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Numerical Investigation of Water Drop Movement within a Microchannel under Electrowetting Phenomenon

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Abstract

The present study investigates the movement of water drop within a microchannel under electrowetting phenomenon. Electrowetting, by applying boundary (line) stress and macroscopic variation in contact angle of surface, operates according to an electric field in order to manipulate small volumes of liquids. Applied electrostatic field makes the conducting drop to move in the direction of the field. Electrowetting phenomenon simulation has been done by application of OpenFoam software in Linux operating system and interFoam solver, by using the method of the volume of fluid (VOF). Numerical modeling has been compared with experimental results has been confirmed, and then has been investigated through three dimensional modeling of the movement of fluid drop in microchannels under electrowetting phenomenon with channel's different heights. An increase in microchannel height at fixed volume of water drop causes the velocity of drop to increase. The movement of the drops under the electrowetting phenomenon stimulation in climbing up the inclined plane in microchannels has been investigated through variable angle toward the horizon. Increasing microchannels angle with the horizon surface decrease the drop ascending velocity.

Keywords: *Electrowetting, OpenFoam, Microchannel height, Inclined plane.*

1. Introduction

Electrowetting phenomenon operates according to electrocapillarity which was first introduced by French scientist, the noble prize winner, Gabriel Lippmann. Accordingly, the wetting behavior of liquid drop varies by applying electric potential field. While there is no electric field, the drop is located on the solid surface in a way which applied forces over the liquid-gas-solid interface all are balanced. This balance causes a contact angle between drop and solid surface to be made. Contact angle decreases, by applying electric field, and it can be said that the drop wets the surface [1]. From among applications of electrowetting phenomenon we can mention some of them such as screen technologies, drop transfer, smart lenses, control micro valves, electric paper, miniature chemistry, energy production and laboratory chips. Kuo et al. [2] investigated the behavior of a water drop in an immiscible ambience (oil). In the presence of olive oil environment, oil causes the velocity of the drop to increase compared to the presence of water drop in the air environment; the presence of water drop in olive oil minimizes or prevents the splitting process of water drop as well. Yi and Kim [3] explored the impact of the distance between electrodes on the electrowetting. Surface contact angle, by increasing the distance between electrodes in a constant voltage, undergoes a little reduction. Krupenkin and Taylor [4]

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utilized reverse electrowetting method which was a new method and whereby they could produce clean electric energy using this method. According to the interaction between the lines of polar drops with moving multi layered dielectric films (in Nano thickness) they could produce the electric power of $10\ \left({}^{W}/_{m^2}\right)$ in the laboratory environment. Mohseni and Dolatabadi [5] conducted the without leakage micro valves simulation as well. Through this mechanism the liquid drop has been used as a valve to adjust the current in the T-junction. The investigation revealed that the pressure drop is significantly dependent on the T-junction angles.

Hong et al. [6] investigated the behavior of the drop with different stimulation frequencies under the electrowetting phenomenon. By the increase of frequency, the impact of tension decreases, and by the reduction of the frequency the electric field decreases. To achieve a constant impact, we need to apply more voltages in higher frequencies. Rajabi and Dolatabadi [7] compared and simulated the electrowetting phenomenon between the flat electrodes and crescent electrodes. Velocity and transformation of drop has been reported according to the results from the crescent shaped electrodes. Mohseni et al. [8] investigated behavior of the drop under the electrowetting phenomenon by numerical examination. The parameters of stimulation voltage, channel dimensions, the length of electrode and the drop velocity have been investigated.

In aforementioned studies, the effect of gravity on the drop has not been studied. In the present study, the numerical investigation of effective parameters variations on the drop velocity under the electrowetting phenomenon has been discussed by the OpenFoam software in the Linux operating system. Primarily, the behavior of drop upon the solid surface is simulated under the electrowetting phenomenon and then the simulated model accuracy will be compared according the experimental results. The present study investigates the impact of parameters of the microchannel height and gravity variation on the drop velocity.

2. NUMERICAL TECHNIQUES

The movement of fluid drop has assumed as incompressible fluid, Newtonian fluid and Laminar flow and therefore the Navier- Stokes equation are considered as it follows:

$$\rho\left(\frac{\partial u}{\partial t}+u.\nabla u\right)=-\nabla p+\nabla.\left[\mu(\nabla u+\nabla v)\right]+\rho g+F_{\gamma}+F_{E} \tag{1}$$

Also, the continuity equation is considered as this:

$$\nabla.u=0 \tag{2}$$

The additive terms F_{γ} and F_E represents surface tension forces and electrostatic field, respectively. Surface tension force F_{γ} is obtained from the continuity model of surface forces (CSF) [9]. Electrostatic field is achieved through Maxwell stress tensor as this:

$$F_E=\nabla.T \tag{3}$$

$$T=\varepsilon\left(EE-\frac{|EE|^2}{2}I\right) \tag{4}$$

Here ε is electrical conductivity coefficient, T is Maxwell stress tensor, I is electric intensity and E is the electrostatic field. For determination of each phase, in this model, a volume fraction (VOF) is defines as follow:

$$\propto = \frac{volume\ of\ fluid}{volume\ of\ control\ volume} \tag{5}$$

$$\propto = \begin{cases} >0,\ <1 & transition\ region \\ 1 & liquid\ phase \\ 0 & gas\ phase \end{cases} \tag{6}$$

The dominant equation over the volume fraction is represented as follows:

$$\frac{\partial \propto}{\partial t} + \nabla.(\propto u) = 0 \tag{7}$$

In transition area density and viscosity are achieved regarding volume fraction:

$$\rho = \rho_1 \propto + \rho_2 (1 - \propto) \tag{8}$$

$$\mu = \mu_1 \propto + \mu_2 (1 - \propto) \tag{9}$$

It's possible to change the wetting behavior of liquid drops by applying electric potential field. While there is no electrical field, the drop is established on the solid surface in a way in which implemented forces over the interface of liquid-gas-solid all balanced. This balance makes contact angle between drop and solid surface as illustrated in figure 1. By applying electric field, contact angle between drop and the surface decreases and in other words the surface would get wet by the drop [1].

The boundary conditions are defined by the well-known Young-Lipmann equation:

$$\cos(\theta_V) = \cos(\theta_0) + \frac{\varepsilon_0 \varepsilon_r}{2d\gamma_{lg}} V^2 \tag{10}$$

Here are γ_{lg} Liquid-gas surface tension, θ contact angle between drop and the surface. ε_0 ، ε_r and d are vacuum and dielectric electrical conductivity coefficient and dielectric thickness, respectively.

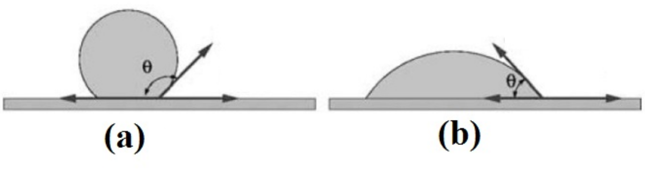


Figure 1: Contact angle definition at the liquid-solid interface. (a) When no voltage between droplet and substrate is applied, (b) when a voltage is applied.

Numerical simulation of fluid drop motion was performed in OpenFoam software by applying boundary conditions based on Young-Lippmann and by interFoam two-phased solver. In order to validate numerical results, by simulation of a mercury drop establishment as a fluid with free surface, over a solid surface under the electrowetting phenomenon, numerical results of the present study has been compared to Alavi et al. [10,11] experimental results . In the following, a drop motion under the electrowetting in the microchannel with different heights has been analyzed. And in the following by changing the angle between microchannel and the horizon surface the impact of gravity on droplet movement in climbing up the inclined microchannel with the height of $250\mu m$ was investigated.

3. RESULTS AND DISCUSSION

This problem is illustrated schematically in the figure 2. Microchannel with the length of 3 mm and the width of 0.5 mm and in the presence of three electrodes in the length of 1 mm in the bottom of microchannel is shown in the figure 2. By the introduction of cell per radius (cpr) unit, the independency of numerical solution is investigated. Primarily, the establishment manner of water drop in volume of $14\mu L$ on a flat surface without applying a voltage was investigated. In this case, the simulation of water drop setting on the solid surface has been performed by considering networks with three different sizes. In figure 3, independence from network has been represented according to the comparison with the drop profile for three different networks with 10, 20 and 30 cell per radius. A mesh corresponding to cpr = 20 is seen to be fine enough after which the numerical results will experience no significant changes.

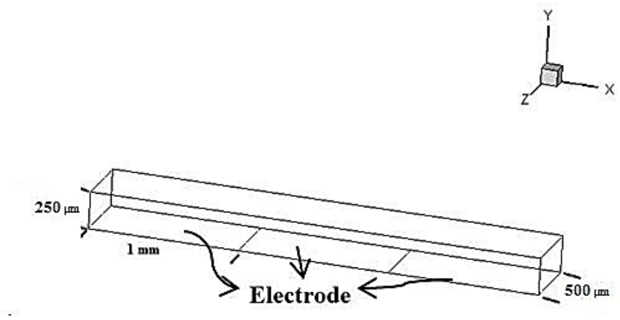


Figure 2: Schematic of the physical model used in numerical simulations.

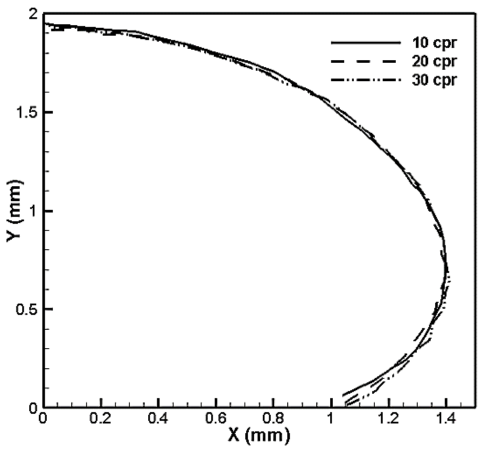
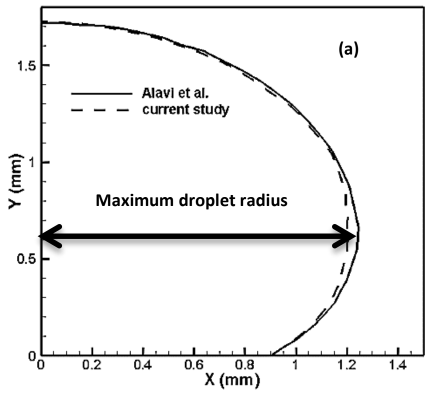


Figure 2: Mesh independency test for a $14\mu L$ drop under normal gravity. The results are given for various mesh sizes characterized by cell per radius.

In order to validate numerical modelling, the results of a mercury drop establishment in the volume of $6\mu L$ on the solid surface both in the existence of electrowetting phenomenon (surface contact angle of 133° by applying 240V) and in the absence of electrostatic field (surface contact angle of 141°) have been compared to experimental results of Alavi et al.[10,11]. In figure 4, the results of the establishment of a mercury droplet in the volume of $6\mu L$ on the solid surface in the presence and absence of the electrowetting phenomenon has been compared to the experimental results of Alavi et al.[10, 11]. According to figure 4, the results of the numerical solution are observed so close in the presence and absence of the electro static field compared to experimental results. Due to the table 1 the error rate of numerical method in this study has been distinguished in comparison with Alavi et al. [10, 11] results. Given to the results achieved (table 1) we observe that maximum error between numerical and experimental results have been related to the radius of the drop and are only about 3 percent.

Table 1: Comparison of discrepancy in the results between current study and Alavi et al. [10, 11].

Modelling conditions	Numerical error percent	
	Error percent in the maximum radius of the drop	Error percent in the maximum height from the surface
Before applying voltage	3	0.1
After applying voltage	3	0.8



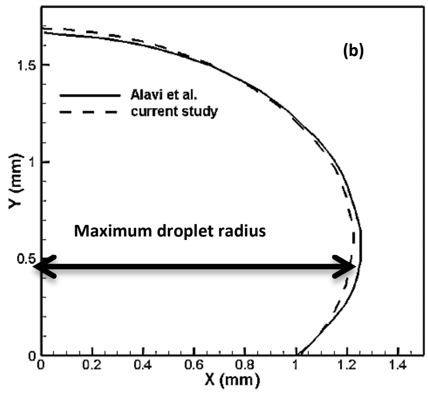


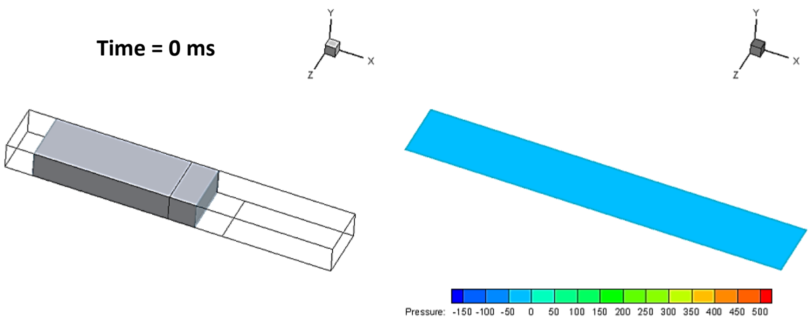
Figure 3: Comparison between current study and Alavi et al. [10, 11] results for free surface profile of a $\mathbf{6\mu L}$ mercury drop. (a) Before the applied voltage, (b) after the applied voltage.

In this level, regarding numerical results validation, the movement of a fluid drop in a microchannel is investigated. With regard to Moon et al. [12] investigation, the type of parylene dielectric with the thickness of $12\,\mu m$ and electrical conductivity coefficient $\varepsilon_r = 2.65$ for the drop movement simulation in the microchannel has been considered. Also, we used a fluoropolymer layer as a hydrophobic material in the bottom of microchannel with the surface balance contact angle $\theta_0 = 120^{\circ}$ (in the absence of electrical field). At first, the water drop movement in the volume of $0.375\mu L$ was investigated in a microchannel with the length, width and the height of $3\,\mathrm{mm}$ ،$0.5\,\mathrm{mm}$ and

$250\ \mu m$ respectively, and in the presence of three electrodes each one in the length of 1mm. A voltage in 106.35° was applied over the active electrode in order to, the reduction of 10° in the surface contact angle between two adjacent electrodes come into existence, according to the Young-Lipmann equation. The movement of water drop in the volume of $0.375\mu L$ at four points in time under the electrowetting 0 ms, 2 ms, 4 ms and 6 ms is illustrated in figure 5. After applying boundary conditions of the contact angles of the walls, it was observed that in 2 ms the drop begins to move in the microchannel. The reason for this movement can be mentioned as the transfer of leading edge water drop from the first inactive electrode to the second active electrode; because by entering the second active electrode in the presence of electrowetting phenomenon, the contact angle of the leading edge water drop decreases compared to the before, and there for an electrostatic force is applied in order to reduce the surface contact angle.

As it's the case, by passing the water drop leading edge from second electrode to the third active electrode the surface contact angle decrease for 10° compared to the second electrode, which leads to the applying of an electrostatic force to the drop and as a result the drop movement through the microchannel is reinforced. The first electrode has the most contact angle and the third one has the least. According to Laplace equation [13], the curvature on the liquid-gas free surface (interface) causes the internal pressure of the drop to increase toward its external gas ambience. Because the curvature of the free surface of the drop through its trailing edge is more, compared to the curvature of the leading edge, consequently, the internal pressure of the drop through trailing edge is more than the pressure through the leading edge (according to figure 5) and this very factor causes the drop to move toward the leading edge.

In order to investigate the influence of the microchannel height on the drop movement under electrowetting, the velocity of drop movement in different conditions has been shown in the figure 6. As it can be seen in the figure, by increasing the height of microchannel, the velocity of the drop movement accelerates. Volume of fluid is constant and equal to $0.375\mu L$ in any condition. The height of microchannel varies from $250\mu m$ to $400\mu m$. By increasing the height of microchannel and because of the constancy of water drop volume through all conditions, the drop surface involving microchannel internal surfaces decreases. Consequently, the effect of the shear stress resulted from the wall on the fluid movement descends. This causes increasing in the velocity of water through the microchannel by increasing the height of microchannel. So the parameter of microchannel height is introduced as an effective parameter in the fluid movement in microchannel which accordingly it's possible to control and plan the fluid movement and reactive nature of the system, as well as the velocity based on the applied voltage.



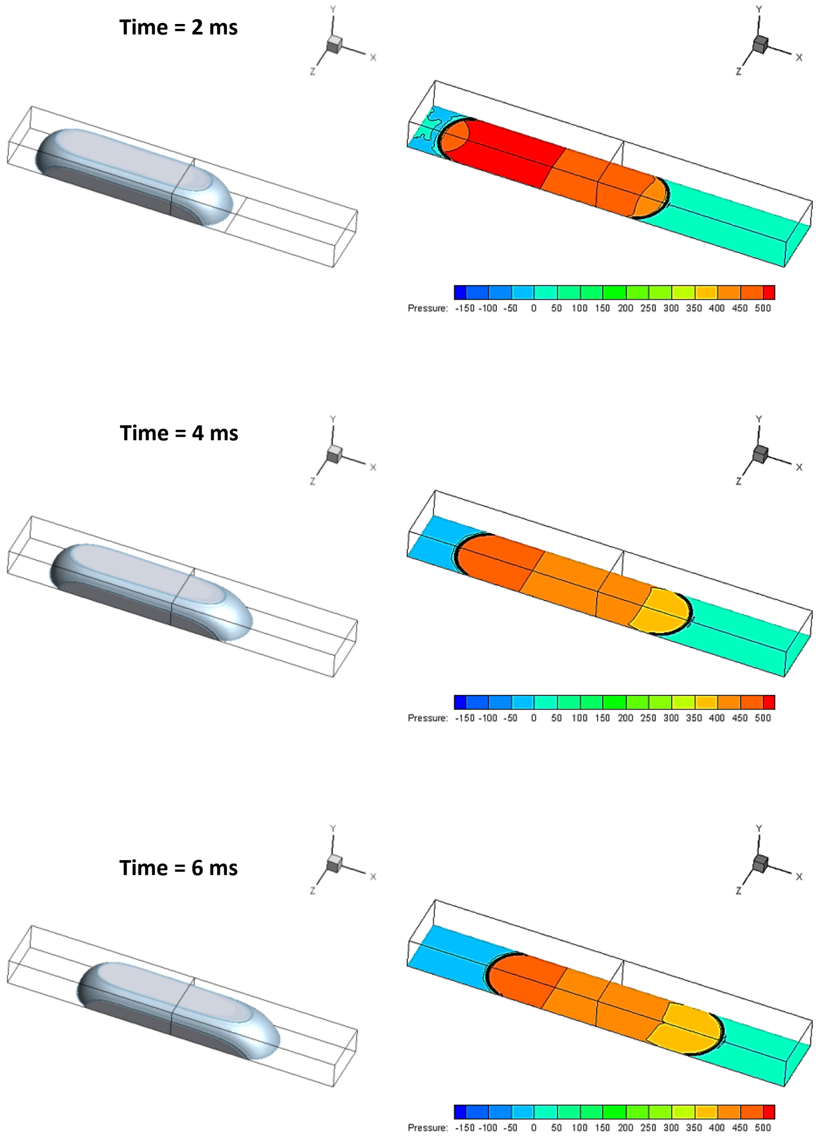


Figure 5: Droplet actuated by electrowetting phenomenon in a microchannel.

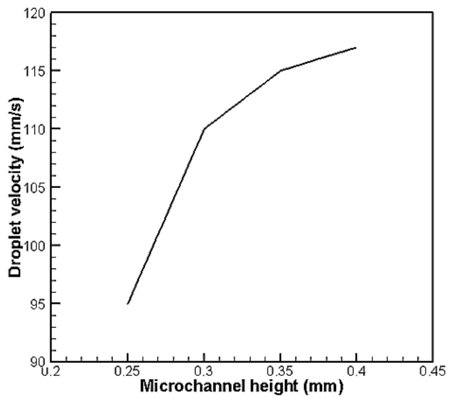


Figure 6: Droplet velocity vs microchannel height.

In the next level, to investigate the impact of gravity on the drop movement under electrowetting phenomenon, the ascending velocity of water drop in the volume of $0.375\mu L$ was measured by changing the angle between the microchannel with the height of 250μ and the width of 0.5mm with horizon surface and by applying 106.35V voltage to active electrode. The angle of inclined surface Ø of microchannel has been investigated from $0^{\circ}$to 60°. The angle between microchannel with horizon surface and the drop movement direction has been illustrated in figure 7.

Ascending velocity variations of water drop through inclined microchannel by applying a constant voltage to the active electrode toward the different angles of inclined microchannel toward the horizon surface is illustrated in figure 8. The gravity in the reverse direction of the drop ascending movement makes a reduction in the velocity. At equation (1), the gravity term, considering the direction of drop movement, applies an opposite force in the direction of movement, therefore, the reduction of the ascending velocity of the drop toward the top of the inclined microchannel is totally justifiable.

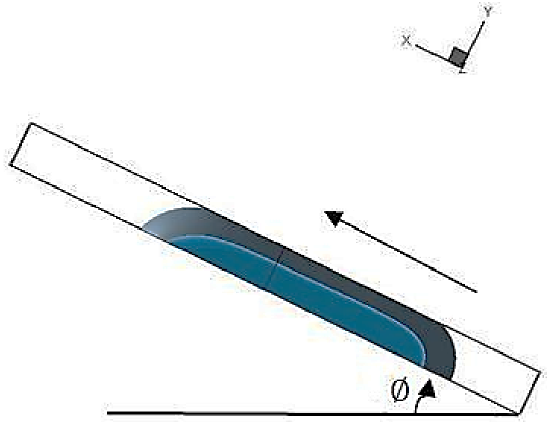


Figure 7: Schematic of definition microchannel inclined angle & motion direction.

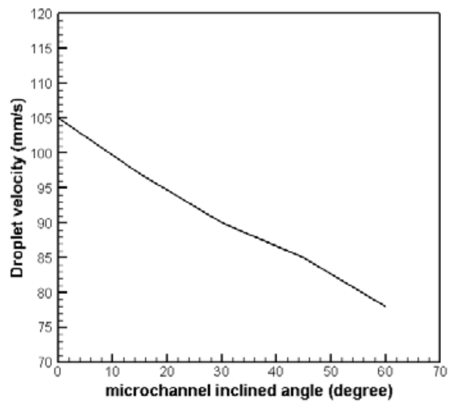


Figure 8: Droplet velocity vs. microchannel inclined angle.

Then, in order to find the amount of voltage threshold of drop movement under electrowetting in the inclined microchannel, a constant gradient angle ($\emptyset = 30^{\circ}$) is considered between the microchannel and the horizon surface. Then, the velocity of drop movement with the volume of $0.375\mu\mathrm{L}$ in the microchannel has been studied by changing the applied voltage to the active electrode. The drop velocity variations through microchannel with a gradient of 30° resulted from changing voltage applied to the active electrode is illustrated in the figure 9. It can be observed, according to the figure, that applied voltages less than 45.56V cause gravity to overcomes the electro static force which makes the drop to go toward the bottom of microchannel (the reason of negative velocity in this area, is the direction of the drop); in the voltage of 45.56V the electro static force is neutralized with the gravity so the drop remains motionless through the inclined microchannel. By applying voltages higher than 45.56V it is observed that, due to the excellence of electrostatic power over the gravity, the water drop in inclined microchannel goes to the top. As a result, the voltage in amount of 45.56V is introduced as the ascending movement of water drop in the volume of $0.375\mu L$ through the microchannel with the height of $250\mu m$ and the width of 0.5mm with the gradient angle of 30° toward the horizon. So this way we can report a voltage for the fluid drop movement threshold, for every microchannel gradient angle with the horizon surface.

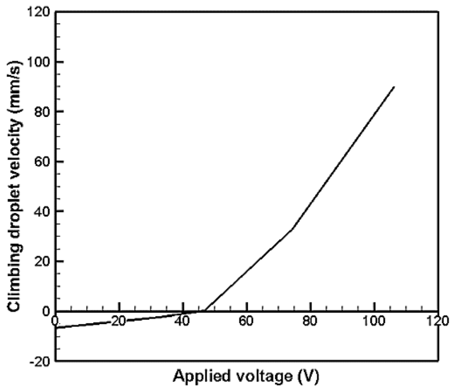


Figure 9: Droplet velocity in the channel vs applied voltage.

Conclusion

This study has discussed numerical simulation of fluid drop movement, by OpenFoam software, under electrowetting phenomenon through microchannel. Results achieved from the simulation of mercury drop establishment under electrowetting have been compared to available experimental results and the numerical simulation accuracy has been confirmed. Next, three dimensional simulation of water drop movement has been performed through microchannel under specific conditions. The height of microchannel and the gravity have been investigated as effective parameters in the velocity of fluid in microchannel under electrowetting. According to the results, an increase in the height of microchannel in order to increase the fluid velocity in microchannel has been suggested. The growth of the angle between microchannel and the horizon surface by applying a constant voltage to the active electrode causes a reduction in the ascending velocity of drop which is easily predictable in respect to the volume force of gravity in Navir–Stoks equation. An applied voltage as a threshold beginning to ascend has reported for the fluid drop in a constant angle of microchannel with horizon surface. The present study has been done as a prospect for more applied studies in the field of electrowetting.

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