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# Understanding Voltage and Frequency Effects on Dielectrophoretic Forces in Microchannel System

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## Abstract

This study presents an innovative pedagogical tool for teaching dielectrophoresis (DEP) and electrokinetics. We developed a cost-effective lab-on-chip device featuring oblique and V-shaped microelectrode arrays within microchannels to demonstrate electric field effects on biological particles in real-time. The device utilizes copper and indium tin oxide (Cu-ITO) microelectrodes with double-sided tape insulators to create controlled microenvironments. Red blood cells suspended in deionized water and EDTA medium (conductivity: 1.5 S/m) serve as model bioparticles for visualization experiments. We manipulate sinusoidal AC signals (5-15 Vpp) while observing particle behavior through microscopy with charge-coupled device (CCD) recording capabilities. The hands-on approach enables direct observation of how voltage amplitude and frequency affect particle polarization and movement, bridging theoretical concepts with experimental reality. The results showed significant improvement in conceptual understanding of electric fields, force interactions, and bioelectronics applications compared to traditional lecture-based instruction. This educational tool addresses key learning objectives in electromagnetism and biophysics by providing immediate visual feedback of abstract concepts. The device's simplicity enables integration into existing laboratory curricula while promoting active learning, scientific inquiry, and critical thinking. The approach demonstrates practical applications of physics principles in biotechnology and medical diagnostics, enhancing student engagement and career relevance. This work contributes to physics education research by offering a scalable, low-cost method for teaching complex electrokinetic phenomena through direct experimentation.

**Keywords:** Dielectrophoresis, hands-on learning, Indium Tin Oxide (ITO), lab-on-chip, Microchannels

## INTRODUCTION

This study presents an innovative pedagogical tool for teaching dielectrophoresis (DEP) and electrokinetics by developing a cost-effective lab-on-chip device featuring oblique and V-shaped microelectrode arrays within microchannels to demonstrate electric field effects on biological particles in real time. Conducting dielectrophoresis (DEP) experiments helps students grasp key physics concepts, including the behavior of electric fields, the effects of polarization, and particle motion.

The development of test devices for biosample analysis has significantly advanced the BioMEMS platform. Various biosamples, including blood, bacteria, and viruses, have been examined using a simple manipulation method that utilizes a non-uniform electric field generated by electrodes (Li et al., 2014; Buyong et al., 2019). This method, widely known as dielectrophoresis (DEP), is especially

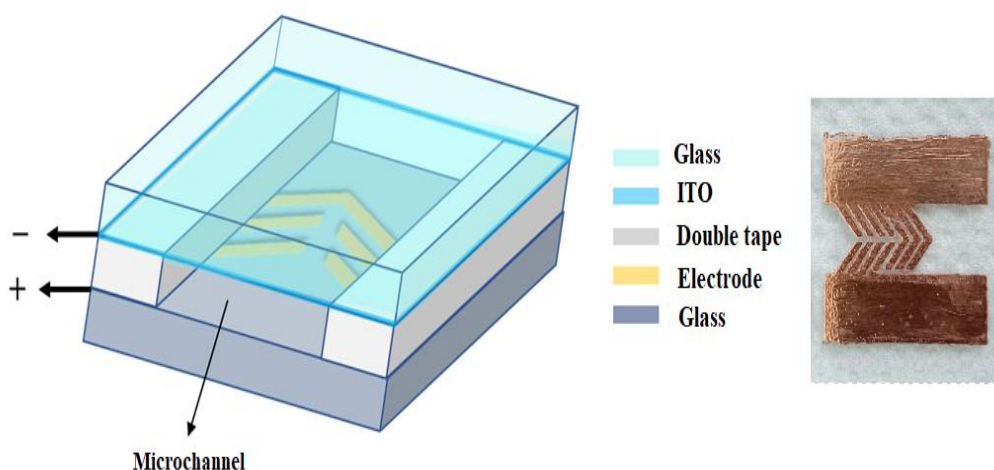
popular for manipulating biosamples (Zhao et al., 2023). Dielectrophoresis provides innovative solutions for bioparticle manipulation, such as separation (Liao et al., 2013; Yasukawa et al., 2020), isolation, direction, or focusing of bioparticles (Iswardy et al., 2017; Iswardy et al., 2025).

Dielectrophoresis relies on a non-uniform electric field generated by an alternating current (AC) source to drive dielectric particles. The application of AC current causes the particles to change direction based on the electric field density, which is influenced by the geometry of the electrodes (Kayani et al., 2012; Zhang et al., 2019). Dielectric particles in a non-uniform electric field may move toward regions of higher electric field density, a phenomenon known as positive dielectrophoresis (pDEP), or toward areas of lower electric field density, called negative dielectrophoresis (nDEP) (Liao et al., 2013). In addition to the properties of the dielectric material and the non-uniform electric field, particle movement is also influenced by voltage and frequency (Hagness et al., 2023). The applied voltage affects the dielectrophoresis force, which moves the charged particles. Since the voltage is related to the electric field, higher voltage results in a stronger electric field, causing the test charge to move according to the field's density. The frequency of the alternating current source in a dielectrophoresis test influences particle polarization, potentially shifting from nDEP to pDEP (Hagness et al., 2023; Philippines et al., 2018). The geometric shape of the electrode used influences the distribution of the non-uniform electric field across the electrode, allowing for the identification of regions with strong or weak electric fields (Khoshmanesh et al., 2011; Buyong et al., 2019).

Syafitri et al. (2023) developed a laboratory-scale ocean wave simulator to study the characteristics of ocean waves using video tracking analysis. In this study, we explore how changes in voltage and frequency can be used as teaching tools to demonstrate variations in dielectrophoretic (DEP) force in physics classes. Previous research has explored the use of non-uniform electric fields for biosample manipulation, such as bioparticle separation, as demonstrated by Tajik et al. (2019). Similarly, Yasukawa et al. (2020) studied the use of oblique electrodes for cell separation based on size. The authors also conducted a preliminary study on the manipulation of *Lactobacillus casei* in a non-uniform electric field generated by oblique electrodes (Khazanna et al., 2024). This experiment varied the voltage amplitude and assessed the performance of the oblique electrodes in characterizing the DEP properties of *Lactobacillus casei*. Hands-on learning helps understand how dielectric particles interact with electric fields and supports medical physics applications like bioparticle separation, capture, and analysis.

## METHODS

In this experiment, we use the same lab-on-chip design and development as Iswardy et al. (2025) to understand how changes in voltage and frequency demonstrate variations in dielectrophoretic (DEP) force (FIGURE 1).



**FIGURE 1.** Design of a cost-effective lab-on-chip device featuring oblique and V-shaped microelectrode arrays within microchannels to demonstrate electric field effects on biological particles

TABLE 1 presents the design specifications of the oblique and V-shaped electrodes used in the device. The measured parameters include the electrode width, electrode spacing, tip spacing, and the angle of inclination for each type of electrode.

**TABLE 1.** Design specification of oblique and V-shaped electrode

<b>Description</b>	<b>Size (<math>\bar{x} \pm SD</math>)</b>
Width of oblique and V-shaped electrodes ( $\mu\text{m}$ )	$561.89 \pm 18.92$
Electrode spacing ( $\mu\text{m}$ )	$121.20 \pm 6.49$
Tip spacing of oblique electrodes ( $\mu\text{m}$ )	$145.47 \pm 7.36$
Tip spacing of V-shaped electrodes ( $\mu\text{m}$ )	$139.84 \pm 3.67$
Angle of oblique electrodes ( $^\circ$ )	$147.47 \pm 1.32$
Angle of V-shaped electrodes ( $^\circ$ )	$56.11 \pm 0.45$

### Sample and Medium Preparation

The sample used in this study was diluted red-blood. The blood sample was collected in a small container and then diluted with EDTA (Ethylene Diamine Tetra-Acetate) to prevent blood clotting. The dilution was performed at a ratio of 1:20 between the sample and the medium. Prior to dilution, the EDTA medium had an electrical conductivity ( $\sigma$ ) value of 1.48 S/m. The conductivity of the test sample diluted at a 1:20 ratio, used in this study, was 1.5 S/m. The diluted blood was then introduced into the inlet section (approximately 1 to 2  $\mu\text{L}$ ) to flow over the electrodes within the microchannel.

### ITO Glass and Microchannel Preparation

Before fabricating the electrodes, the ITO glass is cleaned with acetone to remove fine dust particles. It is then rinsed sequentially with isopropyl alcohol (IPA) and deionized water, followed by drying with a blower. The microchannel fabrication begins by cutting a copper film to match the size of the glass substrate, which is then attached to the cleaned glass. Next, the electrode pattern, printed with toner ink on A4 paper, is cut to the same size as the substrate and placed on the copper for pattern transfer. This transfer process takes about 5 minutes. After pattern transfer, the electrodes are etched by immersing them in a 1 M  $\text{FeCl}_3$  solution for 25 to 30 minutes to remove unwanted copper from the glass surface. The electrodes are then cleaned again with acetone, IPA, and deionized water, and dried with a blower. The final step is connecting the electrodes to the function generator by placing the cable ends, already attached to the generator, onto the electrode terminals and soldering them onto the upper substrate

### Microchannel Testing

Microchannel testing was performed using the biochip connected to a function generator with variable voltage ( $V_{pp}$ ) and frequency (kHz–MHz). DEP-induced manipulation of red blood cells was observed with oblique electrodes at  $135^\circ$  and V-shaped electrodes at  $45^\circ$  within the microchannel (Kuczenski et al., 2011). The test sample was applied to both electrode types, and DEP behavior was monitored microscopically while incrementally increasing voltage and frequency until observable. Data was recorded via the microscope camera and displayed on a monitor. DEP presence was confirmed by cell movement toward regions of high or low electric field, classifying the response as positive or negative DEP. The non-uniform electric field generated by the electrodes produced a dielectrophoresis force that moved the test charge during the process. A higher electrical potential results in a stronger electric field. However, if the distance between the electrodes increases, the electric field strength decreases (Saslow, 2002). The density of the electric field reflects its strength in a given area. A higher electrical potential leads to a more concentrated electric field, allowing the red blood cells in the DEP test to shift positions from one point to another due to the applied electrical potential.

## RESULTS AND DISCUSSION

The 2D simulation of electric fields in the oblique electrode pattern using Quickfield 6.6 software (FIGURE 2) is complete; it helps students visualize how electric field intensity varies across the system. It shows that the strongest field occurs near the electrode tips, while weaker fields appear between the electrodes. This creates a non-uniform electric field, which is essential for understanding how dielectrophoretic (DEP) forces work.

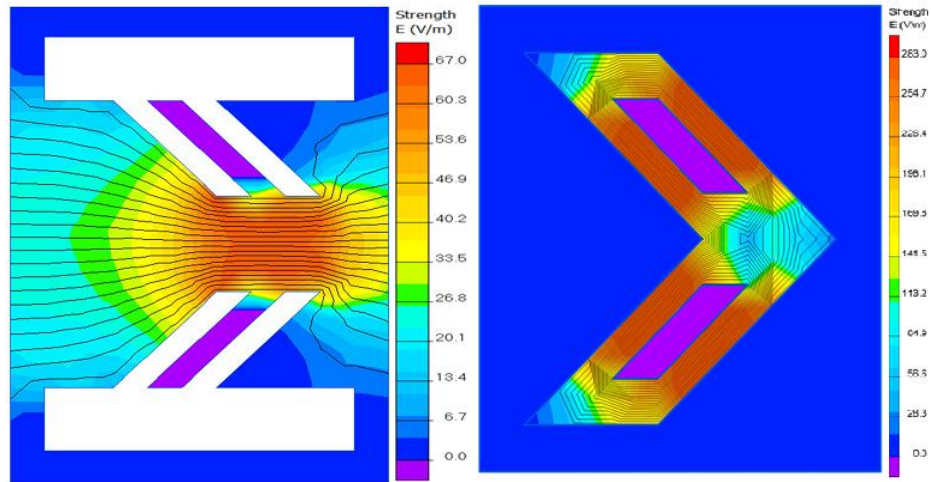


FIGURE 2. The 2D simulation of electric fields in the oblique electrode pattern by Quickfield

By analyzing this distribution, students can better grasp how variations in electric field strength influence particle movement, an important concept in electrokinetics and applied physics. In this study, both oblique and V-shaped electrodes were modeled in 3D to help students analyze and compare regions of strong and weak electric fields based on their distribution patterns. The oblique electrode design produced a non-uniform electric field, with stronger fields along the electrode edges and weaker fields in the center of the microchannel. This variation helps students understand how electrode geometry influences electric field gradients. Similarly, the V-shaped electrode, as shown by simulations from Cheng et al. (2012), generated a strong electric field within the V and a weaker field outside. These simulations provide valuable learning opportunities for students to explore how different electrode configurations impact dielectrophoretic (DEP) force behavior, reinforcing core physics concepts such as field intensity, directionality, and spatial variation. Prior to the application of the electrical signal, the red blood cells exhibit random movement and are dispersed along the electrode channel. FIGURE 3 illustrates the condition of the red blood cells before the application of the electrical signal.

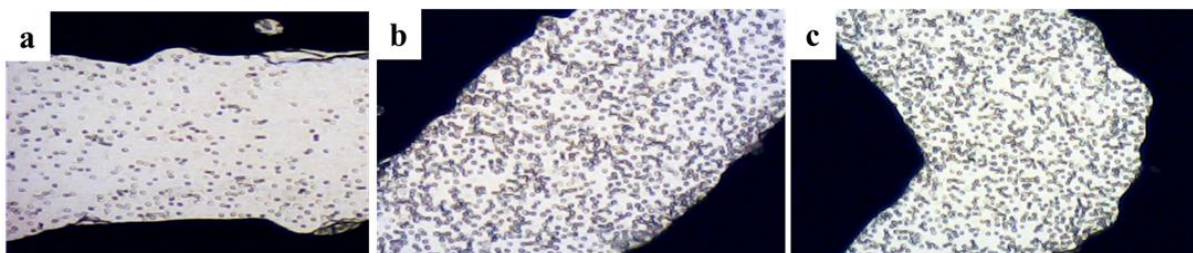


FIGURE 3. Red blood cells prior to the application of the electrical signal in: (a) the oblique electrode tip spacing, (b) the inter-electrode spacing, and (c) the V-shaped electrode region

### The Effect of 5 Vpp Voltage

FIGURE 4 illustrates the effect of a 5 Vpp voltage and various frequencies on the DEP force acting on red blood cells. The results at a 5 Vpp voltage showed that at frequencies between 5-7 MHz, red blood cells exhibited the nDEP phenomenon, causing them to move from the strong field region to the weak field region, specifically to the edges or gaps between the oblique electrodes. At frequencies of 8-14 MHz, red blood cells exhibited pDEP, moving toward the strong-field regions, such as the channel center and the interior of the V-shaped electrodes. This indicates that applying a 5 Vpp voltage is sufficient to generate a non-uniform electric field that induces DEP forces on red blood cells. The relatively low 5 Vpp voltage does not cause Joule heating, allowing red blood cells to remain in good condition. Joule heating, caused by the rise in temperature from electric current in a conductive medium, is an electrokinetic factor that can affect DEP phenomena (Nasir et al., 2022).

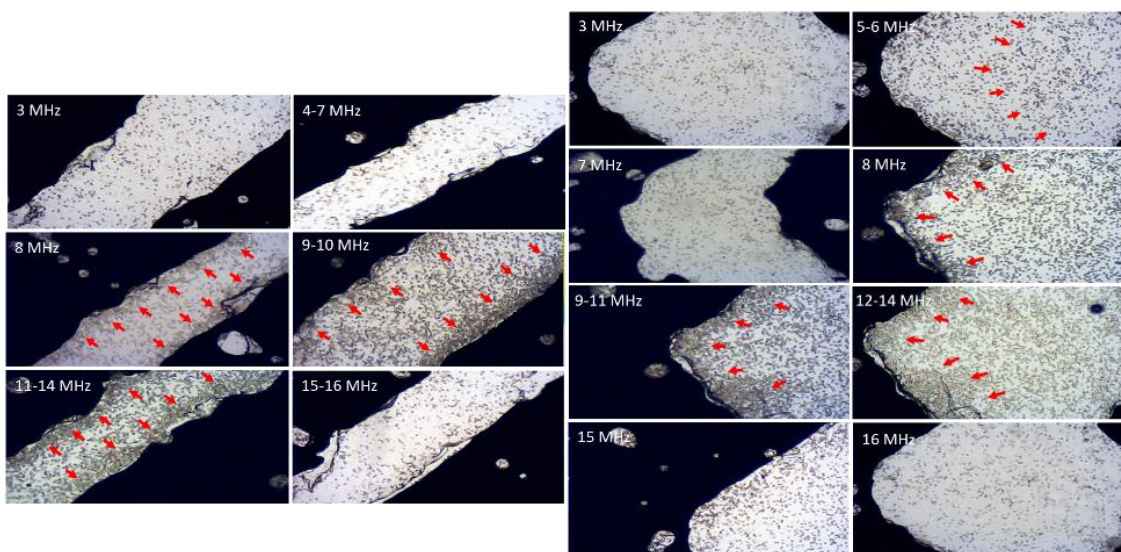


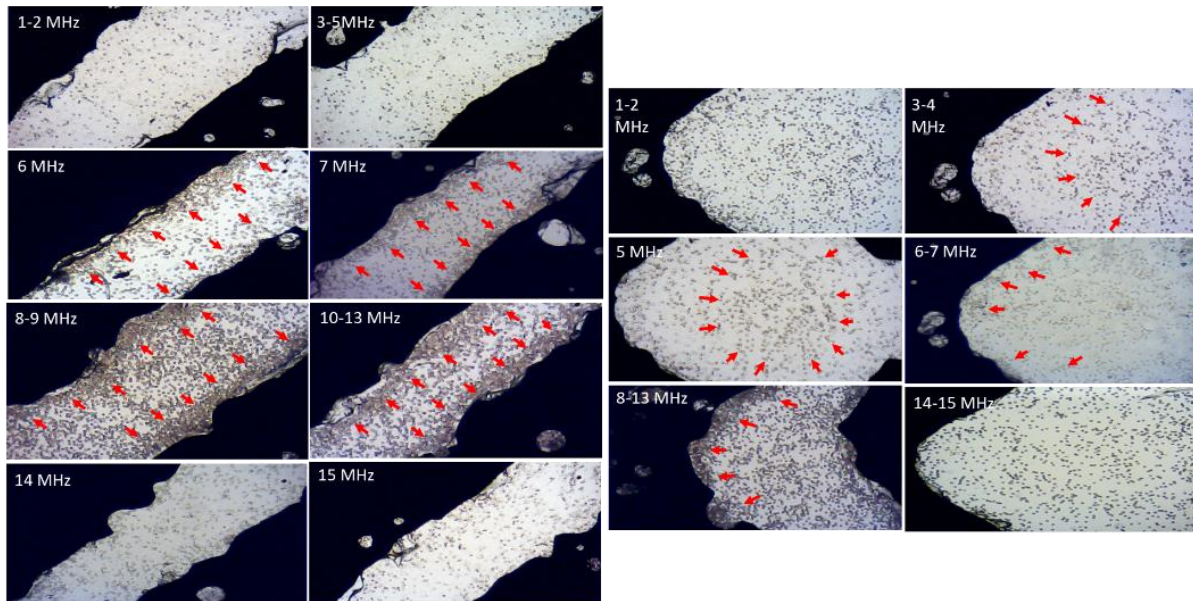
FIGURE 4. Effect of voltage and frequency on DEP force for Oblique and V-shaped electrode configurations at 5 Vpp

### The Effect of 10 Vpp Voltage

This study demonstrates that increasing the applied voltage results in a greater force generated to move the test charge. The dielectrophoresis (DEP) force is the total force acting on charged or uncharged particles due to electric dipoles, which generate either an attractive or repulsive force when the particle is in an electric field gradient. The attractive force pulls particles toward regions of strong electric fields, while the repulsive force pushes them toward areas with weaker electric fields. At lower frequencies, the positive DEP force (FpDEP) dominates over the negative DEP force (FnDEP), whereas at higher frequencies, FnDEP becomes more dominant than FpDEP. However, red blood cells, in particular, tend to experience the nDEP phenomenon at lower frequencies, which may be influenced by factors such as particle size, electrical conductivity, electric field gradient, and applied voltage. High voltage testing amplifies the effect of FnDEP. Additionally, the typical size of red blood cells (7-10  $\mu\text{m}$ ) makes them more susceptible to experiencing nDEP at low frequencies. Besides the effect of DEP forces (FnDEP/FpDEP), the movement of the test sample in the microchannel is also influenced by hydrodynamic forces. As a result, the 3D oblique electrode configuration can be used for directing and aligning red blood cells, while the V-shaped electrode can serve to capture them.

The results at 10 Vpp voltage indicate that increasing the voltage is highly effective in enhancing the DEP force. However, this must be balanced with the need to maintain cell viability. At 10 Vpp, the DEP force is twice as strong as at 5 Vpp as shown in FIGURE 5. A stronger DEP force results in higher and more directed cell movement. Additionally, it can overcome other non-electrokinetic forces acting on the test particles, such as hydrodynamic forces. In microchannels, increasing the voltage generates a DEP force strong enough to push or pull cells against fluid flow, making cells less susceptible to

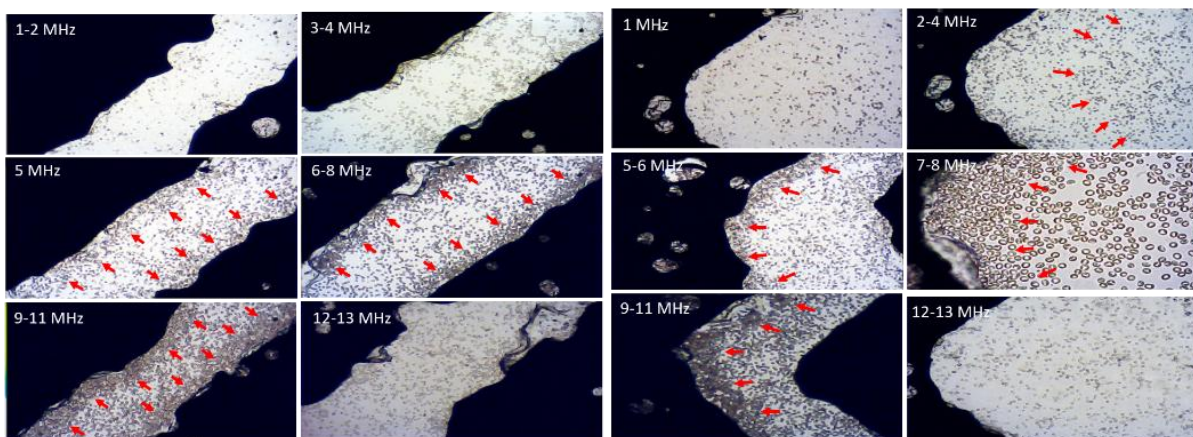
small fluctuations in flow. A strong DEP force can also lift cells from the electrode surface and overcome nonspecific interactions between cells and the microchannel walls.



**FIGURE 5.** Effect of voltage and frequency on DEP force for Oblique and V-shaped electrode configurations at 10 Vpp

### The Effect of 15 Vpp Voltage

At 15 Vpp, the electric field strength is three times higher than at 5 Vpp, producing a stronger DEP force that moves bioparticles faster, enabling quicker manipulation compared to 5 Vpp and 10 Vpp. However, high voltage can cause Joule heating. During experiments at 15 Vpp, some red blood cells appeared immobile, likely indicating cell death (FIGURE 6). This supports findings by Nasir et al. (2022) and Yan et al. (2017) that Joule heating raises temperature, damaging cells, reducing viability, and generating thermal currents that disrupt DEP manipulation. At 10 Vpp and 15 Vpp, the nDEP phenomenon occurred at frequencies of 3.5-5 MHz and 2-4 MHz, while the pDEP phenomenon was observed at frequencies of 6-13 MHz and 5-11 MHz.



**FIGURE 6.** Effect of voltage and frequency on DEP force for Oblique and V-shaped electrode configurations at 15 Vpp

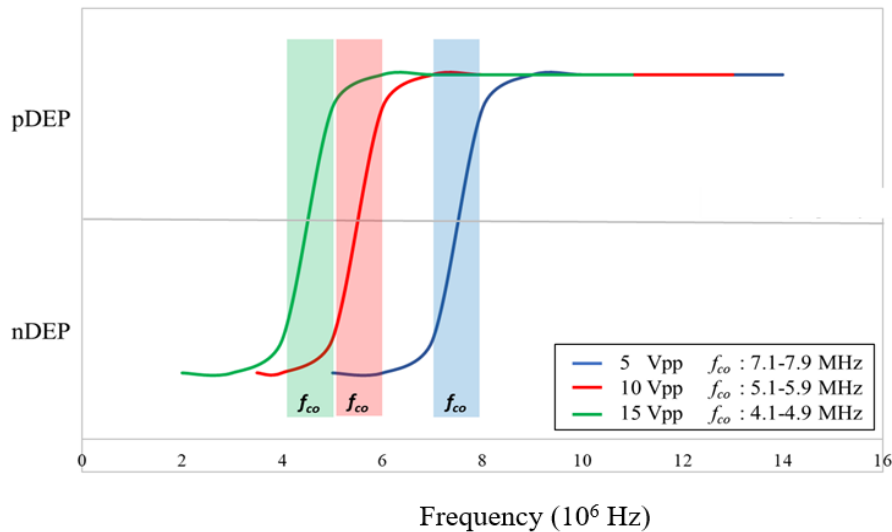


FIGURE 7. DEP red blood cells

FIGURE 7 shows the effect of applied voltage on the DEP behavior of red blood cells. The results align with the DEP bioparticle trends, where low frequencies correspond to negative DEP (nDEP) and high frequencies to positive DEP (pDEP). The crossover frequency ( $f_{co}$ ), where cells transition between nDEP and pDEP, is marked by a background color matching the graph line.

These lab-on-chip experiments help to grasp key physics concepts such as electric fields, charge distribution, and forces by demonstrating how non-uniform electric fields interact with dielectric particles like cells. In particular, the phenomena of negative dielectrophoresis (nDEP) and positive dielectrophoresis (pDEP) provide clear, tangible examples of how particles move in response to electric field gradients either being repelled from (nDEP) or attracted to (pDEP) regions of high field intensity. These experiments are increasingly incorporated into teaching environments, such as undergraduate physics and engineering labs, because they allow students to observe and quantify the forces generated by alternating current (AC) electric fields. This hands-on approach deepens understanding of electrostatics, the behavior of induced dipoles, and the importance of field gradients. Through DEP experiments, students can better visualize how AC frequency affects particle behavior, thereby illustrating complex concepts such as frequency-dependent polarization, crossover frequencies, and the balance of forces in microfluidic systems. Overall, DEP provides a practical platform for exploring electrokinetic phenomena, bridging theoretical physics with real-world applications.

## CONCLUSION

Electrodes with oblique and V-shaped configurations create an electric field gradient that allows bioparticles to be manipulated by applying electrical signals to the electrodes within microchannels. The DEP test on red blood cells at voltages of 5, 10, and 15 Vpp demonstrated that the applied voltage affects the DEP force, with higher voltage values generating a stronger DEP force to move the test charge. The frequency in the DEP test influences the polarization of the particles. The nDEP phenomenon was observed at frequencies of 5-7 MHz, 3.5-5 MHz, and 2-4 MHz, while the pDEP phenomenon occurred at frequencies of 8-14 MHz, 6-13 MHz, and 5-11 MHz. This study demonstrates that voltage and frequency significantly influence the electric field generated by the electrodes and affect the interactions of dielectric particles. Increasing the voltage is highly effective in enhancing the DEP force, enabling faster and more directed movement of cells, as well as overcoming various non-electrokinetic forces acting on the cells, such as hydrodynamic forces. However, high voltage application may cause Joule heating, which can reduce cell viability. Overall, the combination of oblique and V-shaped electrodes shows great potential for use in dielectrophoresis applications involving manipulation, capture, or isolation of bioparticles. The combination of oblique and V-shaped electrodes shows great potential for use in dielectrophoresis testing for the direction, capture, or

isolation of bioparticles. Future research should focus on developing improved electrode fabrication techniques that enable rapid production of electrodes with smooth and precise patterns. Enhancing the fabrication process is expected to optimize electrode functionality and yield more accurate and reliable results in the characterization of dielectrophoretic (DEP) behavior of red blood cells.

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