Influence of Inclined Chip Angles on Dynamic Contact Angle Variations in Digital Microfluidics

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Abstract. The impact of tilted angles on contact angles of water droplets in digital microfluidics was investigated. Experiments were conducted tilting the chip from 0 to 10 degrees at voltage increments of 50V from 250V to 400V DC. Both advancing and receding contact angles of the water droplets were measured at each angle and voltage combination. As the tilted angle increased from horizontal to 10 degrees, the advancing contact angle generally decreased whereas the receding contact angle increased. This trend held for all tested voltages. The changes were more pronounced at higher tilt angles above 5 degrees. Voltage was also found to influence the contact angles, with both advancing and receding angles decreasing with increasing driving voltage. The results provide insight into how tilted surface angles affect wetting properties in digital microfluidics. By understanding these relationships between contact angles, tilt angles and driving voltages, design parameters like maximum operational tilt angles before droplet pinning or instability can be better determined. The findings may assist in designing and optimizing tilted or three-dimensional digital microfluidic devices and applications.

1 Introduction

Digital microfluidics is an emerging technique for manipulation of microliter liquid droplets using electrical forces. By controlling electrode actuation patterns, droplets can be transported, split, merged, mixed and used to carry out complex biochemical assays on a chip [1]. Compared to continuous flow microfluidics, digital microfluidics offers advantages such as reduced sample volumes, programmable fluid control and miniaturization of lab processes. Traditionally, digital microfluidic devices have utilized two-dimensional planar electrode arrays with droplets sandwiched between two parallel plates [2]However, three-dimensional device designs utilizing tilted or non-planar geometries could enable new functionalities. For example, tilted surfaces may facilitate multi-layer fluidic circuits or assist droplets to flow along gradients.
A key parameter governing digital microfluidic operations is the contact angle that liquid forms with the chip surface [3]. Contact angle hysteresis between advancing and receding

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angles determines factors like droplet mobility, splitting and stability during transport. Past studies have focused on contact angle variations with materials, liquid properties and applied voltages. However, the impact of tilted chip angles remains relatively unexplored.
This work investigates how tilted surface angles influence the contact angles of water microdroplets on a digital microfluidics platform. Experiments were conducted tilting the chip between 0-10 degrees while measuring advancing and receding contact angles at different driving voltages. The findings provide fundamental understanding to aid design and optimization of tilted or 3D digital microfluidic systems for enhanced capabilities and applications.

2 Theoretical background

The motion of liquid droplets on a digital microfluidic device is governed by the balance of electrical, interfacial and gravitational forces [4]. When a voltage is applied between the driving electrode and ground electrode, electrical forces are generated which overcome surface tension forces to displace the droplet.
As voltage is increased, electrowetting occurs where the effective solid-liquid interfacial tension reduces according to Lippmann-Young equation [5]:

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

This causes the contact angle θ to decrease towards a more hydrophilic state θ_0. Higher voltages thus lower the contact angle.
Gravity acts as an additional force that competes with electrowetting when tilting the substrate.[6] When a droplet is tilted, the horizontal component of gravity F_g = mg sinα increases, where m is mass, g is gravitational acceleration, and α is tilt angle. This gravitational force opposes the electrowetting force resulting from voltage V.
The Young-Lippmann equation can be modified to account for gravity's effect by including F_g:

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

For tilted surfaces, the apparent contact angle θ_α is related to the intrinsic contact angle θ_V and tilt angle α according to the Cassie formula [7]:

$$\cos(\theta_\alpha) = \cos(\theta_V)\cos(\alpha)$$

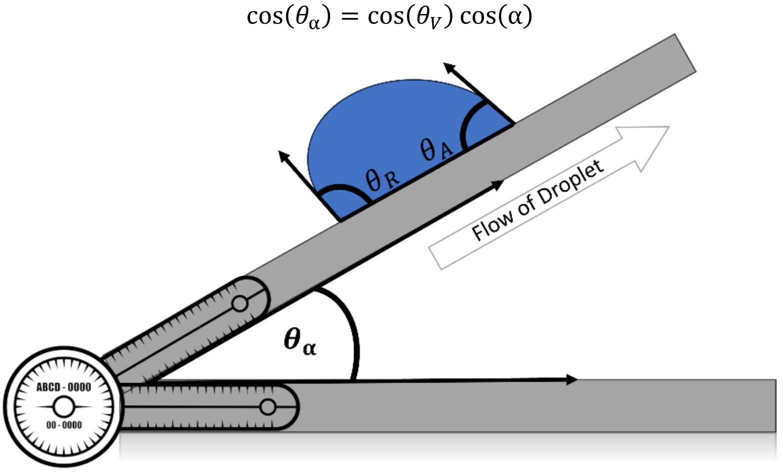

Figure 1. Schematic diagram of an inclined surface with advancing and receding contact angles

According to this relationship, tilting the surface away from horizontal (increasing α) is expected to increase θ_α and reduce wetting [8]. Together, these fundamentals will be used to understand how contact angle varies with applied voltage and tilt angle in digital microfluidics, and their combined influence on droplet behaviour.

3 Materials and Methods

Distilled water was used as the working fluid for all experiments. The digital microfluidic device was fabricated using a printed circuit board (PCB) obtained from Smart PCBs (Rawalpindi, Pakistan). The PCB featured 2mm x 2mm copper electrodes patterned with a 0.2mm gap and acting as the bottom substrate. A transparent grafting tape (Thickness 0.03mm) purchased from an online retailer in Pakistan was used as the dielectric layer atop the electrodes. To introduce wettability, a thin layer of cooking oil obtained from a local market was dispensed and evenly spread across the dielectric surface, acting as the hydrophobic sliding plane for water droplets.

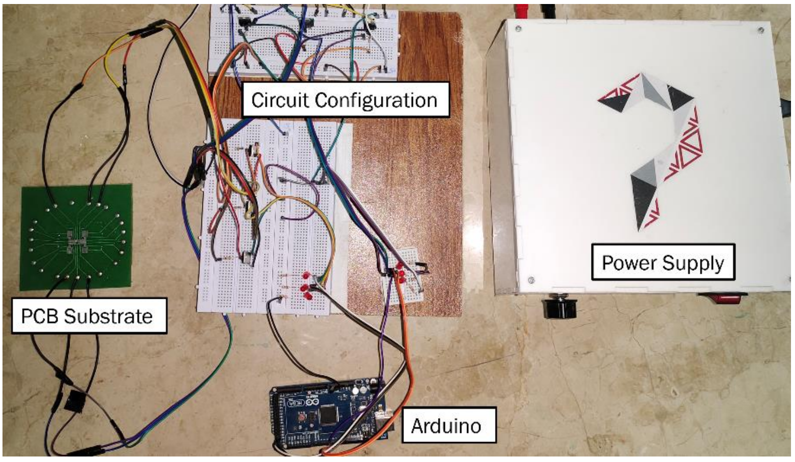

Figure 2 Expérimental Setup

A high voltage power supply (Qosain Scientific, Lahore, Pakistan) rated for 1000V DC with 0.5% maximum ripple and 1mA current limit was used to apply electric potentials. Initially, cooking oil was applied onto the electrode array. Then the grafting tape dielectric was affixed, thereby creating the digital microfluidic chip assembly. The assembled chip was manually tilted from 0 to 10 degrees in 1-degree increments on a protractor stage. The tilt angle was also measured and verified using image analysis in ImageJ software.
Dynamic contact angle measurements and droplet actuation experiments were performed by applying voltages to targeted electrodes underneath while observing through a mobile phone camera (Resolution 1080p, Frame rate 60fps). Images captured during experiments were later analysed using ImageJ software to determine contact angles and velocities. Measurements were repeated 5 times for each experimental condition to obtain average values.

4 Results and Discussion

Our investigation into the influence of inclined chip angles on dynamic contact angle variations in digital microfluidics involved conducting experiments with chip angles of 0 and 15 degrees. The results, depicted in Figure 4, provide insights into the behavior of droplets when a voltage is applied and when it is turned off.

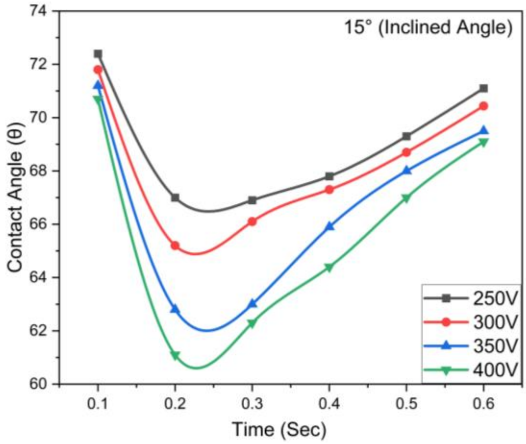

Figure 3 Advanicng CA at Inclined Angle of 15°

At 0 degrees chip angle, the application of voltage rapidly reduces the contact angle, indicating enhanced droplet wetting. Conversely, when the voltage is turned off, the contact angle gradually increases over time, signifying the droplet's inclination to return to its original angle. For the 15 degrees chip angle (Figure 4), the voltage application exhibits a more pronounced reduction in the contact angle compared to 0 degrees. Similarly, when the voltage is turned off, the contact angle gradually increases, demonstrating the droplet's inclination to revert to its initial angle. While the current analysis focuses on the available data for 0 and 15 degrees, further research is warranted to explore dynamic contact angle variations for chip angles within the 0 to 15-degree range.

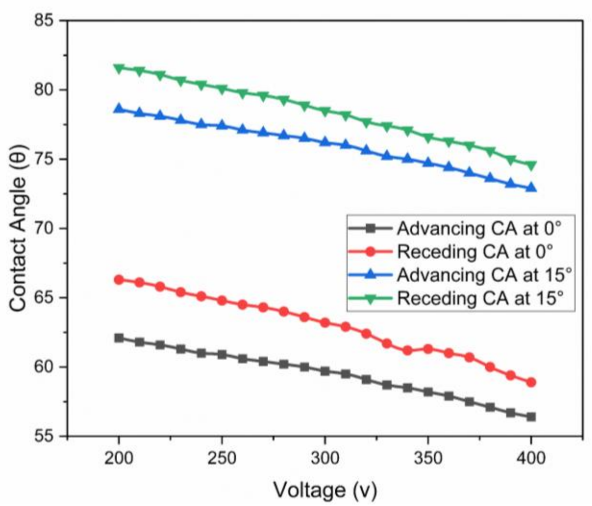

Figure 4 Contact Angle Variation on Different Voltages

Figure 5 depicting the variation of contact angle with voltages ranging from 200 to 400 volts provides further insights into the relationship between voltage application and contact angle reduction. As the voltage increases, we observe a decrease in the contact angle of the droplet on the substrate.

This phenomenon can be explained by the electrostatic forces induced by the applied voltage. At lower voltage levels, the electrostatic forces are relatively weak, resulting in a higher contact angle. As the voltage is gradually increased, the electrostatic forces become stronger, leading to enhanced droplet spreading and wetting on the substrate. Consequently, the contact angle reduces as the droplet experiences increased electrostatic attraction towards the substrate. However, it is important to note that there may be a limit to the contact angle reduction, beyond which further increases in voltage may not have a significant impact on the contact angle.

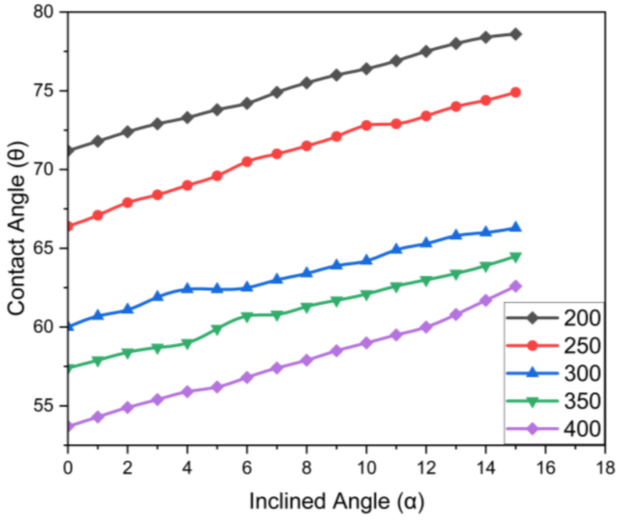

Figure 5 Influence of Inclined Angle of DMF Chip on Contact Angle

The investigation aimed to examine the influence of inclined chip angles on contact angle variation in digital microfluidics. The analysis of the experimental data revealed a noteworthy relationship between chip angle and contact angle. As depicted in Figure 6, the graph illustrates the variation of contact angle with different chip angles. It is evident that as the inclined angle of the chip increased, the contact angle of the droplet on the substrate also increased.

At 0 degrees chip angle, the droplet exhibited improved wetting behaviour, as indicated by a lower contact angle. However, as the chip angle was increased to 15 degrees, the contact angle showed a noticeable increase. This finding suggests that the droplet tends to have reduced wetting and less affinity to spread on the substrate with higher inclined chip angles. The observed increase in contact angle with increased chip angle can be attributed to several factors. Firstly, the change in chip angle alters the geometry of the substrate, affecting the interaction between the droplet and the surface. Secondly, it can affect the balance between gravitational and surface tension forces, influencing the droplet's ability to spread and wet the substrate. These findings emphasize the significance of chip angle in droplet behaviour and highlight the need for careful consideration when designing microfluidic systems. Understanding the impact of inclined chip angles on contact angle variation provides valuable insights for optimizing system performance and achieving desired wetting behaviour.

5 Conclusion

Our research, on how voltage and chip tilt affect changes in contact angles in digital microfluidics, provided insights to improve the design and performance of digital microfluidic systems. To begin our analysis, we found that as the energy density increased, the degree of contact between the droplets decreased. This decrease can be attributed to the effective expansion and cooling of the droplets by the applied voltage. However, it should be noted that there may be times when further increasing the intensity no longer significantly affects the contact angle. Furthermore, our results revealed how different adhesive compositions can affect the changes in contact angle. As the coating thickness increased, the contact area of the droplets also increased. This indicates that higher chip angles result in lower affinity for droplet spreading on surfaces. These issues have implications for optimizing policies. By monitoring voltage levels, researchers and engineers can adjust contact angle to achieve wetting behaviour and improve droplet manipulation and transport efficiency Moreover, it is important to consider adhesives when designing assurance systems that the droplets are wetting characteristic and effective.

References

[1] S. Cho, H. Moon, C. K.-J. of Microelectromechanical, and undefined 2003, “Creating, transporting, cutting, and merging liquid droplets by electrowetting-based actuation for digital microfluidic circuits,” *ieeexplore.ieee.orgSK Cho, H Moon, CJ KimJournal of Microelectromechanical systems, 2003•ieeexplore.ieee.org*, vol. 12, no. 1, 2003, doi: 10.1109/JMEMS.2002.807467.

[2] K. Choi, A. H. C. Ng, R. Fobel, and A. R. Wheeler, “Digital Microfluidics,” *https://doi.org/10.1146/annurev-anchem-062011-143028*, vol. 5, pp. 413–440, Jun. 2012, doi: 10.1146/ANNUREV-ANCHEM-062011-143028.

[3] J. Li and C. J. Kim, “Current commercialization status of electrowetting-on-dielectric (EWOD) digital microfluidics,” *Lab Chip*, vol. 20, no. 10, pp. 1705–1712, May 2020, doi: 10.1039/D0LC00144A.

[4] M. Alistar and U. Gaudenz, “OpenDrop: An Integrated Do-It-Yourself Platform for Personal Use of Biochips,” *Bioengineering 2017, Vol. 4, Page 45*, vol. 4, no. 2, p. 45, May 2017, doi: 10.3390/BIOENGINEERING4020045.

[5] M. Ali, H. Ullah, M. Ali, N. Naeem, H. Abbas, and A. T. Jafry, “Dynamic Contact Angle Variation with Applied Voltage and Droplet Volume in Digital Microfluidics †,” *Engineering Proceedings*, vol. 45, no. 1, 2023, doi: 10.3390/ENGPROC2023045031.

[6] S. F. Shah, A. T. Jafry, G. Hussain, A. H. Kazim, and M. Ali, “A passive and programmable 3D paper-based microfluidic pump for variable flow microfluidic applications,” *Biomicrofluidics*, vol. 16, no. 6, Dec. 2022, doi: 10.1063/5.0125937/2835569.

[7] A. T. Jafry *et al.*, “Double-sided electrohydrodynamic jet printing of two-dimensional electrode array in paper-based digital microfluidics,” *Sens Actuators B Chem*, vol. 282, pp. 831–837, Mar. 2019, doi: 10.1016/J.SNB.2018.11.135.

[8] G. Hussain, A. T. Jafry, S. Malik, S. F. Shah, S. Nishat, and F. R. Awan, “Multifunctional rotational active valve for flow control in paper-based microfluidic devices,” *Sens Actuators B Chem*, vol. 378, p. 133142, Mar. 2023, doi: 10.1016/J.SNB.2022.133142.