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Dynamic Contact Angle Variation with Applied Voltage and Droplet Volume in Digital Microfluidics †

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Abstract: Digital microfluidics allows for controlled droplet movement by applying AC or DC voltages. In this research, we investigated the dynamic contact angle variation of droplets at different voltages and droplet volumes in a digital microfluidics platform. Volumes of 10 μL, 14 μL, and 18 μL were investigated with voltages ranging from 250 V to 400 V. The goal was to investigate how variations in voltage and droplet volume affected the contact angle, specifically by tracking variations in the advancing and receding contact angles. The findings showed that as voltage rises, the contact angle decreases more noticeably in terms of both advancing and receding angles. This shows that higher voltages boost the electrowetting effect and lead to better droplet dispersal and substrate wetting. Furthermore, it was found that across the studied voltage range, the effect of volume on the contact angle was largely consistent. The relation between voltage, volume, and contact angle in electrowetting is better understood from our analysis.

Keywords: digital microfluidics; electrowetting; contact angle; voltage; droplet volume

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1. Introduction

Digital microfluidic platforms have emerged as powerful tools for the precise manipulation and control of minute liquid droplets in diverse scientific and technical domains [1]. Using different electrodes, these platforms generate electric fields that govern the behavior and movement of droplets on surfaces. The contact angle, a fundamental parameter denoting the angle at the liquid–solid interface, plays a crucial role in influencing the behavior, stability, and wetting properties of these droplets [2]. Digital microfluidic (DMF) devices offer several advantages, such as accelerated heat transfer, reduced reagent consumption, and the potential for seamless integration [3].

The contact angle and droplet behavior are also greatly affected by droplet volume. The size, shape, and surface tension of the droplet are all influenced by its volume, which also influences the contact angle and forces driving droplet motion. It is essential to comprehend how voltage and volume together affect the contact angle to optimize the functionality and dependability of digital microfluidics. While previous studies have investigated the effect of either voltage or volume on the contact angle, there is a gap in our understanding of the combined influence of these parameters. Therefore, this research paper aims to systematically investigate and quantify the impact of voltage and volume on the contact angles of droplets using electrowetting. By varying the applied voltage within the range of 250 V to 400 V and utilizing droplets of different volumes, we seek to analyze the resulting changes in the advancing as well as receding contact angles.

The outcomes of this study will provide valuable insights into the fundamental physics governing droplet behavior on digital microfluidic platforms.

2. Theoretical Background

The theoretical background for electrowetting on a dielectric is governed by the Young–Lippmann equation, given below [4].

$$\cos(\theta_V) = \cos(\theta_0) + \frac{\epsilon_r \epsilon_0 V^2}{2\gamma d}$$

Herein, ϵ_r and ϵ_0 are the relative and vacuum permittivity. The thickness of the dielectric layer is represented by d, γ represents the surface tension, and V is the applied voltage. The initial and final contact angles are θ_0 and θ_V.

Young's equation is used to equate forces at the droplet interface as presented in Figure 1 [5].

$$\gamma_{lg} \cos\theta + \gamma_{sl} = \gamma_{sg}$$

$$\cos\theta = \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{lg}}$$

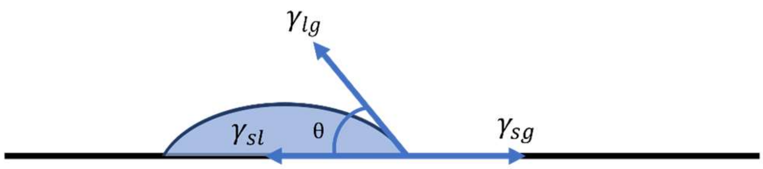

Figure 1. Schematic of surface tension of a liquid droplet acting at the solid–liquid-gas interface.

3. Materials and Methods

Distilled water was used in all experiments. The digital microfluidics platform was fabricated using a printed circuit board (PCB) from Smart PCBs (Rawalpindi, Pakistan). This was coated with grafting tape as the dielectric layer. To ease droplet movement, cooking oil was used to slide the water droplet. A 1000 V DC power supply with 0.5% ripple and maximum current of 1 milliampere was supplied by Qosain Scientific (Lahore, Pakistan).

Figure 2 represents the schematic illustration of our experiment. Once the potential difference was applied, the contact angles and velocity of the droplet were captured by a mobile camera. Quantitative analysis was performed via image analysis using ImageJ software. The size of the electrodes was 2 mm by 2 mm, and the gap between two successive electrodes was 200 µm. Experimentation was performed on water droplets with volumes of 10 µL, 14 µL, and 18 µL. We repeated each experiment 5 times to obtain accurate results.

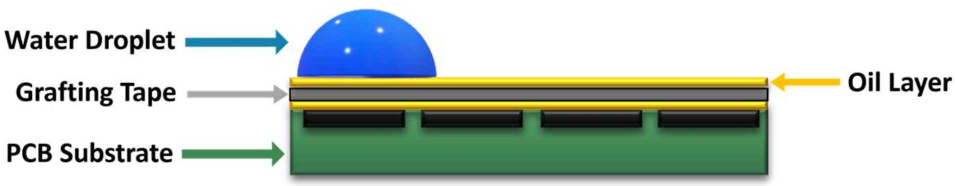

Figure 2. Schematic illustration of the digital microfluidics device.

4. Results and Discussion

The obtained results were analyzed to determine the relationship between voltage, volume, and contact angle. We examined the influence of voltage on the electrowetting effect, which modifies the contact angle (advancing and receding), by applying an electric field, as illustrated in Figures 3 and 4.

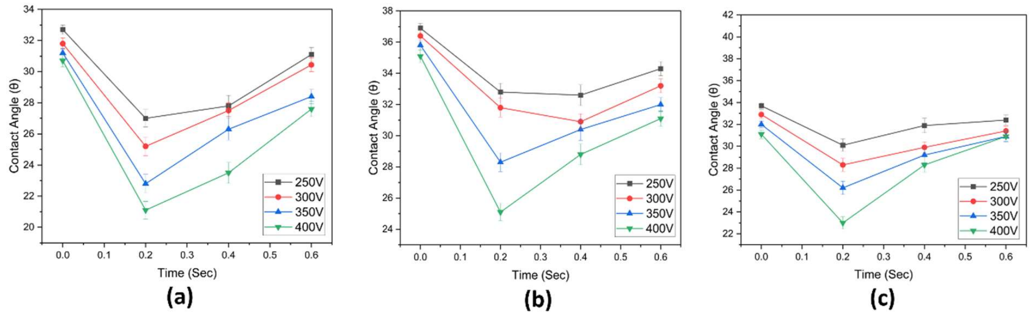

Figure 3. Advancing contact angle of the droplet at different volumes: (**a**) 10 µL, (**b**) 14 µL, (**c**) 18 µL.

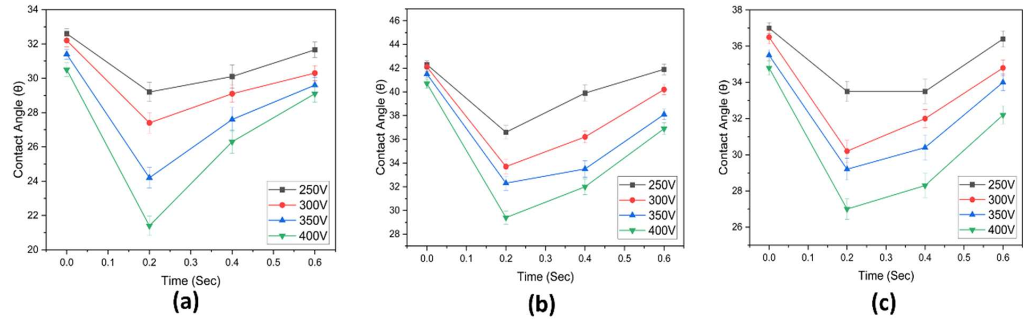

Figure 4. Receding contact angle of the droplet at different volumes: (**a**) 10 µL, (**b**) 14 µL, (**c**) 18 µL.

The results demonstrate that increasing voltage leads to a greater reduction in the advancing as well as the receding contact angles.

As the applied voltage increases, the electric field intensifies at the droplet–substrate interface, leading to enhanced polarization of the liquid molecules in that region. Consequently, the interfacial tension is reduced, prompting the liquid droplet to exhibit increased spreading on the solid surface, resulting in a decrease in the contact angle. The magnitude of this reduction in contact angle becomes more pronounced with higher voltages as the electrowetting effect gains prominence.

When the volume of the droplet is increased (Figure 5), the change in contact angle decreases due to the geometry of the droplet. As the volume of the droplet increases, there is a corresponding widening of its base, leading to an elongation of the three-phase contact line where the droplet interfaces with the solid surface and the surrounding medium. This results in an increase in the total interfacial energy at the contact line. To restore equilibrium, the excess energy arising from the elongated contact line necessitates compensation. The liquid droplet accomplishes this by adopting a larger contact angle. Consequently, with increasing droplet volume, the contact angle expands, leading to a decrease in the change of contact angle with volume.

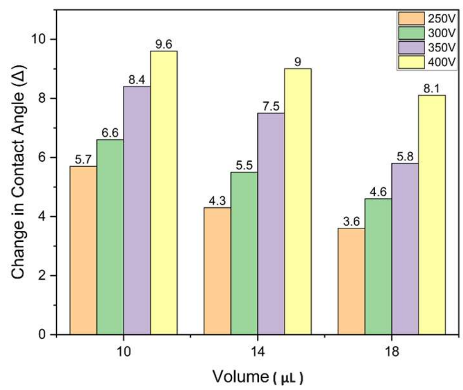

Figure 5. Comparison of change in contact angle with the applied voltage and volume of the water droplet.

5. Conclusions

In conclusion, the findings from this research demonstrate that increasing voltage on a digital microfluidics platform leads to a corresponding increase in the reduction in the contact angle, in terms of both the advancing and receding angles. This indicates that higher voltages enhance the electrowetting effect, resulting in improved droplet spreading and wetting on the substrate. On the other hand, while voltage has a significant influence on the contact angle, changes in droplet volume at a constant voltage show a consistent effect on the contact angle. Specifically, as the droplet volume increases at a constant voltage, the change in the contact angle reduces. These findings contribute to a better understanding of the relationship between voltage, droplet volume, and contact angle in digital microfluidic platforms, enabling researchers to optimize droplet manipulation techniques for improved performance and reliability in number of applications, such as lab-on-a-chip systems, bioassays, and chemical synthesis.

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