Proceedings of the 24th UK Conference of the
Association for Computational Mechanics in Engineering
31 March – 01 April 2016, Cardiff University, Cardiff

Two Droplets interaction on substrate

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ABSTRACT

Dynamics of two droplets interactions on a substrate (droplet impact on a sessile droplet) are numerically investigated using OpenFOAM. The impact speed, location of the impacting droplet, viscosity and surface tension were varied in the numerical studies. We found that when the surface tension dominates the flow, the mass canter of two droplets moves to impacting droplet side. When the inertia dominates the flow, the mass centre moves to the opposite direction.

Keywords: *two droplets; composite location; mass centre; OpenFOAM.*

1. Introduction

Accurate and controlled deposition of droplets on solid surfaces or solid surface with another pre-located sessile droplet is a principle in many of industrial processes or applications such as solid inkjet printing, micro-fabrication, rapid prototyping and electronic packaging [1]. Droplets in touch must overlap and coalesce during the impact process to avoid breaks in the pattern being fabricated. However, surface tension-driven flows that happen when contacted droplets touch can shift droplets location after they have been deposited and such unpredictable movements may make lines break or vary in thickness. Although great progress has been made in the recent coalescence studies on a solid substrates, there are still a few issues to be addressed in the context of its wide applications. To the best of our knowledge, no information in literature on the trend of final footprint location between two consecutively deposited drops which is limited on the variety of impact speed at different lateral displacement, substrate wettability and liquid parameters. The contributions of this work are to study the location trend at different impact velocities, liquid properties, surface wettability and centre to centre displacements. Composite droplet edges will be tracked with time at one displacement case and different velocities to identify coalescence mechanism and its effect on final location.

2. Numerical method and setup

A hemispherical cap sessile droplet deposited with initial diameter D_s=4.4 mm, and located in a steady flow field with static contact angle equal 63°. Glycerol-water mixture liquid used here with density ρ=1220 kg/m^3, viscosity μ=85.8 mPa.s, and surface tension σ=67.1 mN/m. computational domain opened to atmospheric air at 23C° presenting no walls except substrate showing no boundaries influence on the droplet dynamics. A spherical droplet with initial diameter D_o=2.8 mm, generated right to sessile for an overlap ratio $\lambda = 1 - L/D_s$ [1] defined as in Fig.1 and given an impact speed U. The computational domain has given zero initial condition, while the boundary condition was no slip for velocity at substrate and zero gradient for other geometrical boundaries. For pressure, zero gradients applied for substrate, total pressure equal zero are applied on other boundaries. The mesh used was 166*166*45=1,240,020 cells for a domain size 14*14*3.8 (mm) in x, y and z direction respectively. Cell size Δx is $8.4*10^{-5}$, which provides 52 mesh nodes for sessile and 34 nodes for impacting droplet. This mesh resolution considered high enough for our physical demands and our resources abilities.
The governing equations for the two isothermal, incompressible, and immiscible fluids include the continuity, momentum, and interface capturing advection equations based on the VOF method:

$$\nabla . \vec{u} = 0 \quad (1)$$

$$\rho \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} . \nabla \vec{u} \right) = -\nabla p + \nabla . (2\mu S) + \vec{F}_\sigma \quad (2)$$

$$\frac{\partial\alpha}{\partial t} + \nabla.(\vec{u}\alpha) + \nabla.[\vec{u}_r\alpha(1-\alpha)] = 0 \quad (3)$$

Where ρ is the fluid density, $\vec{u}$ the fluid velocity vector, S the viscous stress tensor defined as $S_{ij} = (\partial_i u_j + \partial_j u_i)/2$, μ is the dynamic viscosity, p is the scalar pressure, and $\vec{F_\sigma}$ is the volumetric surface tension force. The volume fraction function α is used to represent a space mesh cell whether is occupied by the dispersed phase or the continuous phase. When the cells are full of the dispersed phase, the value of α is unity; the continuous phase corresponds to zero; when the mesh cells contain both the dispersed phase and the continuous phase, the value of α is between 0 and 1, which denotes an interface between the two phases. $\vec{u}_r$ Is the liquid–gas relative velocity, compressing the interface to improve its resolution [2]. The term α (1- α) limits the effect of the $\vec{u}_r$ to the interface region. Moreover, $\vec{u}_r$ can be calculated as follows:

$$\vec{u}_r = min\left(C_\alpha|\vec{u}|, max(|\vec{u}|)\right)\frac{\nabla\alpha}{|\nabla\alpha|} \quad (4)$$

Where the default value of $C_\alpha = 1$ was used; however, a larger value of C_α can enhance the compression of the interface. The boundedness of α function is guaranteed by a special solver named Multidimensional Universal Limiter for Explicit Solution (MULES) [3]. A new level set field is introduced to provide a more precise interface reconstruction and then reduce the parasitic currents. The LS field is estimated from the VOF field in each time step by $\emptyset = (2\alpha - 1)\Gamma$, Γ is a small non-dimensional number whose value depends on the mesh step size (Δx) at the interface of the two fluids, and it is defined as Γ = 0.75Δx [4]. The LS field is corrected by solving the re-initialization equation:

$$\frac{\partial\emptyset}{\partial t} = sign(\emptyset)(1 - |\nabla\emptyset|) \quad (5)$$

Where $\emptyset$ should satisfy $|\nabla\emptyset| = 1$ by its definition. The normal vector of the interface $\hat{n} = \nabla\emptyset/|\nabla\emptyset|$ can be accurately determined due to the continuity of the LS function. Thus, more precise and smoother interface curvature $\kappa = \nabla\cdot\hat{n}$ can be obtained. Based on the Continuum Surface Force (CSF) model [5], the volumetric surface tension force can be calculated as:

$$\vec{F_\sigma} = \sigma\,\kappa(\emptyset)\delta(\emptyset)\nabla\emptyset \quad (6)$$

Where σ is the surface tension coefficient, and δ is the Dirac function used to limit the influence of the surface tension to a narrow region around the interface. The function of δ is cantered at the interface and takes a zero value in both fluids as:

$$\delta(\emptyset) = \begin{cases} 0 & |\emptyset| > \varepsilon \\ \frac{1}{2\varepsilon}\left(1 + cos\left({}^{\pi\emptyset}/_{\varepsilon}\right)\right) & |\emptyset| \le \varepsilon \end{cases} \quad (7)$$

Where ε is the interface thickness which is chosen as ε = 1.5Δx. The physical properties and the fluxes across the cell faces can be defined using a smoothed Heaviside function:

$$H(\emptyset) = \begin{cases} 0 & \emptyset < -\varepsilon \\ \frac{1}{2}\left[1 + \frac{\emptyset}{\varepsilon} + \frac{1}{\pi}sin\left(\frac{\pi\emptyset}{\varepsilon}\right)\right] & |\emptyset| \le \varepsilon \\ 1 & \emptyset > \varepsilon \end{cases} \quad (8)$$

$$\rho = \rho_g H + (\rho_l - \rho_g)H \quad (9)$$

$$\mu = \mu_g H + (\mu_l - \mu_g)H \quad (10)$$

Results and discussion

Three overlap ratios **λ** = 0.5, 0.34 and 0.18 respectively are implemented in this study as shown in Fig.2. Increasing impact velocity expected to force the final composite droplet to be located on the opposite side of impact. From results, for small impact velocity, droplet composite location was moving gradually towards impact direction (to right), this trend changed at specific critical velocity and composite located away from direction of impact for higher value of velocity. Fig 3 shows the final (steady state, T=0.5s) edges and mass centre location at different values of velocity compared with the mass centre location of two droplets at zero condition for case **λ** = 0.34. Comparing mass centre at before impact, mass centre always located to the right side for a velocity range U= 0.2 - 1.5(m/s). We noticed max location to the right at a critical impact speed U=0.5(m/s) where location trend deflected to the left but still located at the right side of initial mass centre. Mass centre located to the left side of initial mass centre for U=1.5(m/s) and above. To understand the reason behind such non trivial trend of composite location, the right and left edge displacement $X_L, X_R = |d_{L,R}|/D_S + L$ [1] of composite droplets have been tracked with time as shown in Fig.4. For velocity range U= 0.2 - 0.5 (m/s), tracking right edge with time showed spread to right, this spread increase due to increasing velocity. The left edge stayed pinned with substrate showing no spread because of no sensible effect reached from the impact droplet within this range of velocity.

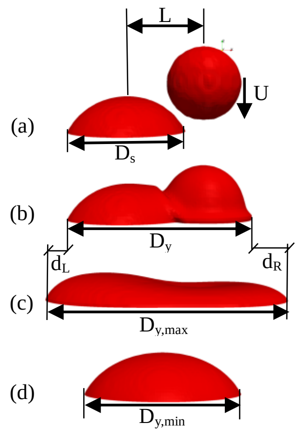

Figure 1: Deposition of two droplets on a solid surface (a); Spread length Dy (b); maximum spread length Dy,max (c); minimum spread length Dy,min (d).

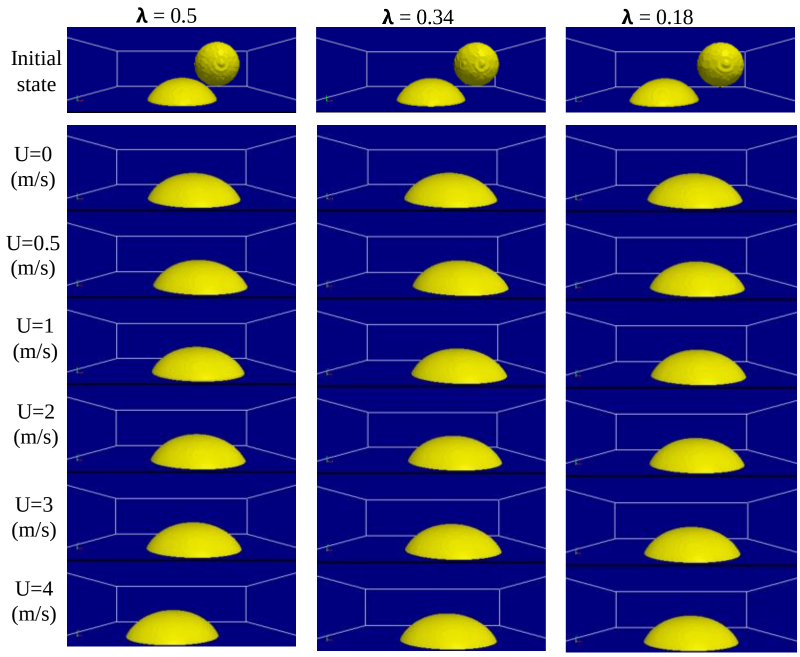

Figure 2: Contour of composite of two droplets at steady state for three different overlap ratios (**λ**) and different impact speeds.

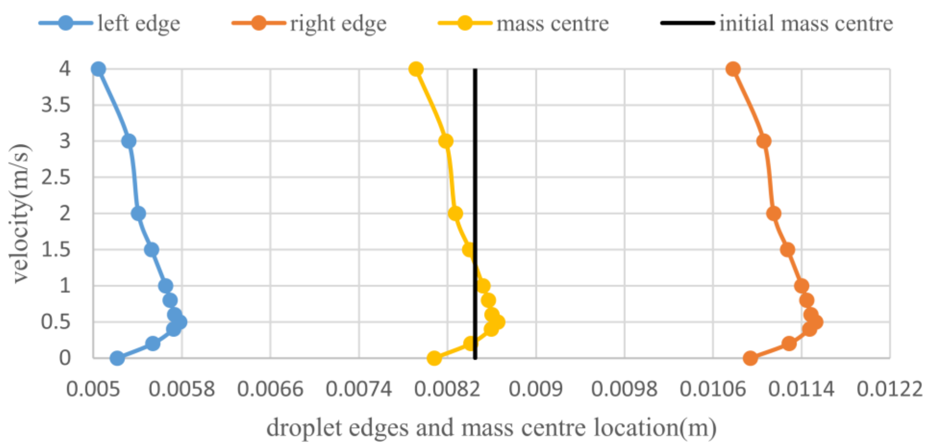

Figure 3: Final edges and mass centre location of composite droplets at different impact speed.

When maximum spread reached, capillary forces effected to recoil the composite due to surface tension.

This recoiling reflected on retracting both right and left edges and considered the reason of locating composite droplet on the side of impact droplet. For bigger impact velocity (U > 0.5 m/s), impact droplet influenced on the left edge of sessile due to bigger liquid wave transferred from the right. Sessile left edge unpinned and exhibited spread to the left, this spreading increases with bigger impact velocity. Sessile left edge unpinned and exhibited spread to the left, this spreading increases with bigger impact velocity. Recoiling due to surface tension represented in retracting of both edges towards equilibrium condition.

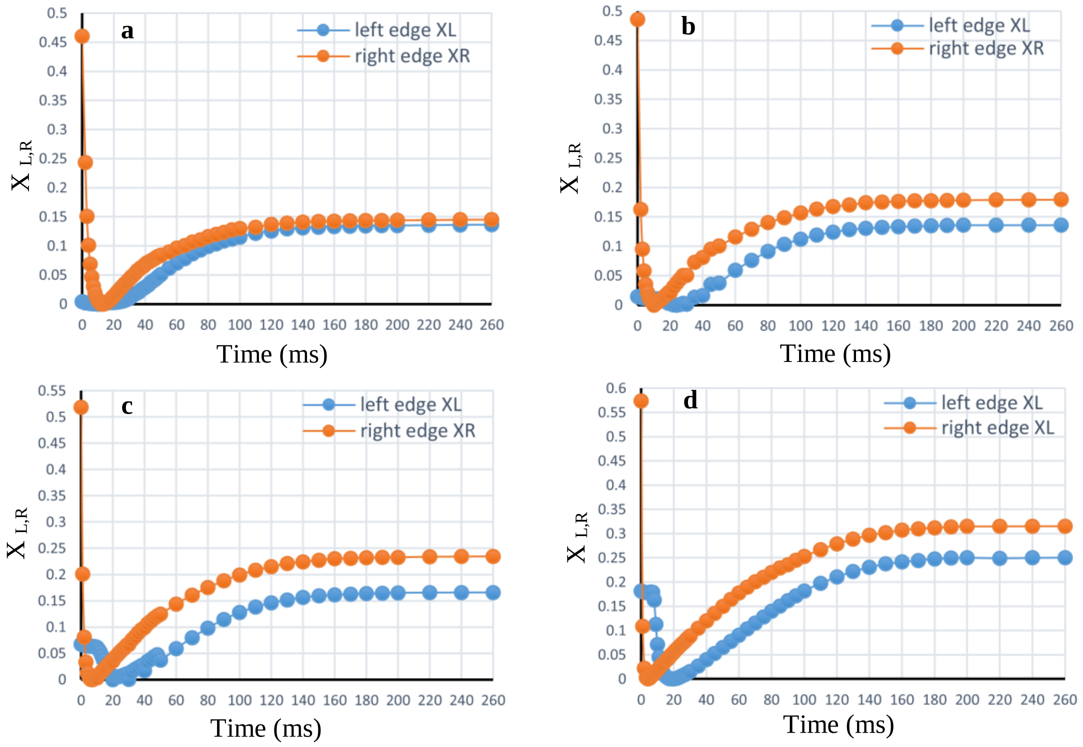

Figure 4: displacement of the right and left edges relative to maximum points.
(a) U= 0.5 (m/s); (b) U= 0.8 (m/s); (c) U= 1.5 (m/s); (d) U= 3 (m/s).

Conclusions

Effect of lateral separation, impact speed and liquid properties on composite droplet location was conducted numerically using OpenFOAM. We found that composite droplet location relative to initial condition controlled by the impacting droplet velocity and liquid properties but showing same non-trivial final location movement for different overlap ratios used in this research. For high value of surface tension, no inertia effect, composite droplet always located to impact side. Opposite happens for lower value of surface tension, inertia dominates and mass centre moves to the opposite direction.

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