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A numerical study on electrowetting-induced jumping and transport of droplet

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1. Introduction

Detachment and removal of droplets from a solid substrate is an essential component in several industrial and biological applications. It is an important procedure in self-cleaning [1], anti-dew [2, 3] and anti-corrosion [4] applications, where removal of droplets from the surface is required. The droplet jumping motion is essential for heat transfer systems to enhance dropwise condensation [5–7] and to promote thermal rectification [8, 9]. The condensate drops which form on the solid surface due to condensation, reduce the heat transfer between the surface and the vapour. Hence, removal of these condensate drops is vital to enhance heat transfer. In addition, detachment and removal of droplets is one of the salient operations in digital microfluidics applications [10, 11]. These applications involve manipulation and removal of droplets to perform mixing, transport and chemical reactions. Apart from its relevance to industrial processes, the basic science of the fluid dynamical aspects of an detaching droplet has attracted several researchers to explore this phenomenon. Therefore, understanding the mechanism of droplet jumping process from a solid surface is of great interest with a practical significance in optimising these applications.

To detach a droplet adhered to a solid substrate, the applied force should be greater than the threshold force with which the drop is attached to the solid surface. Different methods can be employed to actuate such forces leading to droplet detachment. Self-propelled jumping of droplets on superhydrophobic surfaces is observed in many natural water-repellent surfaces and engineering applications. The droplets on these surfaces merge and coalesce with the adjoining droplets. This results in the release of excess surface energy which primarily converts into the kinetic energy of the jumping droplet system. The first experimental study on self-propelled jumping of coalescence induced droplets was reported by Boreyko and Chen [2]. They performed experiments on superhydrophobic surfaces with droplet sizes ranging from 10 μm to 150 μm. The results indicated an increase in the vertical velocity of the droplet system with increase in droplet size. However, after reaching a maximum vertical velocity, a decrease in velocity is observed on further increasing the drop size. To establish a relationship for coalescence induced velocity based on the energy conservation of the coalescing droplets, theoretical analysis based on energy analysis was conducted by Wang et al. [12]. The relationship for the coalescence induced velocity was based on the balance between surface energy, kinetic energy and viscous dissipation. Farokhirad et al. [13] performed lattice Boltzmann simulations to investigate the effects of air inertia and viscosity on the jumping height of the droplet. The results showed that an increase in air viscosity inhibited circulation within the droplet and self-propelled jumping is not noticed. Increase in air inertia resulted in higher jumping heights of the droplet system. Liu et al. [14] performed two dimensional lattice Boltzmann simulations for self-propelled jumping of droplets on textured surfaces.

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Shi et al. [15] investigated three dimensional coalescence-induced droplet jumping behaviour on superhydrophobic complex textured surface by altering the wettability of the textured surface, changing the roughness of the textured surface, controlling the number and size of the droplets by the MRT pseudopotential lattice Boltzmann model.

Droplet detachment is also accomplished from vibrational motion of the solid substrate [16,17]. Kim [18] performed experiments to show that a liquid drop pendant from a solid surface can be effectively detached by vibrating the solid at specific frequency ranges with weak external vibrations. At these frequencies, the drop oscillation was found to exhibit resonant behaviour with the solid motion. A novel way to create a spray was outlined by James et al. [17]. They placed a liquid drop on a vertically vibrating solid surface which lead to the formation of waves along the droplet free surface. While secondary droplets were ejected above a certain critical forcing amplitude, for small forcing frequency, a single drop was ejected from the tip of the primary drop. Movement of mechanical parts can impose several restriction such as difficulties in integration and noise generation in many applications. Some researchers have employed electrostatic forces to disengage droplets from solid surfaces [18,19]. Roux et al. [18] observed continuous bouncing of the conductive droplet between the electrode plates when a uniform electric field is exerted. This uncontrolled back and forth motion of the droplet is controlled by coating the upper electrode with a dielectric layer and by adjusting the electric field direction. The experimental investigations of Koji et al. [19] revealed that a vertical electric field can induce a water droplet to jump up from a superhydrophobic surface. However, the authors insisted on the need of precise control of Coulomb forces to prevent droplet splitting.

Electrowetting has been established as one of the most widely used method for manipulation of liquid droplets [20]. In contrast to chemical and topographical modulations of the solid surface, electrowetting offers better contact angle variations and switching speeds. The droplets can be propagated freely on surfaces along programmable paths where they can be split, merged and mixed with higher degree of flexibility. Huang et al. [21] performed lattice Boltzmann simulations to study diverse droplet behaviours resulting due to spatio-temporal variations in surface wettability. They found that under certain conditions, the droplet displays rapid continuous unidirectional movement. Abdelgawad et al. [11] employed electrowetting technique to manipulate droplet on inclined, twisted and upside-down geometries. More recently, detachment of droplets from solid surfaces has been established through electrowetting [22–24]. Lee et al. [22] introduced droplet jumping by electrowetting and demonstrated the transport of sessile droplets to upper surfaces under diverse electrode configurations. Lapierre et al. [23] presented a technique to dewet droplets on superhydrophobic surfaces through periodic vibrations induced due to electrowetting actuation. This approach allowed them to investigate a large of superhydrophobic surfaces for electrowetting without droplet impalement. Employing square pulse signals in electrowetting actuations resulted in droplet detachment from hydrophobic surfaces [24]. When the pulse width is synchronous with spreading time, it is found that the droplet is detached more easily.

The contributions of this study is threefold. Firstly, we attempt to analyze the governing fluid dynamical aspects involved during wettability-induced droplet jumping. In addition to the experimental studies mentioned above, the present numerical simulations provide additional details of the dynamic flow field and various transient energy conversions which would help to elucidate the mechanism of droplet jumping. In order to optimise the design and efficiency of several microfluidic applications which involve droplet detachment and transport, it is imperative to have a basic understanding of the involved flow physics. In electrowetting actuation, the dynamics of the droplet motion is predominantly governed by the evolution of the moving contact line. The kinetics of the moving contact line in turn depends on the fluctuations of the voltage which govern the surface contact angle. In this work, we examine the influence of the nature voltage fluctuations (pulse characteristics) and resulting kinematic mechanisms of the moving contact line leading to different dynamical droplet behaviour. In this context, we evaluate the effect of various parameters like the nature of the actuating pulse and electrowetting number on the jumping dynamics of the droplet. Secondly, in several cases, it is required to transport droplet when the surrounding medium is not air. While the role of the ambient fluid density may not be prominent prior to jumping, it has a significant effect on droplet dynamics once it lifts-off the surface [25]. Hence, it is crucial to understand the role of the properties of the ambient environment on the dynamic evolution of the jumping droplet. The current work illustrates the effect of gas density and viscosity on the jumping process. Finally, we demonstrate the applicability of electrowetting induced droplet jumping method as an effective tool for droplet transport relevant in microfluidic applications. In this paper, we apply high density ratio based lattice Boltzmann method (LBM) [26] which is based on the Cahn–Hilliard diffuse interface theory for binary fluids. One of the distinct feature of LBM is its easily parallelizable nature which allows to model complex three dimensional simulations by employing advanced high performance computing techniques [27]. This method [26] is based on the model of He et al. [28] which has been further developed to account high density ratios through stable discretisation of the forcing term. The model has been applied for various multiphase flows problems such as droplet impact on wet walls [29,30], dry walls [31], buoyancy induced interfacial mixing [32–33], droplet slipping under shear flows [34] and bubble rise under buoyancy [35].

The remainder of the paper is organised as follows: Section 2 provides the details of the multiphase LBM and the geometry based contact line model. Section 3 briefly outlines the theory of electrowetting while Section 4 describes the problem specification and involved characteristic parameters. The discussion of the numerical results is provided in Section 5. Section 6 describes the regime classification of EW actuated droplet jumping. In Section 7 we demonstrate the applicability on EW-induced droplet jumping for droplet transport and mixing. Finally, we provide concluding remarks in Section 8.

2. Numerical method

In the present study, wettability induced droplet jumping dynamics have been simulated by employing a high-density ratio multiphase lattice Boltzmann method based on the formulation proposed by Lee and Lin [26]. Building upon our previous work [30], we have extended the solver to three dimensions [36,31] in order to investigate the dynamics of droplet jumping. The method employs two particle distribution functions to recover incompressible Navier–Stokes equation \( g_1 \) and a macro interface capturing equation \( f_\gamma \). The model adopts stress and potential forms of intermolecular forcing terms in the momentum equation and the equation for order parameter, respectively. Stable discretization schemes were proposed by Lee and Lin [26] to discretize the forcing terms in each collision step which helped in improving
where $\sigma$ is a constant related to the magnitude of surface tension. The surface tension force $\sigma$ is represented as
\[
\sigma = \frac{(\rho^m - \rho^v_0)^3}{6} \sqrt{2k_B}.
\]

The density of the fluid $\rho$, hydrodynamics pressure $p$ and the velocity $u$ are calculated by taking the moments of the corresponding distribution function:
\[
\rho = \sum_x f_x,
\]
\[
p = \sum_x \rho s^2_c + \frac{\delta t}{2} \rho \partial c^2_a - \rho \partial (\phi - \kappa v^2) \rho | \Gamma_x(u)|_{|x |}
\]
\[
u = \sum_x g_x \delta t \frac{\partial v}{\partial x}.
\]

The relaxation parameter $\tau$ is related to the kinematic viscosity $v = \tau c^2_0$, which can be calculated by a linear interpolation
\[
\tau = \tau_l - (1 - C) \tau_v.
\]

The relaxation times for liquid and vapour, respectively and $C$ is the composition approximated by
\[
C = \frac{(\rho - \rho^v_0)}{(\rho^m - \rho^v_0)}.
\]

Along with the consistent discretizations of the intermolecular forcing terms, the aforementioned two-phase LBE formulation provides necessary stabilization at high density and viscosity ratios. While the mixed difference scheme is used in the pre-streaming collision step, the second order central difference scheme is considered for the forcing terms in the post-streaming collision step. Further details on the discretization schemes can be found in [26].

For the wetting boundary condition, we employ the geometric formulation proposed by Ding and Spelt [37]. This geometric scheme has been also employed in the framework of LBM to investigate the dynamics of impacting droplet onto surface with varying wettability [36]. The procedure essentially involves updating the values of the order parameter (density in the present model) enforcing the following equation:
\[
\n \cdot Vp = - \tan (\frac{\pi}{2} - \theta) |Vp - (n Vp)n|
\]

The developed 3D solver based on the present model has been calibrated to evaluate fluid–fluid and fluid–solid interactions for both static and dynamic scenarios. Various benchmark cases such as verification of Laplace law for a stationary bubble, evaluation of equilibrium contact angle for a droplet resting on a solid surface and experimental comparison of the dynamic case of a droplet impacting on a solid surface have been outlined in our previous paper [36]. In the present study, droplet actuation by electrowetting is realised by varying the equilibrium contact angle. The next section outlines the details of the influence of applied voltage on contact angle which is observed in electrowetting.

### 3. Theory of electrowetting

When a drop is placed in contact with a solid surface, it drives towards its equilibrium configuration by capillary forces. The three phase contact line is balanced by the surface tension forces between pairs of phases forming an equilibrium shape characterised by the contact angle. This is determined by the Young’s law given as:

\[
D = \frac{4}{(\rho_m^m - \rho_v^m)} \sqrt{2k_B}
\]

where $k$ is a constant related to the magnitude of surface tension.
where $\sigma$, $\sigma_l$ and $\sigma_d$ are the liquid–gas, solid–gas and solid–liquid surface tensions, respectively. Lippmann’s original experiment dealt with direct metal and electrolyte interface [38]. However, in such situations, electrowetting based droplet actuation was applicable for very low voltages. Increase in voltage would lead to onset of the electrowet process. In current systems employing electrowetting for droplet control, the solid substrate is provided with a layer of dielectric material over which the droplet is placed. This is more commonly known as electrowetting on dielectric (EWOD) [20].

The presence of an insulating dielectric layer greatly reduces the capacitance of the system. When the electric potential is applied, formation of a layer of charged ions on the dielectric surface and subsequently a layer of oppositely charged ions in the liquid close to the surface takes place. This fringing field at the corners of the electrolyte droplet tends to pull the droplet closer to the substrate and thereby reduces the contact angle. From a thermodynamic point of view, the Gibbs free energy of a system is the minimum energy requirement to create a certain area of that surface and it consists of chemical and electrical components. The chemical component accounts for the natural surface tension of the solid–liquid interface without electric field. The relationship between the equilibrium static contact angle in an electrowetting system and applied voltage $V$ is expressed as

$$\cos \theta_{LV} = \cos \theta_y + \frac{\epsilon \varepsilon_0 V^2}{2d_y \sigma}$$

where $\theta_{LV}$ is the Lippmann–Young equilibrium contact angle, $d_y$ is the thickness of the dielectric layer, $\epsilon$ is the relative dielectric constant of the material and $\varepsilon_0$ is the dielectric constant of vacuum. The second term on the right-hand-side of the equation is known as the dimensionless electrowetting number ($\eta$), which is defined as the ratio of the strength of the electrostatic energy to the surface energy. This number ($\eta$) is always positive due to the voltage-squared term, hence electrowetting always decreases the Lippmann–Young contact angle from the equilibrium contact angle.

After providing a brief review on electrowetting theory, we next proceed to outline the characteristic parameters governing the droplet jumping process under electrowetting, which is the main subject of the present study. We quantify different characteristic parameters of the electric pulse and the relevant scales for normalisation followed by the details of the computational setup.

4. Characteristic parameters and computational setup

A spherical droplet with diameter $D_0$ is initialized on a solid surface such that the three phase contact line makes an angle $\theta_y = 140^\circ$ with the surface. Unless otherwise mentioned, the liquid–gas density ratio ($\rho_l$) and the viscosity ratio ($\mu_l$) are set to be 1000 and 50, respectively for subsequent calculations. However, the effect of viscosity ratio on the impact dynamics is considered later in the subsection where influence of drop viscosity is investigated. All the length scales are non-dimensionalized by the droplet diameter ($D_0$). The time and droplet velocity are non-dimensionalized with capillary inertial time ($\tau_c$) and velocity $u_c$ as defined below:

$$\tau_c = \sqrt{\frac{\rho_c D_0^2}{8 \sigma}}$$

$$u_c = \sqrt{\frac{2 \sigma}{\rho_c D_0}}$$

The size of the droplet of interest considered here, relevant to microfluidic applications, is of the order of micrometers which is smaller than the capillary length. For the parameters corresponding to water droplets, the Bond number is of the order $10^{-4}$, hence the influence of gravity can be assumed to be small. During the wettability-induced jumping process, the surface energy of the drop is converted into kinetic energy and a part of the energy is dissipated due to viscous effect. In order to investigate the transient energy variations involved during the jumping process, we monitor them in the current study. The surface energy is obtained from the free energy density model in our simulations:

$$E_s = \int_V \left( E_0 + \kappa |\nabla \rho|^2 \right) dV$$

where $E_0 = \beta (\rho - \rho^\text{surf})^2 (\rho - \rho^\text{diss})^2$. The free energy density has two components. The first term $E_0$ is the bulk energy related to the thermodynamics pressure by the equation of state. It models fluid component’s immiscibility and separates the fluid into two stable phases. The second component in Eq. (24) is the gradient energy which accounts for the diffusive interfacial region, where $\kappa$ is a parameter associated with the surface tension along the interface.

The dissipation function for a continuum fluid is defined as

$$\phi^* = 2 \left[ \frac{\partial u_x}{\partial x} \right]^2 + \left[ \frac{\partial u_y}{\partial y} \right]^2 + \left[ \frac{\partial u_z}{\partial z} \right]^2 + \left[ \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right]^2 + \left[ \frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x} \right]^2$$

The viscous dissipation is obtained as a time integration of the dissipation function

$$E_d = \int_0^\tau \rho_0 \omega \phi^* dt$$

where $Oh = \mu_l / \sqrt{\rho \sigma D_0}$ is the Ohnesorge number defined as the ratio of viscous forces to inertial and surface tension forces.

Fig. 1 shows the schematic representation of the problem setup. The wettability of the lower wall is controlled by electrowetting. When the voltage is applied, the contact angle decreases due to the reduction in interfacial surface tension. Periodic boundary conditions are imposed on the sides of the domain, while the equilibrium bounce back boundary conditions [39] are used on the top and bottom boundaries to impose the no-slip boundary conditions. It is to be noted that in the present work, we consider a constant contact angle model. A more realistic modelling approach would be to employ dynamic contact angle models [40,41], which however is not the focus of the current study. While analysing the dynamics of droplet jumping through electrowetting, we examine the following two key derived parameters:

(i) The contact diameter ($D_c$) which is defined as the distance between the two three phase contact points on the bottom wall extracted from the mid $y$-plane.

(ii) Average drop velocity ($U_z$) along the $z$-direction, which is given by:

---

Fig. 1. Schematic representation for electrowetting induced droplet transport.
\[
\frac{U}{\rho g} = \frac{\int_{V_{\text{drop}}} U_{\text{}} d\Omega}{\int_{V_{\text{drop}}} d\Omega} \tag{27}
\]

where \( \Omega \) encloses the region where the density (\( \rho \)) is greater than \( \rho' \) which corresponds to the mean density. Along with the above mentioned parameters, we also monitor the transient energy variations as defined previously. We perform grid independence test by comparing the maximum vertical velocity of the droplet (\( U_{\text{max}}^{\text{z}} \)) for \( Oh = 0.0179 \). A variation of less than 1\% in \( U_{\text{max}}^{\text{z}} \) is observed for \( Do = 50, 75 \) and 100. We notice that the interface profiles for \( Do = 75 \) and 100 nearly approaches each other, except small deviations at the bottom part of the droplet. It is worth mentioning that given the diffusive nature of the interface in phase field methods, resolution of the interface with enough mesh points plays an important role to capture the droplet dynamics accurately. This would in turn lead to a higher computational cost. However, advances in parallel adaptive mesh refinement techniques, which have been applied to resolve complex 3D multiphase flows [42], can reduce the excessive computational cost associated with the uniformly refined mesh throughout the domain. Based on the grid convergence test, the droplet diameter was set to be 75 lattice units for the simulations performed in this study hereafter.

5. Results and discussion

We next proceed to evaluate the effect of various parameters like pulse characteristics, electrowetting number, drop viscosity and properties of the ambient fluid on the dynamics of the jumping droplet. Finally, we will demonstrate the application of electrowetting based droplet actuation employed in microfluidic applications involving droplet transport and mixing.

5.1. Influence of pulse characteristics

Unlike previous studies using sinusoidal or trapezoidal waveforms [43] for electrowetting actuation, we consider square waveforms in the present study. Square pulse actuation has been found to be more effective and controllable for droplet jumping [22]. Fig. 3 shows the imposed square waveforms for (a) single pulse and (b) double pulse actuations, respectively. It is assumed that the voltage is applied at \( T^* = 0 \). As the voltage is applied, the contact angle of the lower wall is set to be \( \theta_{LY} \). The duration during which the voltage is applied is known as pulse width (\( T_P \)). After the duration of \( T_P \), the voltage is turned off and the surface contact angle is changed back to its initial value of \( \theta_Y \). In the case of DC EW actuation, there is a constant application of voltage to the solid.

Table 1

<table>
<thead>
<tr>
<th>( Do ) (in lattice units)</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{\text{max}}^{\text{z}} )</td>
<td>0.565</td>
<td>0.579</td>
<td>0.583</td>
</tr>
<tr>
<td>Relative error</td>
<td>3.08%</td>
<td>0.68%</td>
<td>–</td>
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substrate. During this phase, the droplet spreads and recoils to attain a configuration corresponding to the Lippmann–Young contact angle for the given voltage. However, in the case of AC EW actuation, the voltage is applied for a given pulse width and then turned off. During this period, the droplet is still in its spreading or receding phase and has not attained its equilibrium configuration. Double pulse actuation implies actuation of two successive AC pulses within a gap of the corresponding pulse width between them.

5.1.1. AC versus DC electrowetting actuation

The spreading and jumping behaviour of a droplet subjected to electrowetting (EW) depends on the nature of EW actuation. We consider droplet detachment by both DC and AC EW cases. Fig. 4 illustrates the temporal evolution of the droplet detachment process for (a) DC and (b) AC EW actuation scenarios. For the AC EW, a square pulse with $T_P = 2.22$, corresponding to the time taken by the droplet to spread to its maximum extent is considered. The spreading droplet is allowed to attain its equilibrium shape corresponding to $\theta_L = 60^\circ$ until $T^* = 8.27$, after which the contact angle is changed to $\theta_T = 140^\circ$ in the case of DC EW. At $T^* = 7.44$, the interface profile nearly attains its equilibrium shape as shown in Fig. 4 (a). As the surface wettability changes to $\theta = 140^\circ$, the droplet base begins to decrease sharply adjusting to the corresponding local curvature. As the base radius continues to decrease, an inversion in droplet morphology is observed from a broad base-narrow top configuration ($T^* = 8.44$) to a narrow base-wide top system ($T^* = 10.59$) owing to mass conservation. The base radius continues to decrease leading to droplet detachment from the substrate ($T^* = 12.58$). The sequence of events leading to droplet detachment from the surface for AC EW actuation are similar to that of observed for DC EW actuation. However, the notable difference between the two situations is the interface profiles of the droplet at the instant when the surface contact angle is changed to $\theta_T$. Unlike the case for the DC EW actuation, the droplet is in its maximum spread resembling a thin pancake like shape as shown at $T^* = 2.31$. The droplet shape undergoes greater vertical elongation in comparison to the corresponding droplet shapes for DC EW actuation. The last snapshots in Fig. 4(a) and (b) depicts the droplet shapes at $\Delta T^* = 4.47$ and 4.24 ($\Delta T^* = T^* - T_P$), respectively. We observe that the droplet in Fig. 4(b) lifts off to a greater height than that in Fig. 4(a). This illustrates the presence of higher kinetic energy for droplets detaching due to the AC EW actuation.

The kinetics of the above depicted droplet detachment behaviour is illustrated by the temporal evolution of the base diameter ($D_b$), as shown in Fig. 5. Fig. 5(a) and (b) outline the evolution of $D_b$ during spreading and recoiling phases, respectively. For the DC EW actuation, the base diameter $D_b$ increases initially to reach its maximum spread and undergoes recoiling during which it decreases. Eventually, it attains a steady value corresponding to $\theta_L$. The evolution of $D_b$ during the spreading phase shows a steady increase in its value. When the surface contact angle is changed to $\theta_T$ at $T^* = T_P$, the droplet begins to recede leading to decreasing $D_b$. We observe earlier droplet detachment for the AC EW actuation. This difference in droplet jumping behaviour can be explained by the surface energy stored inside the droplet system at $T^* = T_P$. When the droplet behaviour is observed under the DC EW actuation, after attaining its maximum spread it undergoes recoiling, during which some amount of the surface energy is converted into the kinetic energy of the recoiling droplet. This can be noticed from the evolution of $U_z$, as shown in Fig. 6.

After $\Delta T^* = -6.0$, we observe a gradual decrease in $U_z$ before it eventually becomes zero as the droplet attains its equilibrium configuration at $T^* = T_P$. The surface energy stored inside the droplet corresponds to its equilibrium shape. However, at $T^* = T_P$, the droplet undergoing the AC EW actuation is stretched to its maximum spread, resulting in higher storage of surface energy inside the droplet system. As the contact angle changes at $T^* = T_P$, the droplet system begins to minimise its it free energy. The stored surface energy is converted into the kinetic energy resulting in increase in $U_z$. The droplet undergoing the AC EW actuation has higher maximum $U_z$ value due to increased conversion of the stored surface energy into kinetic energy. The observations indicate that under AC EW actuation, the droplet acquires greater jumping velocities as compared to the DC EW actuation. Hence, it would be viable to employ the AC EW based jumping for droplet transport in microfluidic applications.

5.1.2. Effect of pulse width

The duration of the applied voltage is determined by the pulse width ($T_P$), which in turn governs the spreading behaviour of the
droplet. Hence, it is important to investigate the role of $T_R$ on the dynamics of droplet detachment. To investigate the influence of $T_R$, we set $\theta_{LY} = 60^\circ$ and define a parameter $T_{R_p} = (T_R/T_{R_{ho}})$, where $T_{R_{ho}}$ is the time taken for the droplet to spread to its maximum extent for $\theta_{LY} = 60^\circ$. Fig. 7(a) illustrates the temporal evolution of $D_c$ for three different $T_{R_p}$.

It shows that $D_c$ increases with increase in $T_{R_p}$. For $T_{R_p} = 0.5$, the surface contact angle is changed before the droplet attains its maximum spread and subsequently its lifts off the substrate earlier compared to the case with $T_{R_p} = 1.5$. The droplet attains its maximum velocity in Z-direction for $T_{R_p} = 1.0$ as observed from Fig. 7(b). Since for $T_{R_p} = 1.0$, the contact angle is changed to $\theta_L$ when the droplet is in its maximum spread, the surface energy converted into the kinetic energy of the recoiling droplet is also higher. However, for $T_{R_p} = 0.5$ and 1.5, the contact angle is changed during the capillary spreading and receding phases, respectively. Fig. 8 illustrates the velocity field inside the droplet and the surrounding fluid near the interface for (a) $T_{R_p} = 0.5$ and (b) $T_{R_p} = 1.5$. As the droplet interface curvature at the three phase contact line changes due to change in contact angle, we observe flow circulation near this region for both the cases as shown as in Fig. 8. However, the notable differences in the velocity field are observed in the upper region inside the droplet. For $T_{R_p} = 0.5$, we observe the velocity vectors pointing radially downwards due to the inertia attained by the droplet liquid during capillary spreading until $T' = T_R$. The drag induced on the surrounding fluid by this downward moving droplet interface sets up a vortex near the upper region. Due to the opposing sense of movement of the interface near the contact line and the upper bulk region, the corresponding vortex patterns move in anti-clockwise and clockwise directions, respectively. The velocity vectors in the upper bulk region move in radially upward direction and have the same sense of motion with the flow field near the contact region as observed in Fig. 8(b). However, the velocity magnitude near the contact region is higher compared to the velocity magnitude in the bulk region.

5.1.3. Double pulse actuation

We next investigate the influence of double pulse actuation on the dynamics of droplet detachment. Two square pulses with a pulse width $T_p = 2.22$ were triggered at equal intervals. Fig. 9 illustrates the droplet detachment process at two different time instants for (a) $\theta_{LY} = 40^\circ$ (b) $\theta_{LY} = 60^\circ$ and (c) $\theta_{LY} = 80^\circ$. After $T' = 4.44$, the wettability of the surface changes to $\theta_{LY}$ and the section of the droplet in contact with the surface begins to spread. However, as a result of the actuation of the previous pulse, the bulk of the droplet recoils in the upward direction owing to its inertia. This results in the formation of a neck region between the uprising droplet bulk and the spreading contact region. This neck region is clearly observed for all the cases, as shown in Fig. 9. However, the length of the neck is found to increase with decreasing $\theta_{LY}$. As the contact region continues to spread and the bulk droplet continues to rise, the neck region elongates and eventually breaks and forms a satellite droplet resting on the surface. This volume of the satellite droplet increases with decrease in $\theta_{LY}$ as shown in the bottom row of Fig. 9. This can be attributed to the increase in contact diameter at lower $\theta_{LY}$ which lead to greater adhesion forces between the droplet and the solid substrate. The current results show qualitative similarities with the experimental investigation.
conducted by Lee et al. [24]. They observed the formation of satellite droplet when the droplet is actuated using the double square pulse.

5.2. Effect of Lippmann–Young contact angle

Apart from the nature of actuating pulse, the behaviour of the jumping droplet also depends on the applied voltage. The extent to which the droplet spreads depends on the applied voltage, which in turns governs the Lippmann–Young contact angle ($\theta_Y$). We next investigate the influence of $\theta_Y$ on the droplet jumping behaviour. Fig. 10(a) presents the time evolution of the contact diameter for different $\theta_Y$. The pulse width $T_P$ is fixed to be 2.22 for all the simulations considered in this subsection. We observe that the rate of evolution of $D_c$ increases as $\theta_Y$ decreases. After the contact angle changes to $\theta_Y$ at $T = T_P$, a sharp decline in $D_c$ is noticed which eventually converges to zero as the droplet lifts off the surface. The present numerical results do not indicate a general trend in the lift-off time with $\theta_Y$. While the cases with $\theta_Y = 40^\circ$ and $100^\circ$ lift off nearly at the same time, the cases considered with intermediate $\theta_Y$ detach earlier. The lift-off time for the droplet for different $\theta_Y$ depends on the interplay between the surface energy stored in the stretched droplet and the magnitude of $D_c$ at $T = T_P$. Since the droplet is stretched to a greater extent, it has higher surface energy stored inside the droplet system for $\theta_Y = 40^\circ$ when compared to the droplet with $\theta_Y = 100^\circ$. Hence, the droplet retracts faster due to its increased kinetic energy. However, as it covers a larger contact area unlike the slowly retracting droplet with $\theta_Y = 100^\circ$, the lift-off time for both the cases is nearly the same. This behaviour is indicated from the temporal evolution of $U_Z$ shown in Fig. 10(b). We observe increase in $U_Z$ as $\theta_Y$ decreases due to a larger conversion of surface energy into the kinetic energy of the droplet system. Fig. 11 shows the transient variation of (a) surface energy ($E_s$) and (b) viscous dissipation ($E_D$) for different $\theta_Y$. As discussed above, for $\theta_Y = 40^\circ$ the droplet undergoes large deformation from its initial configuration. This excess deformation results in sharp rise in $E_s$ compared to the other two cases considered. The transient variation of $E_D$ also reveal the oscillations which the drop undergoes after it lifts-off the surface. As the droplet morphology changes from prolate to oblate shapes, we observe corresponding oscillations in $E_s$ as time proceeds. These oscillations in surface energy are greater for lower $\theta_Y$. Time variations of viscous dissipation shows an increase in $E_D$ as $\theta_Y$ decreases. This observation can be attributed to the fact that with increase in droplet deformation, the resistance offered by the viscous stresses to the deforming fluid increases. For $\theta_Y = 40^\circ$, the droplet undergoes sharp spreading and intense recoiling. Hence, a sharp rise in $E_s$ is noticed before it eventually lifts off the surface.

5.3. Effect of drop viscosity

The mobility of the droplet during its spreading and receding phases is hindered by viscous forces. Hence, it will be interesting to investigate the effect of viscosity on the jumping behaviour of the droplet subjected to electrowetting. With increase in Ohnesorge number, viscous effects begin to dominate the dynamics of droplet jumping. We perform numerical simulations for $Oh$ numbers ranging from 0.0179 to 0.179. Fig. 12 illustrates the time resolved images of the droplet behaviour which corresponds to those shown in Fig. 4(b), except that the $Oh$ number considered in this case is larger ($Oh = 0.179$). The figure clearly indicates the influence of increased viscous effects leading to suppression of droplet jumping in contrast to the inertia dominated process shown in Fig. 4(b). At $T^* = 0.99$, the droplet has a cusp-like structure on the top as the base continues to expand radially for $Oh = 0.0179$. This results due to the upward propagation of the capillary wave as the droplet spreads across the surface. However, increase in droplet viscosity leads to higher viscous damping resulting in a smooth droplet profile for $Oh = 0.179$. The droplet undergoes higher radial expansion before it begins to recede after $T^* = T_P$ for $Oh = 0.0179$ as observed from the corresponding images at $T^* = 2.31$. While the droplet detaches and lifts off the surface in the last two snapshots shown in Fig. 4(b), the droplet recedes and undergoes secondary spreading for the corresponding time instants observed in Fig. 12.

To further illustrate the effects of viscosity the temporal evolution of instantaneous contact diameter and drop velocity ($U_Z$) are shown in Fig. 13. Before $T^* = T_P$, we observe that both $D_c$ and the maximum contact diameter increases with decrease in $Oh$. However, a reversal in this trend is observed as the droplet

Fig. 7. Time evolution of droplet (a) contact diameter and (b) Z-component of drop velocity for different pulse width ($T_P$): $\theta_Y = 60^\circ$. 
continues to recoil and \( D_c \) decreases. This can be explained by the increased viscous resistance to the movement of droplet liquid during the spreading and receding stages with increase in \( \text{Oh} \) number. For the cases considered, apart from the case with \( \text{Oh} = 0.179 \), we observe the outcome of droplet detachment. The lift-off time is found to increase with increase in \( \text{Oh} \). The delay in lift-off time and suppression of droplet jumping can be attributed to decrease in surface energy stored inside the droplet at \( T = T_r \) as \( \text{Oh} \) is increased. Similarly, the amount of surface energy, which is converted into kinetic energy, lost due to viscous dissipation increases with increase in \( \text{Oh} \). This results in decrease in the evolution of \( U_z \) as observed from Fig. 13(b).

Fig. 14(a) illustrates the transient evolution of surface energy for different \( \text{Oh} \) numbers. With increase in \( \text{Oh} \), the temporal evolution of \( E_s \) decreases. Increase in droplet viscosity results in higher viscous resistance to the moving fluid element which in turn impedes droplet deformation. In contrast to the other two cases, the droplet with \( \text{Oh} = 0.0179 \) continues to oscillate after it lifts off the surface. Fig. 14(b) further asserts the role of drop viscosity resulting in increase in viscous dissipation with increasing \( \text{Oh} \).

### 5.4. Effect of the properties of ambient fluid

The role of the ambient fluid on the behaviour of the jumping drop becomes important after the droplet detaches from the surface. Hence, it is important to understand the influence of the properties of the surrounding fluid on the droplet jumping dynamics. Mukherjee and Abraham [29] investigated the influence of surrounding gas density and viscosity on the crown dynamics of the splash formed when single droplet impacts a thin film. They observed a delay in crown breakup and decrease in rate of increase of crown radius and height with increase in surrounding gas density. They attributed this to the effect of increased drag imposed by the surrounding medium on the crown. We first investigate the influence of gas density \( (\rho_g) \) by varying the density ratio, \( \rho_s = (\rho_s/\rho_g) \). The other parameters are kept fixed as those considered for the case shown in Fig. 4(b). The kinematic viscosity ratio is kept constant at 0.05. It is expected that at high gas densities, the influence of gas on the jumping behaviour will be greater due to the increased effect of drag on the droplet by the surrounding medium. This is illustrated from the time evolution sequence of the droplet shapes shown in Fig. 15 for \( \rho_s = 20 \) (top row), \( \rho_s = 100 \) (middle row) and \( \rho_s = 1000 \) (bottom row). As the droplet begins to recede and attain a spherical shape due to surface tension forces after \( T = T_r \), the drag induced on the droplet increases with increase in \( \rho_g \). At \( T = 4.96 \) we observe that while the droplet is detached from the surface for \( \rho_s = 100 \), the droplet is still in contact with the surface for \( \rho_s = 20 \). The droplet undergoes greater shape deformation for \( \rho_s = 100 \) compared to the nearly spherical droplet shapes for \( \rho_s = 20 \) at \( T = 5.46 \) and 6.12. It is also noticed that at the same instant the droplet jumps to a greater height when the surrounding fluid is less dense due to the lower resistance to the movement of the droplet as it penetrates a lesser dense ambient fluid. Next, let us consider the evolution of \( D_c \) and \( U_z \). In Fig. 16(a), the evolution of \( D_c \) is compared for different density ratios. It is observed that during the initial capillary driven spreading phase the evolution of \( D_c \) is fairly independent of the gas density \( \rho_g \). As time proceeds, with decrease in \( \rho_g \), i.e. increase in the gas density, the rate of increase in \( D_c \) decreases. The lift-off time is found to increase as \( \rho_g \) decreases. We notice that for \( \rho_g = 10 \) the droplet does not detach from the surface and undergoes secondary spreading. The influence of \( \rho_g \) on \( U_z \) is shown in Fig. 16(b). The maximum \( U_z \) attained by the droplet increases with increase in \( \rho_g \), which reiterates the influence of the drag induced by the denser surrounding fluid on the jumping droplet. To investigate the influence of ambient fluid viscosity \( (\mu_s) \), we present simulation results for three different viscosity ratio \( (\mu_s) \): 15, 30 and 50. It is to be noted that changing \( \mu_s \) corresponds to changing \( \tau_s \) while other simulation parameters are kept constant. Fig. 17 illustrates the influence of viscosity ratio on the temporal evolution droplet profiles. We observe that the droplet height for \( \mu_s = 15 \) is nearly constant in the shown snapshots and the variation is observed only in the bottom region of the droplet due to the receding motion of the contact line. This elucidates the resistance offered by the viscous forces of the ambient fluid on the recoiling droplet surface. However, for \( \mu_s = 30 \), we observe that inertial forces attained by the recoiling droplet as a result of the conversion of surface energy into kinetic energy is large enough to overcome the resistance offered by the ambient fluid. Subsequently, this results in droplet detachment and jumping. With increase in \( \mu_s \), the rate of evolution of \( D_c \) and
$U_z$ decreases and increases, respectively as shown in Fig. 18. Increased ambient fluid viscosity results in increased viscous drag on the receding droplet.

6. Kinematic stages of EW-actuated jumping droplet

To further classify regimes of the jumping process shown in Fig. 4(b), temporal evolution of droplet velocity field is shown in Fig. 19. We partition the entire jumping process into four stages: The first stage is (I) the capillary spreading stage during which the liquid mass inside the droplet moves downwards under the action of capillary forces leading to radial expansion of the droplet. A circulatory flow pattern sets up around the droplet due to the drag induced by the downward moving droplet interface on the surrounding fluid as shown at $T^* = 0.99$ in Fig. 19(a). The next stage (II) is the curvature switching stage, during which the local interface curvature near the contact line changes due to switching of the contact angle from $\theta_{LY}$ to $\theta_Y$. The sudden increase in local curvature leads to greater accumulation of droplet liquid inside the peripheral rims. This creates large surface tension forces resulting in accelerated radially inward flow. The sharp change in direction in

![Fig. 9. Time evolution images of EW process with double pulse actuation for (a) $\theta_{LY} = 40^\circ$ (b) $\theta_{LY} = 60^\circ$ and (c) $\theta_{LY} = 80^\circ$.](image)

![Fig. 10. Time evolution of droplet (a) contact diameter and (b) Z-component of drop velocity for different $\theta_{LY}$.](image)
the movement of the contact line leads to the formation of a vortex pattern near the contact edge as observed from Fig. 19(b). The liquid inside the droplet continues to move in radially upward direction under the restraining influence of surface tension forces. The liquid velocity inside the droplet is higher in the upper region of the droplet compared to the base region as observed in Fig. 19(c). This results in vertical elongation of the droplet and the contact diameter continues to decrease resulting in the detachment stage.

![Image of droplet evolution](image-url)

**Fig. 11.** Time evolution of droplet (a) surface energy ($E_s$) and (b) viscous dissipation ($E_v$) for different $\theta_{LY}$.

![Image of droplet evolution](image-url)

**Fig. 12.** Time evolution images of EW process identical to those of Fig. 4(b) except for a larger $Oh = 0.179$.

![Image of droplet evolution](image-url)

**Fig. 13.** Time evolution of droplet (a) contact diameter and (b) Z-component of drop velocity for different Ohnesorge number ($Oh$); $\theta_{LY} = 60^\circ$. 

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(III) of the jumping process (Fig. 19(d)). The high magnitude of the velocity vectors in the lower elongated region, which forms a cusp-like shape, shown in Fig. 19(d) indicate the fast retraction of the lower region due to interfacial tension. In the final stage (IV), the droplet velocity continues to decrease due to drag induced by the ambient fluid and it attains a spherical shape after some oscillations.

7. Application to EW-induced droplet jumping for transport and mixing

Manipulation and transport of droplet is an essential constituent in digital microfluidic applications. In this subsection, we investigate the transport of a droplet subjected to electrowetting, from the bottom surface to the top surface. Fig. 20 illustrates
Fig. 16. Time evolution of droplet (a) contact diameter and (b) Z-component of drop velocity for different gas densities at $\theta_{LR} = 60^\circ$.

Fig. 17. Time evolution images of EW process for two representative viscosity ratios $\mu_r = 15$ (top row) and $\mu_r = 30$ (bottom row).

Fig. 18. Time evolution of droplet (a) contact diameter and (b) Z-component of drop velocity for different gas viscosities with $\rho_r = 1000$: $\theta_{LR} = 60^\circ$. 
droplet transport from the bottom surface to the top plate with confinement ratios (CR) 1.0 (top row) and 2.0 (bottom row). The confinement ratio is defined as the ratio of the distance between the two plates and the droplet diameter. The wettability of the upper surface is fixed at $h = 90/176$. For CR = 1.0, we observe that the droplet is transferred to the upper plate by forming a liquid bridge. Owing to the low confinement ratio, the upper region of the recoiling droplet attaches to the upper surface leading to the formation of a liquid bridge. As time proceeds, the droplet contact area on the upper surface increases while the one on the bottom surfaces decreases. This is attributed to the higher wettability of the upper plate compared to the bottom surface. This is observed from the

![Figure 19](https://example.com/fig19.png)

**Fig. 19.** Instantaneous velocity field along the symmetry $Y$-plane at different time instants: $\theta_y = 60^\circ$. 
reversal in broad base and narrow top layout of the liquid bridge at $T^* = 3.33$ to the narrow base and broad top layout at $T^* = 4.46$. Once transported to the upper surface, the droplet attains its equilibrium configuration corresponding to the wettability of the upper wall. This way of droplet transport through formation of a liquid bridge is termed as the droplet transport in mode A. With increase in confinement ratio, the droplet transport occurs distinctly different termed as mode B, where we observe that the droplet detaches completely from the substrate and is airborne ($T^* = 5.79$). Subsequently, it is transported to the upper surface as observed in the snapshots shown in the bottom row of Fig. 20 for $CR = 2.0$.

Certain digital microfluidic applications require the transport and merging of droplets in order to perform a chemical reaction. In these applications, each droplet which contains a chemical reagent, interacts and coalesces to produce precipitates as the result of the chemical reaction. Droplet manipulation through electrowetting can be employed to actuate such operations leading to chemical analysis and synthesis. We next demonstrate various steps involved during this process in Fig. 21. To visualise the internal flow evolution during droplet impact and coalescence, different coloured passive tracer particles are seeded inside the two droplets. The evolution of
8. Concluding remarks

In this work we employed a high-density ratio based lattice Boltzmann method and performed three-dimensional simulations to investigate the evolution dynamics of electrowetting-induced droplet jumping. A geometry based contact angle formulation has been used to model the three-phase contact line. The effect of voltage pulse characteristics, droplet viscosity and fluid properties of the surrounding medium on the droplet jumping was investigated. Details of transient energy variations among surface energy and viscous dissipation were provided. The main conclusions can be summarised as follows:

(i) The jumping behaviour has been found to be strongly dependent on the nature of electrowetting actuation. A pulse width corresponding to the time taken for maximum spread would lead to higher maximum jumping velocities when compared to other pulse widths. Formation of satellite droplets were observed for the cases involving double pulse actuation.

(ii) Increase in applied voltage provided greater initial droplet spreading. This resulted in higher transient variations of the surface energy and the viscous dissipation. Subsequently, higher lift-off velocities were observed for the cases with lower \( \theta_0 \).

(iii) Depending upon the kinetic evolution of the three-phase contact line, the entire droplet jumping process is classified into four regimes, namely: capillary spreading, curvature switching, detachment, and spherical equilibrium.

(iv) The density and viscosity of the surrounding medium was found to cause a significant influence in determining the final outcome droplet jumping. For higher gas densities, an increase in droplet lift-off time was observed and in some case droplet jumping was suppressed.

(v) For electrowetting driven droplet transport, two different modes of transport were identified based on the confinement ratio. Mode A corresponds to droplet transport through the formation of a liquid bridge. In mode B, the droplet is completely detached from the bottom surface and is airborne before it is transported to the upper plate.

The results and findings indicate that electrowetting based droplet lift-off method can be used as a useful tool in microfluidic applications. The effect of gravity has been neglected in this study which will induce additional complex dynamics into large jumping droplets. This remains to be explored in future study.

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References

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**References**


