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Numerical study of a Reverse Electrowetting Nanogenerator

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ABSTRACT

The direct conversion of wasted mechanical energy into electrical energy is of significant interest, both from an environmental perspective and for applications such as self-powered sensors and electrical circuits in wireless networks. A power generator based on the reverse electrowetting concept has recently been introduced and extensively studied by researchers. A detailed understanding of the influence of design parameters on device performance is essential for further advancement. Accordingly, a reverse electrowetting-on-dielectric (REWOD) has been designed and mathematically modeled. The variable capacitance model is employed, and a numerical code has been developed to simulate the nanogenerator under diverse configurations and operating conditions. A comparison between the numerical results and those reported in the literature has been conducted to validate the simulations. The effects of parameters including dielectric thickness, bias voltage, frequency of mechanical motion, and external load resistance on the performance of the reverse electrowetting nanogenerator are systematically investigated and discussed. We acknowledge that reducing the dielectric layer thickness from 10^{-4} to 10^{-6} significantly enhances device performance, as the output power increases by approximately a factor of 40. Results indicate that increasing the bias voltage amplifies the induced electric field, thereby enhancing water droplet polarization. Furthermore, the nanogenerator's power output is shown to increase with both bias voltage and the frequency of mechanical motion.

Introduction

Ensuring a reliable supply of electrical energy remains one of the fundamental challenges, particularly in wireless applications and in environments where access to conventional power sources is limited. At the same time, mechanical energy in the form of motion is abundant in most practical situations. This has motivated researchers to explore methods of harvesting mechanical energy and converting it into electrical energy.

One promising approach is reverse electrowetting (REWOD), which has emerged as a novel high-power energy harvesting technique [1]. Krupenkin et al. [2] first introduced the concept of converting mechanical energy into electrical energy through reverse electrowetting. They demonstrated that electrical energy could be generated by arrays of microscopic liquid droplets moving across nanometer-thick multilayer dielectric films. This method offers several advantages: exceptionally high power density, the ability to exploit a wide range of mechanical forces and displacements—including those inaccessible to traditional piezoelectric or electromagnetic methods—and the capability to directly generate a broad spectrum of currents and voltages, from a few volts to tens of volts, without the need for voltage conversion. Han et al. [3] conducted a parametric study of a microfluidic power generator based on reverse electrowetting in microchannel geometries. They emphasized that understanding the parameters influencing nanogenerator output is crucial for enhancing performance. Their findings suggested that improved output can be achieved by employing thinner dielectric films with high dielectric constants and strong breakdown resistance, as well as by increasing droplet oscillation frequency.

Further progress was reported by Yang et al. [1], who investigated high-density dielectric layers fabricated using atomic layer deposition (ALD). Aluminum oxide (Al_2O_3), a widely available material, was employed as the dielectric layer. Using ALD films, they achieved high-performance energy harvesting, with a maximum power density of 5.95 mW/cm² from a 45 nm-thick ALD film under a DC bias of

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13.5 V. A thicker 140 nm ALD film, capable of withstanding higher bias voltages, yielded a power density of 11 mW/cm² and an energy density of 22.24 μJ/cm². These results confirmed the suitability of ALD films for reverse electrowetting devices.

Hsu et al. [4] proposed a theoretical framework combining reverse electrowetting with rapid bubble growth and collapse in a self-oscillating process. This hybrid mechanism has the potential to significantly enhance power density and enable energy harvesting from mechanical sources across a wide frequency spectrum, including sub-Hz ranges. Such an approach opens new possibilities for harvesting electrical energy from mechanical sources with very low frequencies, well below 1 Hz. Rusev et al. [5] developed a mathematical model to predict the energy efficiency of reverse electrowetting systems using cost-effective materials. Their analysis showed that, under constant bias voltage, zirconium titanate produced more energy than barium titanate, due to the strong dependence of electrical energy density on capacitance between electrodes and dielectric thickness. While increasing dielectric thickness reduces capacitance and thus energy output. The model did not fully account for frequency-dependent losses, highlighting the complexity of scaling such systems. Yang et al. [6] investigated a dual-dielectric REWOD system using TiO_2 and Al_2O_3 layers. They found that combining a high dielectric constant material (TiO_2) with Al_2O_3 minimized leakage currents and maximized effective power output. Compared to single-layer systems, the TiO_2–Al_2O_3 structure achieved higher power generation, producing a power density of 15.36 mW/cm² at low bias voltage. An increase in the overall capacitance of REWOD energy harvesters can be achieved by augmenting the available surface area [7]. Adhikari et al. [7] numerical study showed that a maximum power density of 3.18 μW/cm² was achieved at 5 Hz for a rough-electrode REWOD energy harvester, approximately four times higher than conventional planar electrodes.

Cheng et al. [8] introduced a slippery lubricant-infused porous surface into REWOD devices. They demonstrated significant inhibitory effects on surface charge trapping and ambient contamination, as well as self-healing and robust performance under extreme working conditions such as low temperature, varying pH, humidity, fouling, and even scratching. Gupta et al. [9] presented a hybrid approach combining REWOD with electromagnetic induction for mechanical-to-electrical energy conversion, eliminating the need for an external bias voltage. Psoma et al. [10] combined REWOD with piezoelectric energy harvesting and investigated the effects of electrode spacing, piston displacement amplitude, NaCl concentration, and droplet volume. Their results showed that at low frequencies, height variations had little effect, whereas at higher frequencies, smaller electrode spacing was more effective. Larger piston displacement amplitudes produced higher output voltages, and solutions with half the salt concentration performed relatively well. Additionally, droplets with larger volumes induced higher voltage output. Schumacher et al. [11] fabricated a REWOD energy harvester using aluminized polyester sheets as functional layers and polycarbonate sheets for mechanical support. Their device offered advantages such as low cost, ease of fabrication, and flexibility, making it suitable for energy harvesting in healthcare applications. Overall, three main REWOD system designs have been reported, all relying on external forces to drive droplet motion at defined intervals: droplets between oscillating plates, droplets between sliding plates, and droplets within microchannels [12].

In the present work, a reverse electrowetting-on-dielectric (REWOD) system based on a droplet confined between two oscillating plates was designed. Since the capacitance of REWOD varies with droplet deformation, a variable-capacitance model was employed. The mathematical framework, which integrates both droplet deformation and the electrical circuit, was numerically solved to examine in detail the influence of key parameters on device performance.

Device description and mathematical model

The phenomenon of electrowetting is defined as the change in the contact angle between a liquid and a solid surface resulting from the application of a potential difference between them [5]. In contrast, reverse electrowetting occurs when external mechanical motion induces a variation in the capacitance between the electrode and the dielectric, thereby causing electric charges to flow through the load resistance. The principle of reverse electrowetting is schematically illustrated in Fig. 1. In this configuration, a conductive liquid is positioned between two dielectric substrates, one at the top and one at the bottom. The bottom substrate is coated with a metallic layer that functions as an electrode. These electrodes are connected to an external voltage source (bias voltage). The bias voltage induces polarization within the droplet relative to the electrode. External mechanical energy subsequently alters the shape and contact angle of each droplet relative to the spacing between the two substrates. As a result, the interface between the droplet and the substrate changes, leading to a variation in capacitance. This mechanism is analogous to a variable capacitor system; hence, the electrical energy generated through reverse electrowetting is strongly dependent on the surface capacitance and the applied bias voltage [1].

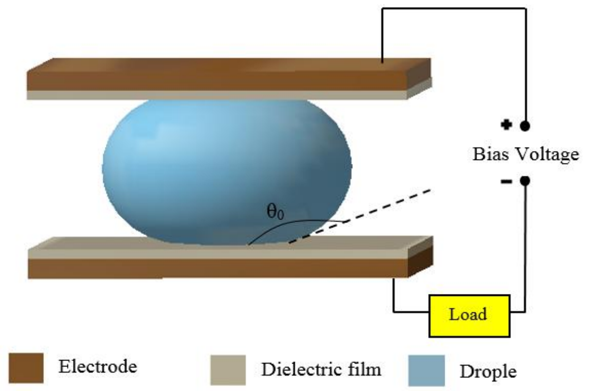


Fig. 1. Schematic of the REWOD device

Mathematical Model

To simulate the performance of a reverse electrowetting-on-dielectric (REWOD) device under varying mechanical motions, it is necessary to mathematically model both droplet deformation and the associated electrical circuit. Consider first a droplet confined between two surfaces. As illustrated in Fig. 2, the following geometric relationship (Eqs. 1-8) can be expressed:

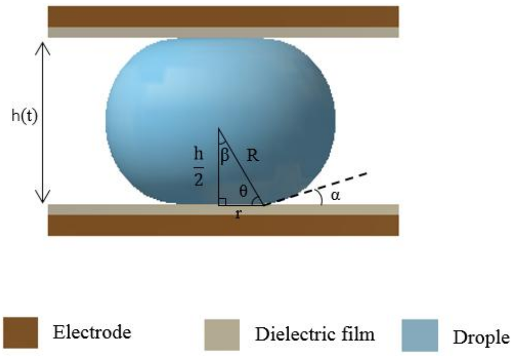


Fig. 2. Schematic of a droplet between the electrodes

$$r = R\sin\beta = R\sin(\frac{\pi}{2} - \theta) \tag{1}$$

$$h = 2R\sin\theta \tag{2}$$

The capillary free energy (Ecap) is given by the Young equation [5].

$$E_{cap} = A_{sa}(t)\gamma_{sa} + A_{sl}(t)\gamma_{sl} + A_{la}(t)\gamma_{la} - V\Delta P \tag{3}$$

Where γ_{sa} is interface tension between solid and air, γ_{sl} is ¡nterface tension between solid and liquid, γ_{la} is interface tension between liquid and air, A_{sa}, A_{sl}, A_{la}, are area solid/air, solid/liquid, and liquid/air respectively. V and P are liquid droplet volume, and Laplace pressure respectively.

This energy is equal to the work doen by an external forece as:

$$E_{cap} = F_{ext} \times h(t) \tag{4}$$

Using Young-Laplace equation [13], pressure difference between the inside and outside of the droplet can be written as:

$$\Delta P = \frac{2\gamma_{la}}{R(t)} \tag{5}$$

Combined equations 2-5 result:

$$\sin\theta = \frac{[A_{sa}(t)\gamma_{sa} + A_{sl}(t)\gamma_{sl} + A_{la}(t)\gamma_{la} - F_{ext} \times h(t)]h(t)}{4\gamma_{la}V} \tag{6}$$

Droplet deformations induced by mechanical forces during compression and expansion are illustrated in Fig. 3.

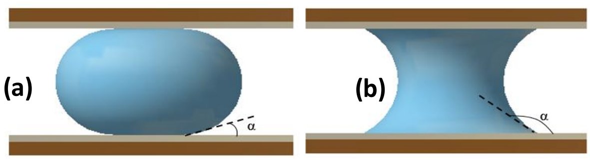


Fig. 3. Schematic of droplet deformations (a) compression, (b) expanssion

The contact angles between the droplet and the surface in these two positions are, respectively, as follows:

$$\alpha = 90 - \theta \tag{7}$$

$$\alpha = 90 + \theta \tag{8}$$

Modified Capacitor Model

As reported in the literature [2,4], the capacitance of the device is often assumed to be constant. However, in a reverse electrowetting-on-dielectric (REWOD) system, both the distance and the shape of droplet-dielectric layer interface vary continuously, which directly influences device performance. In the present work, these variations are explicitly considered and mathematically modeled. A schematic representation of the capacitor is shown in Fig. 4. It consists of a droplet positioned between two dielectric films, each coated with an electrode. This configuration can therefore be regarded as three capacitors connected in series. The interaction between the air and the dielectric films is neglected and is not included in the modeling.

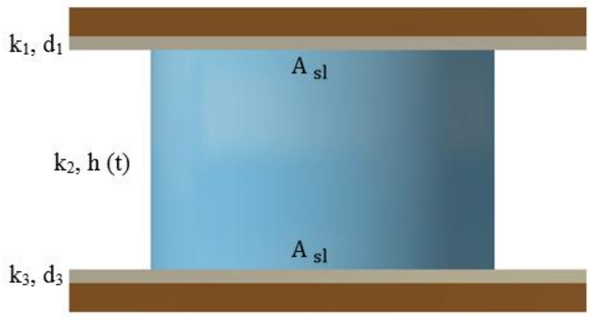


Fig. 4. Schematic of the considered capacitor

Since the shape of droplet continusly varies all the corresponding values are changing with time. The three series capacitors are calculated by Eqs. 9-16:

$$C_1(t) = \frac{k_1\varepsilon_0 A_{sl}}{d_1} \tag{9}$$

$$C_2(t) = \frac{k_2\varepsilon_0 A_{sl}}{h} \tag{10}$$

$$C_3(t) = \frac{k_3\varepsilon_0 A_{sl}}{d_3} \tag{11}$$

$$A_{sl} = \frac{V}{h(t)} \tag{12}$$

Where V is the droplet volume $(\pi r(t)^2 h(t))$, k is dielectric constant, ϵ_0 is relative permittivity of vacuum, A is interface area, d is width of the dielectric layer.

Equlivalent capacitance of these series capacitors are:

$$\frac{1}{C} = (1 + \cos\omega t)^2[\frac{1}{C_{01}} + \frac{1}{C_{02}} + \frac{1}{C_{03}}] \tag{13}$$

Where

$$C_{01} = \frac{k_1\varepsilon_0 \frac{V}{h_{max}}}{d_1} = \frac{k_1\varepsilon_0 A_{sl}}{d_1} \tag{14}$$

$$C_{02} = \frac{k_2\varepsilon_0 \frac{V}{h_{max}}}{h_{max}} = \frac{k_2\varepsilon_0 A_{sl}}{h_{max}} \tag{15}$$

$$C_{03} = \frac{k_3 \varepsilon_0 \frac{V}{h_{max}}}{d_3} = \frac{k_3 \varepsilon_0 A_{sl}}{d_3} \qquad (16)$$

C_{01} and C_{03} are capacitance of the layers and C_{02} is the capacitance of the droplet at t=0.

Output Current and Voltage

The equivalent circuit model of REWOD nanogenerator is shown in Fig. 5.

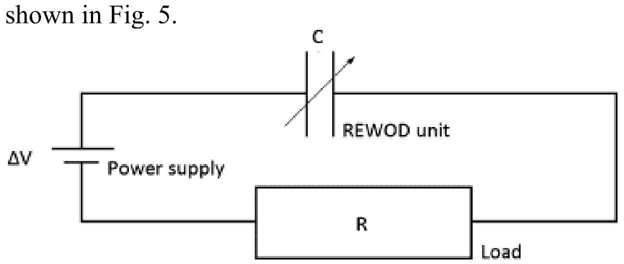


Fig. 5. Equivalent circuit model of REWOD

C is the variable capacitance, R is the external load. The value of total charge (Q) varies over time (t) and therefore the electrical current value is obtained using Eqs. 17-24:

$$I = \frac{dQ}{dt} \qquad (17)$$

The generated power is :

$$U_C - U_{bis} = IR \qquad (18)$$

Uc is the transient voltage (Uc=Q/C). Considering discharge electrical current (-I) the following differential equation is achived.

$$\frac{dQ}{dt} + \frac{Q}{RC} - \frac{U_{bis}}{R} = 0 \qquad (19)$$

At t=0, $Q=U_{bis}C_0$

Then the energy generated per one wetting-dewetting cycle can be expressed as [2]:

$$E = \int_0^T \left(\frac{dQ}{dt}\right)^2 R\, dt \qquad (20)$$

To be more general these equations are rewritten in dimensionless form as follow:

$$\hat{Q} = \frac{Q}{Q_0} = \frac{Q}{U_{bis} C_0} \qquad (21)$$

$$\hat{t} = \frac{t}{T} \qquad (22)$$

$$a \frac{d\hat{Q}}{d\hat{t}} + \frac{\hat{Q}}{4}(1 + \cos 2\pi\hat{t})^2 - 1 = 0 \qquad (23)$$

$$\hat{Q}(\hat{t} = 0) = 1$$

Where

$$a = \frac{RC_0}{T} \qquad (24)$$

Model Validation

These equations were solved numerically. To verify the validity and accuracy of the model, comparisons were made with the results reported by Rusev et al. [5]. The REWOD device under consideration consists of a water droplet together with $BiTiO_3$ and paraffin dielectric layers, characterized by the following properties:

V=5 (μL), f= 1(Hz), d1= 1 (μm), k1=200, k2= 78.9, k3=20, R=1000kΩ, U_{bis}=20v.

As seen in Table 1 good concordance between the average output power for one cycle is observed.

Another comparison was also carried out with the results reported by Yang et al. [1]. Their REWOD device consists of a mercury droplet and an Al_2O_3 dielectric layer, characterized by the following properties:

V=5E-9 (m^3), f= 4(Hz), d_1=d_3= 85 E-9 (m), k_1=k_3=8.57, k2= 78.9, k2=1, R=1000kΩ, U_{bis}=20v.

Figure 6 compares the current calculation obtained in the present work with the results reported by Yang et al. [1]. As shown, the two sets of results are in good agreement. This demonstrates that the proposed mathematical model and numerical procedure provide a reliable approach for simulating the performance of the REWOD device.

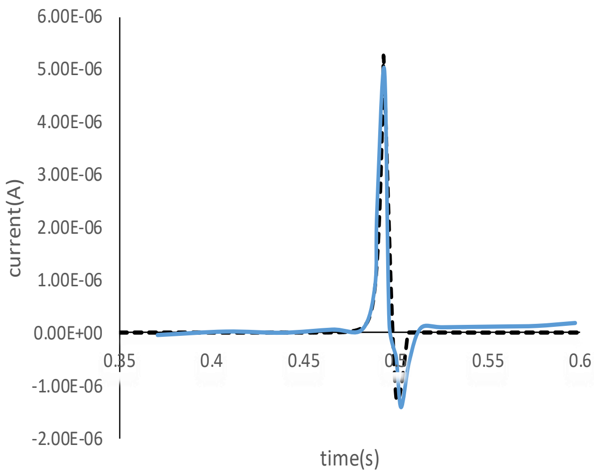


Fig. 6. Comparison of the present current calculation (blue) with the results of Yang et al. (dashed black) [1]

Table 1
Comparsion between the results of the present works and the previous reported results.

Current (peak to peak) (A)		Average output power (W)	
Yang et al. [1]	Present work	Rusev et al. [5]	Present work
5.6E-6	5.6E-6	2.5E-8	2.79E-8

RESULTS AND DISCUSSIONS

The simulated REWOD device consists of a water droplet, polydimethylsiloxane (PDMS) serving as the dielectric layer, and two copper electrodes. Under the specified conditions (oscillating external force amplitude = 0.0002 N, frequency = 1 Hz, γsl = 0.041 N/m, γla = 0.0618 N/m,

γ_{sa} = 0.0239 N/m, U_{bias} = 10 V, R = 50 kΩ, $d_1 = d_3$ = 1 μm, and V = 5×10^{-9} m³), Figs. 7a and 7b illustrate the variations in overlap area between the droplet and the electrodes, as well as the gap between the two dielectric layers. These parameters are shown to vary with the frequency of the external force acting as mechanical motion. The corresponding variations in the contact angle between the droplet and the surface, representing droplet deformation under compression and expansion, are presented in Fig. 7c.

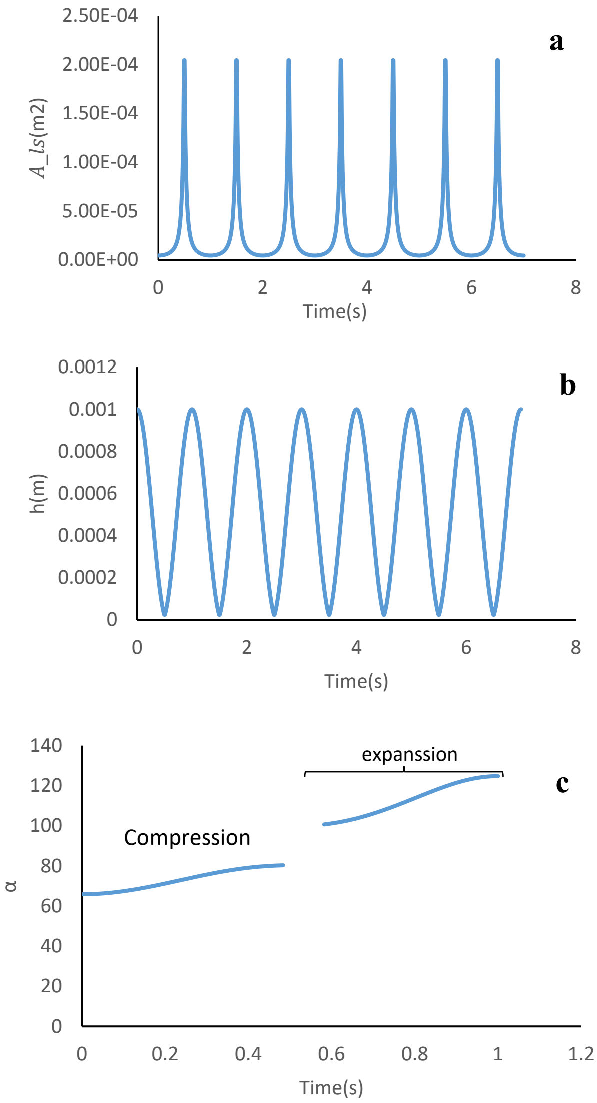


Fig. 7. Response of the droplet to the external forces with f=1 Hz, (a) overlap area between the droplets and the electrodes, (b) gap between the two dielectric layers, (c) variations in the contanct angle

The electrical characteristics of the device under the specified conditions are presented in Fig. 8. During compression of the device (i.e., when the external force is applied), the gap between the dielectric layers decreases and the overlap area between the droplets and the electrodes increases. As a result, the amount of stored electrical charge rises, leading to an increase in both output current and power. Upon release of the external force, the capacitor discharges and the output power returns to zero.

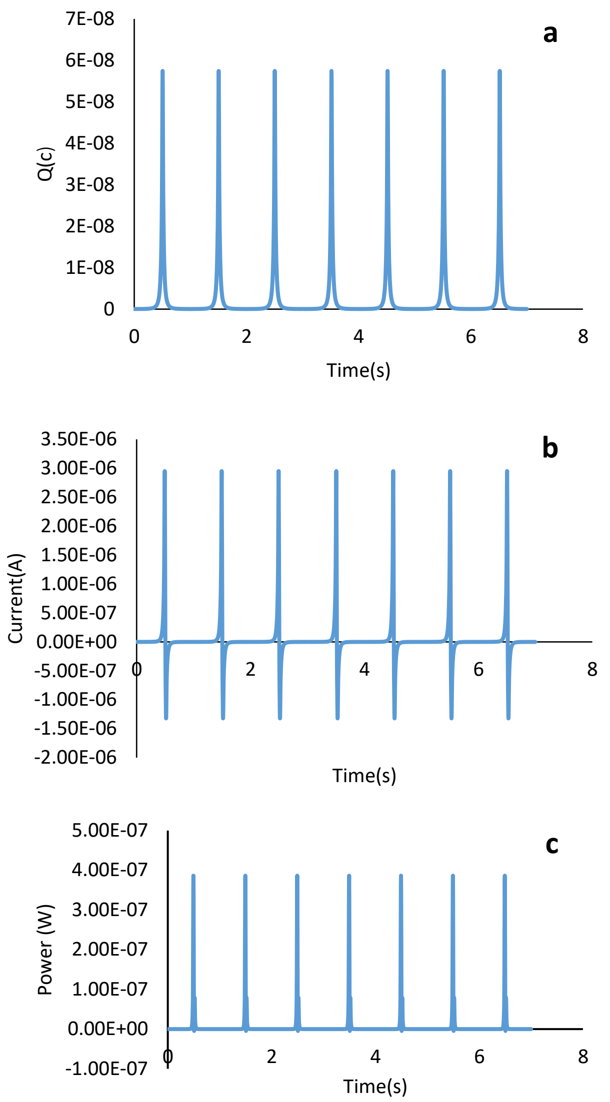


Fig. 8. Electrical response of the REWOD t the external forces with f=1 Hz, (a) electrical chargers, (b) output current and (c) output power

For a given external load, the influence of bias voltage on the output power is illustrated in Fig. 9. As observed, the bias voltage exerts a significant effect on the performance of the REWOD nanogenerator, with the impact becoming more pronounced at higher frequencies of mechanical motion.

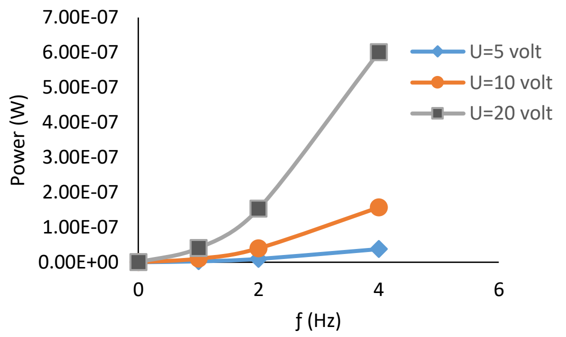


Fig. 9. Power output at different frequencies and bias voltages; R=50kΩ, V=5μL, $d_1=d_3$=1μm, $k_1=k_3$=2.8

To show the performance of the device, the power desity for different bias voltages and frequencies is presented in Table 2.

Table 2
Power density at different frequencies and bias voltages; R=50kΩ, V=5μL, $d_1=d_3=1\mu m$, $k_1=k_3=2.8$

Power density (μW/cm²)	Bias voltage (v)	Oscillating Frequency (Hz)
0.4	20	1
0.31	10	1
6.15	20	2
1.13	10	2
13.1	20	4
4.46	10	4

The effects of different combinations of bias voltage and external load resistance on the power output are illustrated in Fig. 10 for a given frequency. As observed, at low bias voltages the influence of the external load is less pronounced than at higher bias voltages. In general, increasing both the bias voltage and the external load enhances the power output. It should be noted, however, that higher bias voltages demand greater input energy. Moreover, the maximum permissible value of the external load is constrained by device characteristics such as dielectric breakdown strength, dielectric thickness, electrolyte properties, and charge trapping at the interface [14]; further increases lead to deterioration in device performance.

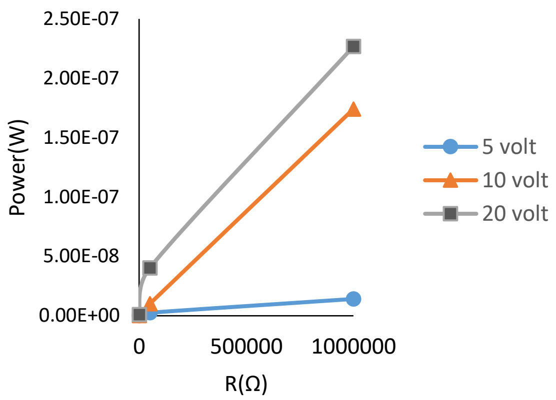
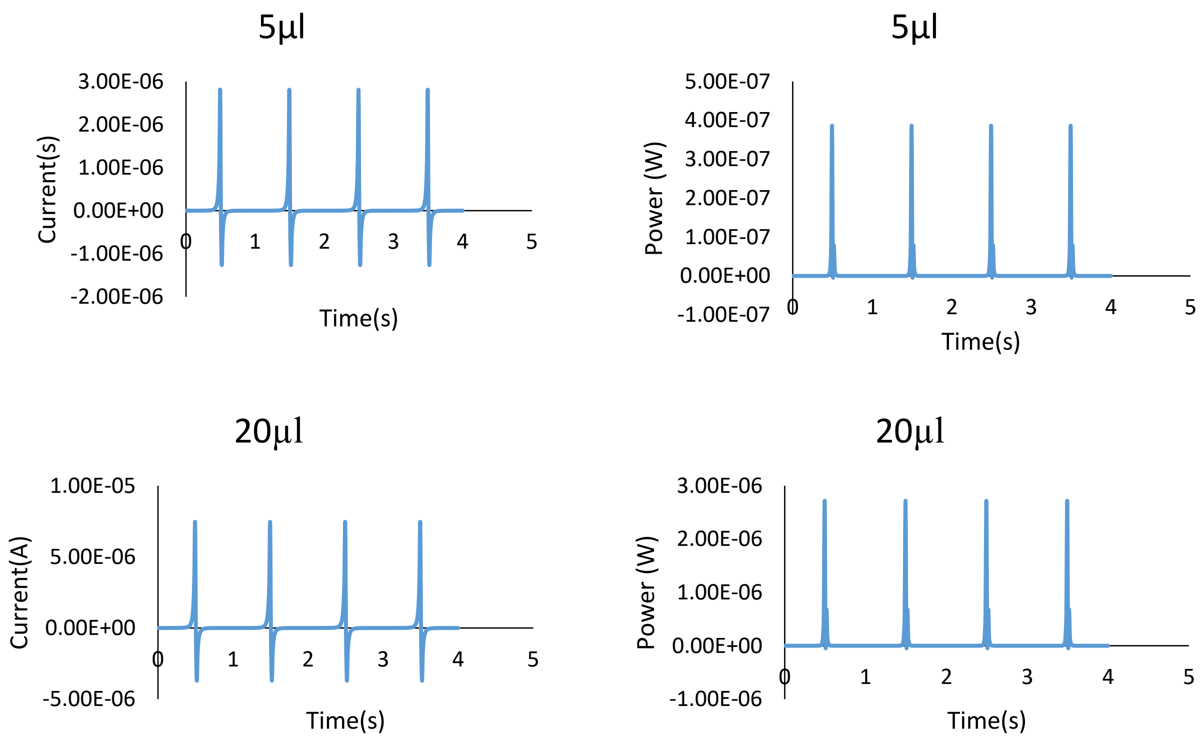


Fig. 10. Power output at different external load and bias voltages; f=1Hz, V=5μL, $d_1=d_3=1\mu m$, $k_1=k_3=2.8$

The effects of droplet volume on the power output and generated current of the REWOD device is presented in Fig. 11. Results indicate that increasing the droplet volume from 5 μL to 50 μL leads to a rise in both current and output power. This enhancement can be attributed to the larger contact area established between the droplet and the dielectric surface during force application. A greater contact area increases the effective capacitance, thereby facilitating the accumulation of a higher density of electric charges on the dielectric layer.



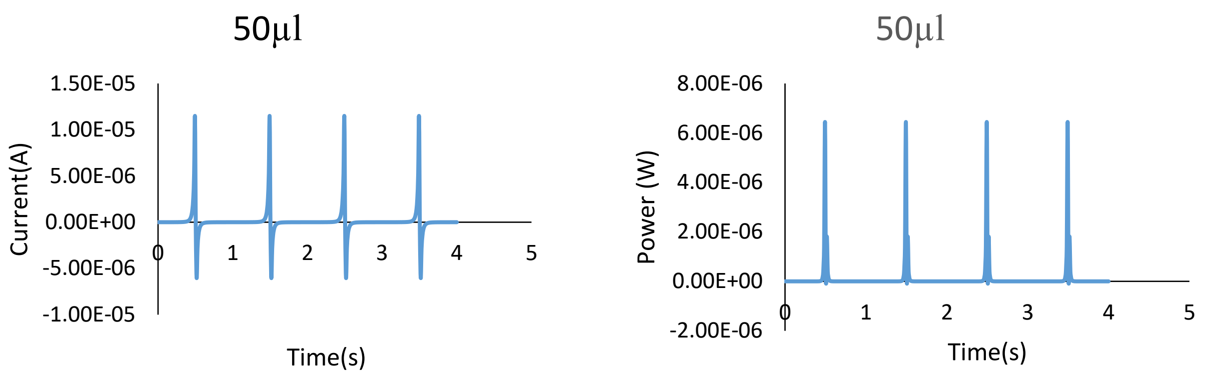


Fig. 11. Power output and generated current at different droplet volumes; bia1s voltages=5v, f=1Hz, d_1=d_3=1 μm, k_1=k_3=2.8

The effects of bias voltage and dielectric layer thickness on the power output are illustrated in Fig. 12. Charge trapping at the interface between the droplet and the dielectric layer increases with rising bias voltage, leading to higher current output. This, in turn, enhances the power output under a constant external load.

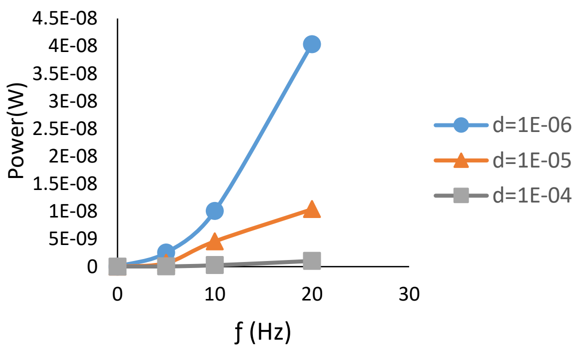


Fig. 12. Power output at different external load and bias voltages; f=1Hz, V=5μL, R=50kΩ, k_1=k_3=2.8

CONCLUSION

A reverse electrowetting-on-dielectric (REWOD) system was designed and mathematically modeled. To capture its behavior, a variable capacitance framework was applied, and a numerical code was developed to simulate the nanogenerator across different configurations and operating conditions. The validity of these simulations was assessed by comparing the numerical results with previously reported findings in the literature. The output characteristics reveal that increasing the volume of the water droplet enlarges the contact area between the droplet and the dielectric layer, thereby enhancing the capacitance and enabling greater storage of electric charge. Furthermore, raising the bias voltage generates a stronger electric field across the nanogenerator, which induces dipole polarization within the water droplet. When frequency and electric force are applied, the number of polarized charges increases, ultimately resulting in higher current and greater output power from the nanogenerators. Consequently, achieving higher frequencies requires an array of droplets and electrodes. It was also observed that as resistance increases, the electric current decreases; however, the average output power continues to rise until the load resistance reaches a value equal to the device resistance which is more than 1 MΩ.

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