Non-dimensional numerical study of droplet impacting on heterogeneous hydrophilicity/hydrophobicity surface

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Heterogeneous hydrophilicity/hydrophobicity surface involves many applications such as dropwise condensation, but droplet dynamics on such surface is not well understood. Here, droplet impacting on heterogeneous surface was described by non-dimensional conservation equations. The volume of fluid (VOF) method tracked the gas-liquid interface. A set of parameters such as impacting velocity, drop size etc. were combined to form three key non-dimensional parameters of We, Oh and \( \beta_i \) (size ratio of hydrophilic dot to drop). Numerical simulations agreed with impacting outcomes on uniformly hydrophilic or hydrophobic surface in references. For drop dynamics on heterogeneous surface, the regime maps containing complete-drop, single-drop-pinching-off and multi-drops-pinching-off were demonstrated over a wide range of \( \text{We} = 1–100, \text{Oh} = 0.001–1 \) and \( \beta_i = 0.5–10 \). The increased \( \beta_i \) enlarges the complete drop regime. The single-drop-pinching-off mode involves combined wall adhesion and surface tension induced short wave mechanism, while the multi-drops-pinching-off mode is caused by the propagation and interference of capillary waves from both ends of an elongated liquid column. The superposition principle was found for the first time: drop patterns include an adhesion part on the wall, similar to that on a hydrophilic surface, plus a rebounding part, similar to that on a super-hydrophobic surface. Spreading diameters are increased by \( \beta_i \) at smaller \( \text{We} \) and moderate or larger \( \beta_i \), but they are not influenced by hydrophilic dot sizes at large \( \text{We} \), under which inertia force thoroughly suppress effects of surface tension and wall adhesion. The present findings of this paper are helpful to design hydrophilic/hydrophobic surface and ensure droplet completeness during the impacting process.

1. Introduction

Super-hydrophobic surfaces are characterized as having low surface energies and water contact angles (WCA) greater than 150°. These surfaces exhibit the lotus effect to have applications such as dropwise condensation, self-cleaning and oil-water separation [1–5]. Alternatively, hydrophilic surfaces exhibit WCA less than 90°. Hydrophilic materials are encountered in our daily life and they are also ubiquitous in nature (e.g., plant and tree leaves, Nepenthes pitcher plant) [6]. Combining the two states of hydrophilicity and hydrophobicity on the same surface opens exciting new functionalities and possibilities in a wide variety of applications from dropwise condensation, cell, droplet, and hydrogel micro-arrays for screening to surface tension confined microchannels for separation and diagnostic devices [7–13]. The important concept for these applications is to form micro/nano droplet array on the combined surface. The cell embedded in droplet array should not be crossed infected. In other words, droplets should not be mutual interfered. The requirement of “one cell, one well” should be satisfied [14].

Recently, droplet formation on super-hydrophobic surface patterned with hydrophilic dots has drawn a lot of interest. The phenomena and related mechanisms are not well understood at this stage. This paper tries to answer the question of how to satisfy the requirement of “one cell, one well” by non-dimensional numerical simulation. Fig. 1 shows the studied problem. A droplet with its diameter of \( d_0 \) impacts on the hydrophilic dot, having a diameter of \( d_s \). The maximum spreading diameter is \( d_{\text{max}} \). The drop will have a stabilized diameter of \( d_s \) (see Fig. 1b). The ordered hydrophilic dots form the dot array. The distance between two centers of hydrophilic dots is \( d_p \).

Fig. 2 shows top and side views of the impacting process. Two drops are not interfered if \( d_p > d_{\text{max}} \) (see Fig. 2a). Alternatively, the two drops may be interfered if \( d_p < d_{\text{max}} \) (see Fig. 2b). Another important issue is to ensure the non-breakup during drop impacting process. Fig. 2c is a perfect case with complete drops on the patterned surface. However, if a daughter drop is generated, a
Fig. 1. A drop impacts on hydrophobic surface patterned with hydrophilic dots ($d_0$ is the initial drop diameter, $d_i$ is the hydrophilic dot diameter, $d_{\text{max}}$ is the maximum spreading diameter, $d_s$ is the stabilized drop diameter, $d_p$ is the distance between two hydrophilic dots).

Fig. 2. The interaction or non-interactions between two drops during their impacting on the hybrid surface.
small disturbance will cause the deviation of the daughter drop trajectory (see Fig. 2d). It is possible for the ejected drop to impact on another mother drop adhered on the surface. Such case should be avoided for practical applications. Thus, the requirement for “one cell, one well” is: (1) $d_{\text{max}} < d_i$; (2) complete drop during impacting process. In order to satisfy the requirement, we shall investigate effects of various factors such as drop size $d_0$, hydrophilic dot size $d_i$, impacting velocity $u_0$ on $d_{\text{max}}$. Besides, it is necessary to explore the condition under which the daughter drop generates during impacting process.

Chaudhury & Whitesides [15] noted that a surface having a surface energy gradient could cause drops to move uphill. This motion was the result of an imbalance in the forces due to surface tension acting on the solid-liquid contact line on the two opposite sides (“uphill” or “downhill”) of the drop. Mock et al. [16] performed impact experiments of drops on arrays of hydrophilic spots on the background of a perfluorinated polymer. The results showed that the drops spontaneously self-center on the lithographically generated pattern. Kim et al. [17] used the locally populated hydrophilic region on super-hydrophobic surface to investigate the drop impacting dynamics. The post-impact phenomenon was paid great attention to control the drop vectoring and morphing of droplets. They declared that their study offers wettability-engineered surfaces as a new method to manipulate droplet behavior, with ramifications for surface microfluidics and fluid-assisted templating applications.

In general, droplet dynamics on heterogeneous surface has attracted a lot of interest. For drop impacting on a hybrid surface, even though various phenomena were reported, together with the description of the functionality of these devices or systems, the daughter droplet generation and maximum spreading diameter are not investigated in the literature. The objective of this paper is to provide a general analysis. In order to do so, the governing conservation equations are transformed into the non-dimensional ones. The simulated results are thoroughly compared with the impacting outcomes for drop impacting on a uniformly hydrophilic or hydrophobic surface. Then, the paper focused on the discussion of drop impacting on a heterogeneous surface. The new findings include the capillary wave induced drop breakup mechanism and the self-similarity behavior of the pinching neck development. The superposition principle was found for the first time. The transition boundaries of drop breakup and non-breakup were given over a wide range of We, Oh and $\mu_h$. Effect of hydrophilic dot size on the drop spreading diameters is thoroughly studied. The conclusions are helpful for the heterogeneous surface design and selection of running parameters to prevent the drop from breaking up.

2. Numerical simulation

2.1. Governing equations

A two-dimensional computation (see Fig. 1) was performed using the Volume of Fluid (VOF) method. The method is structured to solve a single momentum equation throughout the domain, while the resulting velocity field is shared among the phases. The governing equations are as follows.

The advection equation of the volume fraction:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \hat{v} \mathbf{x}) = 0 \quad (1)$$

The continuity equation:

$$\nabla \cdot \hat{\mathbf{v}} = 0 \quad (2)$$

The momentum equation:

$$\frac{\partial}{\partial t} (\rho \hat{v}) + \nabla \cdot (\rho \hat{v} \hat{v}) = -\nabla p + \nabla \cdot [\mu (\nabla \hat{v} + \nabla \hat{v}^T)] + \rho g + \sigma k \nabla \alpha \left( \frac{\rho}{\sigma (\rho_1 + \rho_2)} \right) \quad (3)$$

in which

$$\rho = \rho_l (1-x) + \rho_g x \quad (4)$$

$$\mu = \mu_l (1-x) + \mu_g x \quad (5)$$

In Eqs. (1)–(3), $\alpha$ is the void fraction, $t$ is the time, $\hat{v}$ is the velocity vector, $\rho$ and $\mu$ are density and viscosity respectively, $\sigma$ is the surface tension force, $g$ is the gravity acceleration ($g = 9.81 \text{ m/s}^2$). The subscripts $l$ and $g$ denote the liquid and gas phase respectively.

$k$ is the interface curvature having the expression of $k = \nabla \cdot \hat{n}$.

The contact angle that the fluid makes with the wall boundary adjusts the surface normal in cells near the wall. This dynamic boundary condition results in the curvature adjustment of the surface near the wall. Assuming a contact angle of $\theta$ at the wall, the surface normal at the live cell next to the wall is

$$\hat{n} = \hat{n}_e \cos \theta + \hat{t}_w \sin \theta \quad (6)$$

where $\hat{n}_e$ and $\hat{t}_w$ are the unit vectors normal and tangent to the wall, respectively.

2.2. Treatment of dynamic contact angle

Because heterogeneous surface is involved, two static contact angles $\theta$ are used in the computation: $\theta = 60^\circ$ in hydrophilic dot ($d < d_i$), and $\theta = 150^\circ$ in hydrophobic region ($d > d_i$). Real impacting process is a dynamic one. Thus, dynamic contact angle should be carefully treated. In each computation step, a dynamic contact angle is needed. Dynamic contact angle is a function of contact line velocity. Various expressions exist on dynamic contact angle on contact line velocity [19,20]. One essential result relating spreading velocity to dynamic contact angle is obtained in the theoretical analysis of Cox [21]:

$$Ca = \left( \ln(z^{-1}) - \frac{Q_1}{f(\theta_d)} + \frac{Q_2}{f(\theta)} \right)^{-1} [g(\theta_d) - g(\theta)] + O\left( \frac{1}{\ln(z^{-1})} \right)^3 \quad (7)$$

where $Ca$ is capillary number at contact line, $\theta_d$ is dynamic contact angle, $Q_1$ and $Q_2$ are constants associated with outer flow and wall slip, $z$ is a small dimensionless parameter associated with the microregime of contact line, $f(z)$ and $g(z)$ are the functions obtained in Ref. [21]. The study is based on the creeping velocity field in the corner and thus it is valid for both spreading and receding cases. Eq. (7) is suitable for theoretical analysis, but it is difficult to be used for numerical simulation.

A more empirical correlation for dynamic contact angle is given by Kistler [22] as

$$\theta_d = f_H(Ca + f_H^{-1}(0)) \quad (8)$$

where $Ca$ is defined as $Ca = \mu u_{ct}/\sigma$, $u_{ct}$ is the contact line velocity which is obtained by $u_{ct} = \frac{\dot{u}}{r}$, $r$ is the spreading radius, $f_H^{-1}$ is the inverse function of the “Hoffman’s” empirical function which is

$$f_H = \arccos \left\{ 1 - 2 \tanh \left[ \frac{5.16}{1 + 1.31 x^{0.95}} \right] \right\} \quad (9)$$
In our study, Eqs. (8) and (9) calculated $h_{\text{d}}$. When the contact line is in hydrophilic region, $h_{\text{d}} = 60/C_{176}$ is applied to compute $h_{\text{d}}$. Alternatively, when the contact line is in hydrophobic region, $h_{\text{d}} = 150/C_{176}$ is applied to compute $h_{\text{d}}$. The treatment of $h_{\text{d}}$ is fulfilled by writing the User Defined Function in the code.

2.3. Non-dimensional governing equations and parameters

Because it is difficult to reach general conclusions due to too many parameters involved, we transformed Eqs. (1) and (3) into non-dimensional form. The non-dimensional parameters are defined as

$$Z = \frac{z}{d_0}, \quad R = \frac{r}{d_0}, \quad U = \frac{u}{u_0}, \quad V = \frac{v}{u_0}, \quad \tau = \frac{\tau u_0}{d_0},$$

$$\Theta = \frac{\rho}{\rho_1}, \quad \Psi = \frac{\mu}{\mu_1}$$

where $Z$ and $R$ are the non-dimensional coordinates in height and radial directions, respectively. $U$ and $V$ are the scaled velocities in the two coordinates, $u_0$ is the drop impacting velocity at the beginning of the drop contacting the wall. Eqs. (1)–(3) become

$$\frac{\partial \alpha}{\partial \tau} + \nabla \cdot (\mathbf{V} \alpha) = 0$$

Fig. 3. The non-dimensional computation domain and grid generation.
\[ \frac{\partial}{\partial t}(\Theta \dot{V}) + \nabla \cdot (\Theta \nabla \dot{V}) = -\nabla P + \nabla \left[ \frac{\Psi}{Re} \nabla \cdot \dot{V} + \nabla \cdot \dot{V} \right] \\
+ \Theta \frac{G}{We} \frac{1}{K} \nabla \cdot \frac{\Theta}{0.5(\Theta_{1} + \Theta_{2})} \] \tag{12}
\[ \nabla \cdot \dot{V} = 0 \] \tag{13}
\[ Re = \frac{\rho \omega d_0}{\mu_0}, \quad We = \frac{\rho \omega d_0}{\sigma}, \quad P = \frac{P}{\rho \omega d_0}, \quad G = \frac{gd_0}{\mu_0} \] \tag{14}
where \( Re \) is the Reynolds number, \( We \) is the Weber number, \( P \) is the non-dimensional pressure, \( G \) is the non-dimensional gravity acceleration. By comparing Eqs. (1) and (3) and Eqs. (11) and (13), the non-dimensional densities and viscosities for the liquid and gas phases are
\[ \rho_{1}^* = \Theta_{1} = 1, \quad \rho_{2}^* = \Theta_{2} = \frac{\rho_{2}}{\rho_{1}}, \quad \mu_{1}^* = \frac{\mu_{1}}{\mu}, \quad \mu_{2}^* = \frac{\mu_{2}}{\mu}, \quad \Psi_{1}^* = \frac{\Psi_{1}}{\rho_{1}}, \quad \mu_{2}^* = \frac{\Psi_{2}}{\rho_{2}} \] \tag{15}
The non-dimensional surface tension force becomes
\[ \sigma^* = \frac{1}{We} \] \tag{16}
When air-water system is used at the atmospheric pressure and room temperature of 20 °C, \( \rho_{1} = 1000 \text{ kg/m}^3, \rho_{2} = 1.225 \text{ kg/m}^3, \mu_{1} = 10^{-3} \text{ Pa·s}, \mu_{2} = 1.79 \times 10^{-3} \text{ Pa·s} \) and \( \sigma = 0.073 \text{ N/m} \). The non-dimensional physical properties in Eqs. (15) and (16) can be determined at given \( Re \) and \( We \) numbers. \( P \) and \( G \) in Eq. (14) are
\[ P = \left( \frac{Re \mu_{1}}{We \sigma} \right)^2 \frac{P}{\rho_{1}} \] \tag{17}
\[ G = \frac{Re \mu_{2}^3}{We^3 \sigma^3 \rho_{1}} \] \tag{18}

2.4. Initial and boundary conditions for non-dimensional computations

A droplet with its initial diameter of \( d_0 \) falls down at the start of zero velocity at a height of \( h \) (see Fig. 1). The droplet impacts on the hydrophilic dot with the diameter of \( d_0 \). The contact angle is 60° for the droplet spreading diameter \( d < d_0 \), but it becomes 150° for \( d > d_0 \). Fig. 3 shows the non-dimensional problem, with a non-dimensional drop diameter of \( D_0 = 1 \). The non-dimensional radius is \( R_0 = 0.5 \). The computation domain are \( Z = 5 \) and \( R = 5 \). We set an initial droplet velocity \( U' \) at \( Z = 5 \) so that it has an impacting velocity of \( U_0 = 1 \) at \( Z = 0 \) due to the gravity acceleration of \( G \). The initial condition sets the drop velocity of \( U' \), zero velocities and \( P_{\text{atm}} \) beyond the drop boundary. \( P_{\text{atm}} \) is calculated by Eq. (17) with \( P = 1.013 \times 10^{5} \text{ Pa} \).

![Fig. 4. The ranges of We and Oh computed in this paper (△ for adhesion, ○ for rebound as ellipsoid; ◆ for rebound as long liquid column).](image)

**Table 1**
The nine runs in this study.

<table>
<thead>
<tr>
<th>run</th>
<th>( Re )</th>
<th>( We )</th>
<th>( \rho_{1}^* )</th>
<th>( \rho_{2}^* )</th>
<th>( \mu_{1}^* )</th>
<th>( \mu_{2}^* )</th>
<th>( \sigma^* )</th>
<th>( P_{\text{atm}} )</th>
<th>( C )</th>
</tr>
</thead>
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<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.1</td>
<td>1.79 \times 10^{-3}</td>
<td>1</td>
<td>1.90</td>
<td>( \text{52} \times 10^{-7} )</td>
</tr>
<tr>
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<td>10</td>
<td>1</td>
<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.1</td>
<td>1.79 \times 10^{-3}</td>
<td>1</td>
<td>0.02</td>
<td>( \text{52} \times 10^{-10} )</td>
</tr>
<tr>
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<td>10</td>
<td>1</td>
<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.1</td>
<td>1.79 \times 10^{-3}</td>
<td>0.01</td>
<td>1.90 \times 10^{-4}</td>
<td>( \text{52} \times 10^{-13} )</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>1</td>
<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.01</td>
<td>1.79 \times 10^{-3}</td>
<td>1</td>
<td>190.13</td>
<td>( \text{52} \times 10^{-10} )</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>1</td>
<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.01</td>
<td>1.79 \times 10^{-3}</td>
<td>0.1</td>
<td>1.90</td>
<td>( \text{52} \times 10^{-6} )</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>1</td>
<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.01</td>
<td>1.79 \times 10^{-3}</td>
<td>0.1</td>
<td>0.02</td>
<td>( \text{52} \times 10^{-9} )</td>
</tr>
<tr>
<td>7</td>
<td>1000</td>
<td>1</td>
<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.001</td>
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<td>1</td>
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<tr>
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<td>1</td>
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<td>0.001</td>
<td>1.79 \times 10^{-3}</td>
<td>0.1</td>
<td>190.13</td>
<td>( \text{52} \times 10^{-12} )</td>
</tr>
<tr>
<td>9</td>
<td>1000</td>
<td>1</td>
<td>1</td>
<td>1.225 \times 10^{-3}</td>
<td>0.001</td>
<td>1.79 \times 10^{-3}</td>
<td>0.01</td>
<td>1.90</td>
<td>( \text{52} \times 10^{-12} )</td>
</tr>
</tbody>
</table>

Note: In each run, \( \beta_i \) is changed from 0 to 10.0.
and momentum equations was fulfilled by a first-order implicit scheme.

2.5. Running parameter ranges

Here, the controlling parameters are \( Re \), \( We \) and \( \beta_0 \). For air-water system at atmospheric pressure and room temperature, once \( Re \) and \( We \) are given, \( C \) is determined. \( \beta_0 \) is to be solved during the computation. Other parameters are the Ohnesorge number (\( Oh = We^{0.5}/Re \)) and Bond number (\( Bo = 0.25g \cdot We \)). The computations involve about 120 runs, with each run having a specific combination of \( Re \), \( We \) and \( \beta_0 \). Table 1 lists \( Re \), \( We \) and a set of non-dimensional parameters for 9 groups of runs. Each run contains different \( \beta_0 \) from 0 to 10. Because \( Oh \) can be expressed as a function of \( Re \) and \( We \), the controlling parameters can also be expressed as \( We \) and \( Oh \), instead of \( We \) and \( Re \). Fig. 4 plots the ranges of \( We \) and \( Oh \), in which the curve of \( We = Oh^2 \) characterizes the \( Re = 1 \) boundary.

3. Comparison with experiment and theoretical work

**Comparison regarding drop dynamics:** Computation results are compared with experiments of Sichalo et al. [26], in which wax (low wettability) and glass (high wettability) were used to study the surface wettability effect on impacting dynamics. Two experiments of Exps. 4 and 7 are involved for comparison (see Table 2 for running parameters and physical properties). Before the formal computation, the sensitivity of non-dimensional grid lengths on computation results for Exp. 7 is examined. Three grid lengths of 0.02, 0.01 and 0.005 are used in \( E_1 \) region (see Fig. 3). The non-dimensional spreading diameters \( \beta = d/d_0 \) with the grid length of 0.02 are slightly larger than those with the grid lengths of 0.01 and 0.005. There is no difference of \( \beta \) when the grid lengths of 0.01 and 0.005 are used. The computation accuracy is ensured with the grid length of 0.01 in \( E_1 \) region. We note that drop impactance process majorly happens in \( E_1 \) region, rough grid length can be used in \( E_2 \) region and it has no influence on the impacting outcomes.

Fig. 5a shows the comparison between our predicted spreading factor \( \beta = d/d_0 \) and measured ones. The match is excellent for both hydrophilic surface (\( \theta = 15^\circ \)) and hydrophobic surface (\( \theta = 100^\circ \)). Specific time with six data points is marked in the curve of hydrophobic surface: \( \tau = 0.1, 0.6, 2.0, 3.8, 5.2 \) and 7.3. The former three refers to the spreading stage, while the latter three refers to the receding stage. Fig. 5b shows the comparison between measured drop shape and simulated one at each specific time. For all the images, the drop covering widths of measurements and simulations are almost identical. The studied problem in this paper is a two-dimensional and axisymmetric problem due to the exactly symmetric boundary condition. During the spreading stage, the drop shape has almost no difference between measurements and simulations. During the receding stage (see images at \( \tau = 3.8 \) and 5.2 in Fig. 5b), experiments in the left column give the side view presentation. Blue areas in right column represent the cross sectional view of the droplet shape, while dashed curves represent the droplet shape based on side view. The difference between side view presentation and cross sectional view presentation is due to the concaved interface in the center droplet region during the receding stage. In summary, measurements and simulations are matched well.

**Comparison regarding maximum spreading diameter:** Maximum spreading diameter \( d_{\text{max}} \) is influenced by \( Re \), \( We \), \( Oh \) and surface wettability: \( \beta_{\text{max}} = d_{\text{max}}/d_0 = f(Re, We, Oh, \theta) \). An & Lee [27] summarized the scaling law method [28,29], energy balance method [30–32] and momentum balance method [33,34] to correlate \( d_{\text{max}} \). Maa et al. [31] presented the correlation for drop impacting with low viscosity fluid as

\[
\left[ \frac{1}{4} (1 - \cos \theta) + 0.2 \frac{We^{0.5}}{Re^{0.33}} \right] \beta_{\text{max}}^3 - \left( \frac{We}{12} + 1 \right) \beta_{\text{max}}^2 + \frac{2}{3} \beta_{\text{max}} = 0
\]

German & Bertola [32] modified Eq. (19) into Eq. (20) so that the correlation is suitable for high viscosity fluid.

\[
\left[ \frac{1}{4} (1 - \cos \theta) + 0.07 \frac{We^{0.5}}{Re^{0.45}} \right] \beta_{\text{max}}^3 - \left( \frac{We}{12} + 1 \right) \beta_{\text{max}}^2 + \frac{2}{3} \beta_{\text{max}} = 0
\]

Table 3 shows the comparison between our simulated maximum spreading factors with predictions using Eq. (19) for \( Oh < 0.1 \) (low viscosity liquid) and Eq. (20) for \( Oh = 0.1 \)–1 (high viscosity liquid). Two surfaces of \( \theta = 60^\circ \) and \( \theta = 150^\circ \) are involved. The simulated maximum spreading factors agree with the predictions for low viscosity liquid (\( Oh < 0.1 \)). The deviation between them is less than 10%, which is acceptable and reasonable. The \( Oh = 1 \) case yields the deviation of 16.2% for hydrophilic surface and 14.7% for hydrophobic surface. Eq. (19) is based on experiments which have sufficient data resource in the literature. Both numerical simulations and predictions with Eq. (19) gave reasonable results for low viscosity liquid. However, maximum spreading diameters have insufficiently measured data to support Eq. (20) for high viscosity fluid impacting process, which needs detailed investigation in the future [32].

**Comparison regarding stabilized drop diameter:** After the drop dissipates all the kinetic energy and reach the minimum surface energy, the drop is stabilized on the wall with its diameter of \( d_s \). The stabilized spreading factor is defined as \( \beta_s = d_s/d_0 \) relating to the initial drop diameter. Rioboo et al. [35] gave the correlation as

\[
\beta_s = \frac{2 \sin^3 \theta}{\sqrt{2(1 - \cos \theta)(2 - \cos \theta - \cos^2 \theta)}}^{1/3}
\]

Eq. (21) told us \( \beta_s \) only depend on the contact angle \( \theta \), having nothing to do with other parameters such as the impacting velocity. \( \beta_s \) is 1.61 when \( \theta = 60^\circ \), but it is 0.50 when \( \theta = 150^\circ \). Our numerical simulation yields the two values of 1.62 and 0.48 at the two contact angles, matching the predictions by Eq. (21) well.
4. Results and discussion

4.1. Effect of surface wettability on drop dynamics

Corresponding to Table 1 and Fig. 4, we summarized the drop dynamics on uniformly hydrophilic or hydrophobic surface first. In the range of $Re = 10$–1000, $We = 1$–100 ($Oh = 0.001$–1), Palacios et al. [36] showed that drops adhere on hydrophilic surface without rebounding during impacting process. Antonini et al. [37] showed that drop rebound occurs on super-hydrophobic surface, covering the same $Re$ and $We$ ranges. Drops either jump or adhere on the surface with $Oh < 0.1$. Our computations matched the results given in Palacios et al. [36] and Antonini et al. [37].

<table>
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<th>$We$</th>
<th>$Oh$</th>
<th>$\beta_{max}(\theta = 60^\circ)$ Predictions in Ref.</th>
<th>$\beta_{max}(\theta = 60^\circ)$ This paper</th>
<th>dev (%)</th>
<th>$\beta_{max}(\theta = 150^\circ)$ Predictions in Ref.</th>
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<th>dev (%)</th>
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<td>100</td>
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<tr>
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<td>2.43</td>
<td>2.63</td>
<td>8.23</td>
<td>1.52</td>
<td>1.47</td>
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<tr>
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<td>100</td>
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<td>3.20</td>
<td>13.0</td>
<td>2.54</td>
<td>2.55</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 3: The comparison between our numerical simulations with those in references on either uniformly hydrophilic surface or hydrophobic surface.

Note: The predictions used the Mao et al. [31] model for $Oh < 0.1$, and German & Bertola [32] model for $Oh \geq 0.1$.

Fig. 5. Comparisons of spreading factors and droplet morphology between our numerical simulations and experiments in the literature (note: in the images of $\tau = 3.8$ and $5.2$ of the computation results, dashed curves are for side views and blue areas are for cross sectional views).
elongated liquid column at high \( \text{We} \) and low \( \text{Oh} \) numbers, under which inertia force significantly exceeds viscous force and surface tension force (see Fig. 4). With decrease of \( \text{We} \) and increase of \( \text{Oh} \), surface tension force and viscous force become important, yielding smaller drop deformation. Drops behave ellipse shape instead of elongated liquid column. Our computations agreed with the observations by Richard & Quéré [38], Tsai et al. [39] and Hao et al. [40].

On super-hydrophobic surface, two extreme conditions of (\( \text{We} = 1, \text{Oh} = 0.001 \)) and (\( \text{We} = 100, \text{Oh} = 1 \)) yield drop adhesion. The former involves drop adhesion due to large Bond number having large gravity force related to surface tension force, while the latter refers to viscous effect induced wall adhesion.

Fig. 6 shows drop dynamics for \( \text{Re} = 1000, \text{We} = 100 \) and \( \text{Oh} = 0.01 \), noting that non-dimensional drop size and time are used. Fig. 6a shows drop patterns on uniformly hydrophilic surface with \( \theta = 60^\circ \), behaving drop adhesion. Fig. 6b shows thoroughly different drop patterns on uniformly super-hydrophobic surface with \( \theta = 150^\circ \). Seeing Fig. 6b, the adhered drop begins to be lifting up after \( \tau = 5 \). The drop completely leaves the wall at \( \tau = 8 \). The elongated liquid column appears during rebounding process. A smaller daughter drop is thoroughly separated from its mother drop at \( \tau = 9 \). The daughter drop is caused by the contraction of the liquid column tip.

Fig. 6c used the heterogeneous surface with \( \beta_i = 1.0 \) (equal size of hydrophilic dot and initial drop diameter). For \( \tau = 6 \), Fig. 6b shows similar drop patterns as those on uniformly super-hydrophobic surface. Drop spreads but it is being lifting up at the end of this stage. Following \( \tau < 6 \), drop patterns are different from Fig. 6b. Fig. 6c shows a drop part always sticking the wall with its size exactly identical to hydrophilic dot. The elongated liquid column part is being formed plus the generation and separation of a small daughter drop. The liquid column is thoroughly separated from the adhesion part at \( \tau = 13 \).

Fig. 7 plots \( \beta = d/d_0 \) versus \( \tau \) for the same running parameters identical to Fig. 6. The curves for the three surfaces coincide during early inertia spreading stage with \( \tau < 0.2 \). In the latter spreading stage with \( \tau > 0.2 \), the hydrophilic surface has faster spreading velocities and larger maximum spreading factor \( \beta_{\text{max}} \) than the other two surfaces. The hydrophilic surface attains \( \beta_{\text{max}} = 3.2 \) at

![Fig. 7](image-url)
In this study, the non-condensable gas induced non-wetting is consistently reduced by the Laplace pressure, which is significantly larger than 90°. During the inertia spreading stage, the Laplace pressure is the driving force but the inertia force resists spreading. The inertia spreading can be scaled by a time scale of $\tau = 6.0$, beyond which the droplet recedes and oscillates on the horizontal plane, until the energy is completely dissipated. The heterogeneous surface has the same spreading curve as the super-hydrophobic surface until spreading diameter recedes to hydrophilic dot diameter. Since then the adhesion part is confined within the hydrophilic dot. However, the super-hydrophobic surface continuously reduces the droplet diameter to zero. Then, the droplet jumps away from the surface.

Figs. 6 and 7 are further explained here. For all the three surfaces, the impacting dynamics can be divided into three sub-stages: inertia dominant spreading stage, viscosity dominant spreading stage from the end of inertia stage to the maximum spreading diameter, and receding stage beyond the maximum spreading diameter. During the inertia spreading stage, the Laplace spreading diameter, and receding stage beyond the maximum spreading diameter, have larger attracting force between liquids and solid to yield faster traveling speed of the three-phase contact lines and smaller contact angle to ensure the minimum surface energy of the droplet. The droplet at the final state.

During the receding stage, Figs. 6 and 7 illustrate different behaviors for the three surfaces. The hydrophilic surface decreases the spreading factor to a specific value, followed by the oscillating of spreading diameters to dissipate energy, until a stabilized contact angle is reached to have a minimum surface energy. The super-hydrophobic surface shortens the spreading diameter to zero and the droplet will jump out of the surface. For the heterogeneous surface, when spreading diameter is decreased to the size of hydrophilic dot, the contacting diameter keeps constant, under which the three-phase contact line is pinched at the junction of the hydrophilic region and super-hydrophobic region. This is the major mechanism to arrest liquid on the hydrophilic dot.

Generally, the impacting dynamics on the three surfaces can also be analyzed from the energy conservation point of view. At the beginning of a droplet contacting the wall, the total energy of the system is the droplet kinetic energy and the droplet surface energy. The impacting process dissipates energy, which is dependent on surface wettability. For a hydrophilic surface, the residual energy after the energy dissipation behaves the surface energy of a spherical crown of the droplet, having a specific contact angle on the wall. A super-hydrophobic surface dissipates less energy due to the weak interaction between liquid and wall. Most of energy is dissipated at the gas-liquid interface after the droplet jumps out of the wall. For the heterogeneous surface, the hydrophilic dot can arrest the liquid. Because the hydrophilic dot is small, the droplet may keep the constant contacting diameter but with varied contact angles to ensure the minimum surface energy of the droplet at the final state.

### 4.2. Three types of drop patterns

Fig. 8 shows three drop patterns on heterogeneous surface with $Re = 1000$ at $\beta_i = 0.5$ (hydrophilic dot is half to initial drop diameter). Fig. 8a shows the complete drop pattern with ultra small $We = 1$, at which inertia force and surface tension force...
are equally important to the drop dynamics. The drop finally sticks on the wall without drop breakup. Fig. 8b shows the run with $\text{We} = 10$. Following $\tau > 4$, two drop parts are formed: a sticking part on the wall and a daughter drop part out of the wall. The latter is fully separated from its mother drop at $\tau = 5$. We call this as the single-drop-pinching-off pattern. Fig. 8c shows the drop pattern with $\text{We} = 100$, generating an adhesion part on the wall and an elongated liquid column.

Fig. 9. The drop breakup mechanism of the short wave mode with $\text{Re} = 1000$, $\text{We} = 10$, $\text{Oh} = 0.003$ and $\beta_i = 0.5$. 
suspending in the air. A set of daughter drops are fragmented, called the multi-drops-pinching-off pattern.

4.2.1. The single-drop-pinching-off mechanism

Fig. 9 examined how wall adhesion effect and surface tension effect influence the single-drop-pinching-off with \( \text{We} = 10 \). The left and right sides illustrate pressure and velocity fields, respectively. The drop is being lifted up at \( \tau = 2 \). The whole drop has upward velocities. The wall adhesion of the near wall liquid and the excessive kinetic energy in the upper region of the droplet form a thin neck to eventually separate the droplet into two parts. The neck thinning process causes the capillary wave propagation. Capillary pressure across the gas-liquid interface is written by the Young-Laplace equation: 

\[
\Delta p = \sigma \left( \frac{1}{r_1} + \frac{1}{r_2} \right),
\]

where \( r_1 \) and \( r_2 \) are the curvature radius in the circumferential direction and height direction, respectively. With the neck formation, both \( r_1 \) and \( r_2 \) are decreased to increase \( \Delta p \). During the drop breakup process, the liquid transport from the neck to the upper droplet part is accelerated. Meanwhile, the liquid transport from the wall substrate to the neck is suppressed due to the wall adhesion. These two effects are the major mechanism for the drop breakup. The narrowed neck further increases the capillary pressure. The two parts are successfully separated at \( \tau = 4.2 \) in Fig. 9.

The capillary wave propagation is similar to the short wave mode \([41,42]\). The short-wave mode is a local mode in the vicinity of the jet tip, it was also called the end-pinching for Stokes flows in Stone et al. \([43]\), Stone & Leal \([44,45]\) and Stone \([46]\). One shall remember the hydrophilic dot role on the single-drop-pinching-off. The wall adhesion prevents the whole drop from leaving out of the wall and causes downward flow within the sticking drop. The wall effect promotes the neck formation and drop breakup.

Basaran \([47]\) noted that the dynamics near pinch-off exhibits self-similar behavior due to the orders of magnitude difference between local length and time scales and global scales. Keller & Miksis \([48]\) proposed a scaling theory governing interface rupture. They took the liquid within a thinning axisymmetric thread to be inviscid and the motion to be irrotational. They further took the ambient fluid to be a passive gas like air and neglected its dynamics. We verified that our computation results agree with the scale law in Fig. 10. The horizontal coordinate is the scaled time

\[
t' = (t_b - t) / \sqrt{\rho_l \tau_0 / \sigma},
\]

where \( t_b \) and \( t \) are the breakup time and

\[
\tau_0 = \frac{\rho_l \rho_u \beta \sigma}{\mu_l \mu_u}.
\]

Fig. 10. The scaled liquid film thickness relative to drop initial diameter versus scaled breakup time (\( \text{Re} = 1000, \text{We} = 10, \text{Oh} = 0.003, \beta_l = 0.5 \)).

Fig. 11. The multi-drop generation process with \( \text{Re} = 1000, \text{We} = 100, \text{Oh} = 0.01 \) and \( \beta_l = 1.0 \).
time, respectively. \( \sqrt{\frac{\rho b_0^3}{\sigma}} \) is the capillary time. The vertical coordinate is the scaled liquid film thickness at the neck: \( h = \frac{d_{\min}}{d_0} \), where \( d_{\min} \) is the neck diameter (or call liquid film thickness) at time \( t \), \( d_0 \) is the initial drop diameter. Our simulations yield the pinch-off phenomenon to obey \( d_{\min}/d_0 = 0.136r^{0.70} \). The power law exponent of 0.70 approaches the value of 2/3 suggested by Keller & Miksis [48].

4.2.2. The multi-drop-pinch-off mechanism

Fig. 11 shows velocity fields at \( We = 100 \). In contrast to those shown in Fig. 9 at low \( We \) number, the high \( We \) number cuts the elongated liquid column into a set of daughter drops by several times. We call this mode as the multi-drop-pinch-off pattern. The first time drop breakup happens at \( \tau = 12 \), which is similar to the single-drop-pinch-off shown in Fig. 9. Following \( \tau < 12 \), an elongated liquid column forms. Capillary waves generate at both top and bottom ends of the liquid column. They propagate towards the liquid column center (see images for \( \tau \geq 13 \) in Fig. 11). Daughter drops are sequentially separated from the long liquid column. Drop breakup along the long liquid column was called the long wave mode in the literature [41,42]. The long wave mode can be considered as the stretch of the short wave mode. When the liquid column is significantly long, capillary waves from top tip and bottom tip meet and interfere with each other, promoting the formation of drop neck and breaking up of the liquid column. The multidrops-pinch-off pattern can be regarded as a hybrid mode: the first time short wave breakup and long wave liquid column breakup, together with the wall adhesion effect.

4.3. The three drop impacting regimes

Fig. 12 shows the newly identified superposition principle for drop impacting a heterogeneous surface. Drop impacting behaves complete drop regime on hydrophilic surface (see first row in Fig. 12). It is noted that ultra large \( We \) number may involve drop splash regime [36], but it is not interested in this paper. The second row of Fig. 12 shows drop impacting on a hydrophobic surface. With continuous increase of \( We \) and decrease of \( Oh \), drop adhesion, rebound as a spheroid or as a long liquid column consecutively occur. Capillary wave induced drop breakup takes place along the elongated liquid column.

For drop impacting a heterogeneous surface, an adhesion part always sticks on the wall. Ultra small \( We \) and large \( Oh \) show complete drop regime, similar to that on a uniformly hydrophilic or hydrophobic surface. The moderate \( We \) and \( Oh \) yield single-drop-pinch-off regime, with an adhesion part similar to that on a hydrophilic surface, and a rebounding part similar to that for drop impacting on a hydrophobic surface. Multi-drops-pinch-off regime happens with large \( We \) and small \( Oh \). Therefore, covering a wide range of \( We \) and \( Oh \), drop impacting outcome on a heterogeneous surface consists of an adhesion part on the wall, similar to that on a uniformly hydrophilic surface, and a rebounding part, similar to that on a uniformly hydrophobic surface. This behavior is called the superposition principle in this paper.

The above analysis shows the important effect of hydrophilic dot on drop impacting. A remain question is that at what size of the hydrophilic dot begins to apparently influence the drop patterns. The sensitivity of hydrophilic dot on impacting outcomes is presented in Fig. 13. The drop impacting outcomes are almost identical on a hydrophobic surface (\( b_i = 0 \)) and on a heterogeneous surface with \( b_i = 0.01 \). For both impacting cases, there is no adhesion drop on the hydrophilic dot. The whole drop completely rebounds out of the surface. The superposition principle is not valid for such ultra small hydrophilic dot such as \( b_i = 0.01 \). When \( b_i \) is increased to 0.1, the superposition principle is valid because the hydrophilic dot successfully confines a small drop part on the wall. Fig. 13 shows that a too small hydrophilic dot is not helpful to confine the drop on the wall. A critical \( b_i \) can be 0.1 to apparently influence the drop impacting process.

Fig. 14 plots drop impacting regimes and transition boundaries with controlling parameters of \( We, Oh \) and \( b_i \). The range of \( b_i \) is from 0.5 to 2.0. Complete drop regime, singe-drop-pinch-off regime and multi-drops-pinch-off regime take place in the right and bottom region, middle region, and top-left region, respectively.

![Fig. 12. The superposition principle of drop impacting on hybrid surface, consisting of an adhesion part on the wall, similar to that on a hydrophilic wall, and an ejecting part, similar to drop rebounding on a super-hydrophobic wall.](image)
The drop impacting regimes reflect the relative importance of one force relative to another, characterized by \( W_e \) and \( O_h \). Attention was paid to the effect of \( \beta_i = d_i/d_0 \) on the transition boundaries. The increased \( \beta_i \) narrows single-drop-pinching-off regime and multi-drops-pinching-off regime, but enlarges complete drop regime. The enlarged hydrophilic area increases attractive force between wall and liquid, enhancing the wall adhesion effect to keep the drop completeness.

Josserand and Thoroddsen [49] pointed out that as the impacting velocity is increased, the drop will splash eventually. The splashing threshold was characterized by the so-called splashing number proposed by Stow & Hadfield [50] and Mundo et al. [51], which incorporated the inertia, viscous stress, and surface tension in the form of \( K = W_e R e^{0.5} \). For impacts at \( K > 3000 \), one expects a splash. The nature of the splash has been split into two categories: prompt and corona. A prompt splash releases droplets directly from the breakup of the tip of the advancing lamella, whereas in the corona splash the intact lamella rises away from the substrate, forming a bowl-like structure, which subsequently breaks up into fine droplets. We plot the drop impacting regime in terms of \( K \),

![Fig. 13. Drop impacting outcomes at small \( \beta_i \) with \( Re = 1000, We = 10 \) and \( O_h = 0.01 \).](image1)

![Fig. 14. The drop impacting regimes in terms of \( We, O_h \) and \( \beta_i \).](image2)
Fig. 15. The drop impacting regimes in terms of Re, K and β. (■ multi-drop-pinching-off regime, ● single-drop-pinching-off regime, ▲ complete-drop regime, — transition from complete-drop regime to single-drop-pinching-off regime, —— transition from single-drop-pinching-off regime to multi-drops-pinching-off regime).

Fig. 16. Effect of We and β on spreading factors versus time at Re = 1000.
Fig. 17. Effect of We on spreading factors at Re = 1000 and βᵣ = 1.0 (note: the run with We = 1 belongs to the abnormal run due to ultra large Bond number).

Re and βᵣ in Fig. 15. The breakup regime majorly occurs in the top-right region. The enlarged hydrophilic area (βᵣ) narrows the breakup regime and enlarges the complete drop regime. Here, we note that the present drop breakup is caused by the surface tension induced capillary wave pinching-off mechanism, happening in the short or long liquid column suspending in the air, which is different from splashing on the wall surface. However, the splashing number is still useful to characterize the drop impacting regime in this study. Figs. 14 and 15 are useful to choose running parameters to reach the “one cell, one well” target.

4.4. Drop spreading diameter

Fig. 16 shows spreading factors (β = d/d₀), noting that only adhesion drop on the wall is considered for rebound situation. Fig. 16a shows that during the spreading stage of β < βᵣ, spreading velocities are decreased when the drop travels beyond the hydrophilic dot, since then the three β curves deviate with each other. Fig. 16c–d shows that the β curves almost coincide for the three βᵣ values at high We. Surface wettability influences drop spreading at small We, but does not affect drop spreading at large We, agreeing with the conclusion drawn by Šikalo et al. [52] and Antonini et al. [53] for spreading on a uniform wettability surface. Fig. 16b–d shows that βᵣ is increased by increasing We with We in the range of 10–100, but Fig. 16a also shows a large βᵣ at small We = 1. Fig. 17 explains the effect of We on βᵣ, which is increased from We = 100 to 10, but re-increased from We = 10 to 1. Spreading on the wall is governed by inertia force, gravity force, viscous force and surface tension force. Inertia force and gravity force are driving forces for drop spreading, but viscous force and surface tension force resist drop spreading. The four forces are combined to form non-dimensional parameters of Re, We and Bo. Bond number (Bo) characterizes the importance of gravity relative to surface tension:

\[ Bo = \frac{ρg d₀^2}{σ} \]  

Once Re and We are given, Bo can also be expressed as

\[ Bo = \frac{Re^4 \mu_Γ^4 - g}{4We^2 \sigma \rho} \]  

Examining Fig. 17 with Re = 1000, the curves of We = 100 and 10 correspond to Bo = 6.3 × 10⁻² and 6.3 × 10⁻¹. The ultra-low Bond number leads to spreading dominated by We. Smaller βᵣ exists for smaller We. The We = 1 curve has a high Bo = 6.3, for which gravity force is almost one magnitude larger than surface tension force, making easy for liquid deformation from spherical shape to flattened shape on the wall. This explains the re-increased β values from We = 10 to 1 in Fig. 17. Our finding is consistent with Wu and Li [54], in which they stated that surface coverage area of a droplet is larger at higher Bond number.

4.4.1. Maximum spreading diameter

Continued from Figs. 16 and 17, Fig. 18 summarized how We, Oh and βᵣ influence βᵣ, covering wide parameter ranges, which are analyzed as follows:

βᵣ at We = 1 and Oh = 0.001: Under these circumstances, gravity force is almost one magnitude larger than surface tension force. The large gravity force effect makes easy drop deformation to have large covering area on the wall. Thus, βᵣ values are larger (see Figs. 16 and 17 and black curve in Fig. 18a).

βᵣ at small or moderate We (see Fig. 18a and b): Spreading of a droplet on the wall means strong drop deformation. One shall
remember that inertia force causes droplet deformation, but surface tension force resists drop deformation. The two forces are combined to form We. This explains why \( \beta_{\text{max}} \) values are larger by increasing We from Fig. 18a and b.

Spreading on the wall consists of inertia dominant spreading stage and viscosity dominant spreading stage. The former is not influenced by surface wettability, but the latter is affected by surface wettability. If the hydrophilic dot is smaller than the spreading diameter at the end of inertia spreading stage, the maximum spreading diameter \( d_{\text{max}} \) or spreading factor \( \beta_{\text{max}} \), should not be influenced by the non-dimensional hydrophilic dot size \( \beta_i \). A transition point exists at which the hydrophilic dot size equals to the spreading diameter at the end of inertial spreading stage, beyond which the hydrophilic dot does affect the maximum spreading diameter, and the maximum spreading diameter should be increased by increasing hydrophilic dot size, because there is an excessive hydrophilic area covered in the viscosity dominant spreading stage. This analysis is thoroughly verified in Fig. 18a and b, in which there is an insensitive region of \( \beta_{\text{max}} \) versus \( \beta_i \), and an increased \( \beta_{\text{max}} \) region by increasing \( \beta_i \).

\( \beta_{\text{max}} \) at large We = 100 (see Fig. 18c): When We is sufficiently large such as We = 100 shown in Fig. 18c, inertial force becomes important to thoroughly suppress the effect of surface tension and surface wettability of the wall, explaining constant \( \beta_{\text{max}} \) by continuous increase of hydrophilic dot size. Liquid viscosity still apparently influences maximum spreading diameters. Low viscosity fluid such as Oh = 0.01 makes easy for drop deformation to cover larger spreading area on the wall, but high viscosity fluid such as Oh = 1 would not deform the droplet too much to have smaller spreading area on the wall (see the three curves in Fig. 18c).

4.4.2. Stabilized spreading diameter

Stabilized spreading factor is defined as \( \beta_s = d_s/d_i \), in which \( \beta_s < 1, = 1, \) and \( > 1 \) indicate the stabilized drop within the hydrophilic dot, at the hydrophilic dot margin, and out of the hydrophilic dot, respectively. Fig. 19 shows the relationship between \( \beta_i \) and \( \beta_s \). When the hydrophilic dot is small such as \( \beta_i = 0.5 \), the stabilized drop is out of the hydrophilic dot boundary (\( \beta_s = 1.26 \)). At moderate \( \beta_i = 1.0 \) and 1.5, the stabilized drop is successfully confined by the hydrophilic dot at its margin (\( \beta_s = 1.0 \)). As the hydrophilic dot size is increased to \( \beta_i = 2.0 \), the drop is inside the hydrophilic dot (\( \beta_s = 0.81 \)).

Finally, we discussed how to use the findings of this paper. The objective of this paper is to provide a general analysis on droplet impacting heterogeneous surface. The first question is how to keep droplet completeness during impacting process. Figs. 14 and 15 gave the answer. Practically, a specific combination of hydrophilic dot size \( d_i \) and initial droplet diameter \( d_0 \) yields the value of \( \beta_i \). The given working fluids such as water and air specified physical properties such as liquid viscosity \( \mu \), density \( \rho \) and surface tension \( \sigma \) between gas and liquid. When a droplet falls down from a height...
of $\beta$, the impacting velocity is estimated as $u_0 = (2gh)^{0.5}$. Holding $u_0$, Reynolds number $Re$, Weber number $We$ and Ohnesorge number $Oh$ can be determined in Section 2. Once $\beta$, $We$ and $Oh$ are known, a specific data point can be marked in Fig. 14. If such data point is located in the complete drop regime, the droplet completeness can be ensured after impacting. Otherwise, the droplet will be broken up. The second question is to determine the maximum spreading diameter $d_{\text{max}}$. Fig. 18 decides $d_{\text{max}}$, which is a key factor to design the heterogeneous surface to prevent droplets from being interfered with each other.

5. Conclusions

Drop impacting on heterogeneous surface is investigated. Governing equations and boundary conditions are described in non-dimensional form. Controlling parameters are $We$, $Re$ (or $Oh$) and $\beta_i$. Drop breakup and spreading are paid great attention. The findings are as follows.

- Due to wall adhesion of hydrophilic dot, there is an adhesion part on the wall. For drop impacting on a hybrid surface, partial rebound happens at moderate or large $We$, which is different from that on a uniformly super-hydrophobic surface, on which complete rebound occurs under similar condition.
- Two modes of drop breakup exist. Single-drop-pinning-off is caused by wall adhesion and excessive kinetic energy in the upper part of the droplet. Capillary wave is generated during the neck thinning process to accelerate the breakup. For multi-drops-pinning-off, the first time breakup is similar to single-drop-pinning-off. Then, capillary waves are generated from both ends of an elongated liquid column. They meet and interfere with each other to promote the liquid column breakup.
- For drop impacting on a heterogeneous surface, drop patterns include an adhesion part on the wall, similar to that on a hydrophilic surface, and a rebounding part, similar to that after impacting on a super-hydrophobic surface. This behavior is called the superposition principle.
- Figs. 14 and 15 summarized complete drop regime, single-drop-pinning-off regime, multi-drops-pinning-off regime and their transition boundaries. The increased $\beta_i$ narrows the drop breakup regime but enlarges the complete drop regime.
- At small or moderate $We$, $\beta_{\text{max}}$ is not changed by hydrophilic dot size if the dot size is smaller than the spreading diameter at the end of inertia spreading stage, beyond which $\beta_{\text{max}}$ is increased by increasing hydrophilic dot size. Ultra high $We$ completely suppresses the surface wettability effect to have constant $\beta_{\text{max}}$ versus $\beta_i$.
- When the hydrophilic dot is small such as $\beta_i = 0.5$, the stabilized drop is out of the hydrophilic dot. At moderate $\beta_i = 1.0$ and 1.5, the stabilized drop is successfully confined by the hydrophilic dot at its margin. As the hydrophilic dot size is increased to $\beta_i = 2.0$, the drop is inside the hydrophilic dot.

Conflict of interest

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.068.

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