accurate, while the numerical calculations in Method 2 may encounter some singularity issues when the motion is highly irregular. However, Method 2 can be used for calculation based on the data collected in experiments and finite-element method (FEM) simulations. Therefore, through the numerical calculation in Method 2 it is possible to calculate the force \( F \) for the situation without an analytic solution, such as the sliding freestanding triboelectric-layer (SFT) mode TENG. The scales of the input force \( F \) and input power of common TENGs are estimated and given in Supporting Information Table 2 and Note 5.

Here the derived that the force \( F \) may make either positive or negative work for the TENG, depending on the directions of the motion and the force. (Supporting Fig. S1) The effective input mechanical energy \( (E_{in, eff}) \) only considers that contributed by the positive work (expressed as \( Fdx \geq 0 \)), since usually the negative work made will be dissipated as the heat energy, if there is no other energy conversion mechanism in the system. The ratio \( \eta \) between the output electrical energy \( E_{out} \) and the effective input mechanical energy \( E_{in, eff} \) per cycle is defined as the single-cycle energy conversion efficiency, which is given by:

\[
\eta = \frac{\oint VdQ}{\oint Fdx/dt} \geq 0
\]  

(8)

It should be noted that in this article the efficiency is only calculated by assuming the ideal condition. The additional external forces in practical applications, either conservative or dissipative ones, may result in the different energy conversion efficiency, which is worth to be investigated in future research.

To compare operations and efficiencies between different TENGs, the minimum-required input force \( F \) to drive TENG as respect to the displacement \( x \) was calculated by using Method 2. The parameters of TENGs and the displacement \( x \) were preset, and then the \( V \) and \( Q \) were mostly calculated through equations derived by Niu et al. [17], and \( E_{es} \) were calculated from equations in Supporting Information Note 2, while some data (including that for lateral sliding (LS) mode while \( x > 0.98l \), and SFT mode) were obtained through FEM simulations by using COMSOL Multiphysics or LTspice software package. The \( F \times x \) plots under the CMEO were plotted as the red cycles in Fig. 2, in which edge effects were considered in contact-separation based modes (contact-separation (CS) mode, single-electrode contact (SEC) mode, and contact freestanding triboelectric-layer (CFT) mode). Besides, if the displacement followed the trigonometric functions, \( F-x \) plot was also simulated while directly connecting to an external resistance load for different modes, forming cycles of energy output (CEO), as shown in Fig. 3. The detailed parameters and analytical formula were described in Supporting Information Table 1 and Note 4. For TENG modes with analytical solutions (CS, LS with \( x < 0.98l \), SEC, and CFT modes), the calculation results of CMEO were double confirmed by that derived from Method 1. At the same time, we also calculated the corresponding \( V-Q \) plots. It was confirmed that the total output energy extracted from the \( F-x \) plots through the both methods and that from the \( V-Q \) plots were perfectly consistent to each other (Supporting Fig. S4), which validated our previous derivations and calculations. It was worth noting that the CEO had much lower output energy compared to that of CMEO as demonstrated previously [21], even though the optimized resistance was used to maximize the output energy. Besides, since the structure of FT mode is always symmetrical, its \( F-x \) plot is also symmetric as respect to the \( x \)-axis.

2.3. Experimental verification

It is essential to conduct experimental measurement to confirm that our model is universally applicable for analyzing force and input energy in TENG. It is usually difficult to directly measure the electrostatic force during the experiment. Here the numerical calculations in Method 2
provide a possible approach to calculate the electrostatic force as well as the F-x plot.

Herein, we used a fabricated CS-mode TENG to verify our approach, with the electrical measurement circuit as shown in Fig. 3a. The fabrication method has been reported previously [31]. The periodic motion of this TENG was preset as driven by a linear motor, with its distance and velocity shown in Fig. S7a. The V-Q plots under different external resistance loads were measured as shown in Fig. S7b. Fig. 3b and c illustrated the measured V-Q plot and the calculated F-x plot through Method 2 under 100 MOhm, respectively, the area difference between two plots is less than five percent. The experimental details are concluded in Supporting information Note 6. The calculation of the F-x plot starts from the measurement of the V-Q-x relationship under a certain resistance load, and then the power on the load and the total electrostatic energy were calculated according to Supporting information Note 2. Finally, the electrostatic force is solved through Eq. (7). It is worth noting that the extracted output energy per cycle from these two plots are approximately identical. These results demonstrate the capability of the Method 2 to analyze the electrostatic force during the experiments, as a useful tool to conduct further modeling of TENG.

2.4. Single-cycle energy conversion efficiency of TENG for different modes

To investigate the impact of the maximum displacement $x_{\text{max}}$ on the TENG performance, the single-cycle energy conversion efficiency $\eta$ was calculated by Eq. (8) versus $x_{\text{max}}$. Fig. 4 illustrated the $\eta$ of different TENG modes. The red line represents the efficiency of TENG under CMO (\(\eta_{\text{CMO}}\)), and the dot represents that of TENG under CEO with the optimized external resistance load (\(\eta_{\text{CEO, opt}}\)). The short-circuit transferred charges $Q_{\text{SC}}$ are also plotted as the blue lines, which are consistent with the results from previous studies [17,32]. As we notice, the limited efficiency $\eta$ in the small $x_{\text{max}}$ is usually related to the limited charge transfer amount, as clearly shown in plots for CS and LS modes. For SEC mode, there is a maximum value of the efficiency $\eta$ existing by balancing impacts from two aspects as stated below. Before the maximum point, the enhancement of the efficiency $\eta$ is related to the
increased charge transfer. And after that, the suppressed efficiency $\eta$ is due to the small electrostatic force under the weak electrostatic induction in a large displacement. We notice that the minimum-required input force $F$ in SEC mode is almost as same as or even larger than that in CS mode, as shown in Fig. 3c. Therefore, due to the limited energy output capability and the high input energy required, the maximum efficiency $\eta$ can only reach about 7.5% as simulated. On the contrary, the efficiency $\eta$ of all the double-electrode modes TENG can approach nearly 100%. For both CFT and SFT modes, the $\eta$ of CMEO in the ideal condition is always 100% considering that the input force $F$ is always making positive work. However, when we consider CEO, input force may also do negative work due to unbalanced status, so their $\eta$ of CEO cannot achieve 100%.

2.5. Electromechanical modeling of the Rotary Freestanding TENG

The theoretical model established for the force and energy opens the possibility to model TENG-based systems in both mechanical and electrical points of view, namely electromechanical modeling. Therefore, a new theoretical system can be developed in the near future to thoroughly understand the performance of TENG. Here we just demonstrate an example of applying the electromechanical modeling method on the rotary freestanding (RF) mode TENG, in which the high output has been demonstrated [33,34]. In the rotational systems, it is more meaningful to use the torque ($\tau$), the angle ($\alpha$), and the angular velocity to replace the force, the displacement, and the velocity, respectively. Previously, all the studies about its output performance are based on a certain pre-defined angular velocity as provided by the motor. However, in practical situation, sometimes the high angular velocity may not be easily achieved under the natural kinetic source, and thus the performance of the TENG may be suppressed. To understand the output we may obtain practically, it is necessary to reveal the relationship between the torque applied on the device and the corresponding angular velocity, which can be addressed through electromechanical modeling method as discussed below.

Here a typical RF-TENG structure is utilized. As shown in Fig. 5a, the upper and lower triboelectric layers of the TENG are freestanding dielectric layer and static metals, respectively, and the metals are also segmented to work as electrodes. This structure utilizes the wind cups (or blades) above itself to collect mechanical energy such as the wind energy to generate electricity. Fig. 5b showed the schematic diagram of the operation mechanism. To simplify the model, the gap angle between electrode A and B is ignored. The angular width of each electrode is $\theta_0$, and the rotation angle of the freestanding layer is represented by $\alpha$. According to the previous work done by Jiang et al. $Q_{sc}$-$\alpha$ equation is easily to be derived under short-circuit condition [35], as shown below:

\[
Q_{sc} = \begin{cases} 
\frac{w^2 \pi \sigma N}{2}, & 2k\theta_0 \leq \alpha \leq (2k + 1)\theta_0 \\
\frac{(2k + 1)\theta_0 \pi \sigma N}{2}, & (2k + 1)\theta_0 \leq \alpha \leq (2k + 2)\theta_0 
\end{cases}
\]  

where $N$ is the number of grating units in the freestanding layer, $r$ is radius of TENG, and $\sigma$ is charge density. Furthermore, the electrostatic energy can be given by the following equations:

\[
E_i = \frac{(Q_{sc} - Q)^2}{2C}
\]

The required torque to drive this TENG can be derived by partial differential of the electrostatic energy over $\delta \alpha$.
where $\beta$ is $\frac{1}{2} \pi r^2$. In the actual environment, the dissipative force, which may originate from air resistance or dynamic friction, is inevitable. Therefore, the electromechanical model was built with the dissipative force involved [36,37]. Usually, we can directly assume the dissipative force/torque is proportional to the angular velocity, namely the damping force/torque. Therefore, the mechanical governing equation can be obtained by using Newton’s second law:

$$\ddot{\theta} = J_0 \omega_0 \ddot{\theta} + c_0 \dot{\theta} + \frac{1}{R} \left( \omega_0 \right)^2 \dot{\theta} = M_w$$  \hspace{1cm} (11)

where $J_0$ is the total inertia torque, $c_0$ is the damping torque, $R$ is the external resistance, and $M_w$ is the torque provided by the external source, which usually can be assumed as a constant. Besides, we can obtain the following electrical governing equation of TENG based on the current source model of TENG, while connecting to an external load resistance $R$ (Supporting information Note 7):

$$C_T V + \frac{1}{R} \left( \omega_0 \right)^2 \dot{\theta} = \frac{1}{R} \left( \omega_0 \right)^2 \dot{\theta}$$  \hspace{1cm} (12)

where $V$ is the output voltage, $C_T$ is the capacitance of TENG, $R$ is the external resistance. By solving these two equations, we notice that the TENG will eventually rotate in a constant angular velocity, which is proportional to the external torque $M_w$. This result is consistent with experimental results [38]. The steady-state angular velocity can be derived as: (The detailed derivation information can be obtained from Supporting information Note 7)

$$\omega = M_w / R c$$  \hspace{1cm} (13)

From this solution, we can obtain some interesting results: the angular velocity is determined by the structural factor $\beta$, external load resistance $R$ and damping factor $c$. In Fig. 5c-e, with a constant angular velocity, the voltage-angle plot, $V$-$Q$ plot and torque-angle (M-$\theta$) plot are simulated. The efficiency of this system can be given as:

$$\eta = \frac{\beta^2 R}{\beta^2 R + c}$$  \hspace{1cm} (15)

Therefore, the proposed electromechanical modeling method can be used to reveal the characteristics of TENG in practical situation, and potentially optimize the system toward its maximum performance.

Rotary TENGs represent a special case considering the rotational motion can be continuously unidirectional. For non-rotational TENGs, a spring system is usually applied to ensure the back-and-forth displacement, and then the energy of the damping term in the spring should be considered [28,30,39–41]. On the other hand, the conservative force provided by the spring can recycle the energy loss induced by the negative work into the potential energy, and then release that in the following cycles, which may improve the efficiency. In fact, the highest recorded efficiency to date in TENG was achieved in a TENG-spring coupled system [42]. Therefore, electromechanical modeling of TENG-spring coupled systems are well worth to be investigated in the future.

3. Conclusion

In summary, we have developed a theoretical model and methods to simulate the force and mechanical energy in TENG, and understood the energy conversion process under the ideal condition. To reveal the mechanical energy input, we have demonstrated two methods to derive and calculate the minimum-required input force to overcome the electrostatic force in TENG. The derived energy input as indicated by the $F$-$x$ plot is compared with the energy output as reflected by the $V$-$Q$ plot, and then the efficiencies for different TENG modes are simulated and analyzed. Based on these methods, an electromechanical model was built for an RF-TENG to reveal the performance under a certain
external mechanical input. We believe that it is possible to thoroughly understand the performance of various TENGs in a deeper level based on the proposed model. This model and methods will serve as a milestone in the field of TENG by opening the possibility to understand and optimize the performance through simultaneously considering both mechanical and electrical energies.

4. Methods

4.1. Fabrication and measurement of the CS mode triboelectric nanogenerator

A CS mode TENG was fabricated with the area of 5 cm × 5 cm and the maximum displacement is 2 cm. Firstly, 60 µm Cu films were attached on acrylic plates as electrodes, and then a PTFE film with thickness of 200 µm was attached on one of the Cu electrode. The relative permittivity of PTFE film is 2.1.

The motion of the TENG was triggered by a linear motor, as shown in fig. S7a, and the measurements of the transferred charges and voltage were simultaneously conducted by two Keithley 6514 electrometers, with the measurement circuit shown in Fig. 3a.

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Author contributions

G.X. X.L. and Y.Z. conceived the idea, derived the equations, conducted the simulation, discussed the data and prepared the manuscript. X.X. and J.F. contributed to the experiment and manuscript preparation. W.D. helped the simulation. All the authors have approved the final version of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2019.02.035.

References

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