DROPLET IMPACT ON A HYDROPHOBIC SUBSTRATE WITH CIRCULAR GROOVES

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Summary Droplet impact on a substrate with circular grooves is investigated by direct numerical simulation. The flows are fully resolved by a Navier-Stokes solver coupled with a diffuse interface model, which has been validated previously. We identify the transition regimes from the Cassie-Baxter to the Wenzel state, investigate flow details that are not accessible experimentally, considered previously, study the interplay between viscosity, inertia, surface tension, wettability and geometry in the penetration transient.

INTRODUCTION

Substrate such as lotus leaves covered by hydrophobic pillars in nano- and micron- scales, is known to form a super-hydrophobic surface (with apparent contact angle above 150°), on which water droplets can be easily removed. Water-repellent properties are appreciated both in nature, e.g. for insects living on water, and in practical applications, e.g. for the design of self-cleaning car windows and clothes. The property of superhydrophobicity lies in the fact that the drops reside on the top of micropillars, i.e., in the Cassie-Baxter state. As a result, the rough substrate exerts very little drag on the droplets moving on it. However, this property may be lost under certain circumstances. Recent experiments of drop impact on textured substrates displayed that the drop could impale the micropillars and stick to the substrate, i.e. entering the Wenzel state [1, 2, 3]. Such transition is irreversible, and therefore, it is critical for the design of superhydrophobic substrate to know how the transition from the Cassie-Baxter to the Wenzel state occurs. Two possible events that could lead to the transition have been proposed in [1]: i) touch-down of the meniscus between pillars to the substrate and ii) depinning and downward motion of contact lines from the pillars. Based on these two models, the authors in [1] analyzed the corresponding impalement pressure with respect to solid fraction. Despite recent progresses in experiments and theoretical analysis, the flow details of the transition and related mechanisms remain unclear. In this paper we study the drop impact on the substrate with circular grooves using direction numerical simulation. The flows are fully resolved by a Navier-Stokes solver, and the fluid-fluid interface and moving contact lines are tracked by the diffuse interface method [4, 5, 6]. A systematic study of the transition from the Cassie-Baxter to the Wenzel state is performed with respect to the flow parameters, as well as the geometrical parameter of the grooves. Several interesting phenomena in the drop impact will be presented. The interplay between inertia, viscosity, surface tension and wettability is also analyzed.

METHODOLOGY AND PROBLEM STATEMENT

Problem statement and governing equations

We consider here a spherical liquid drop of radius a impacting on a solid substrate with circular grooves at a speed of U. The viscosity and density of the drop are μ and ρ, respectively, and the ratio of viscosity (density) of the surrounding fluid to that of the drop is denoted by λ_μ (λ_ρ). The equations of motion are the Navier-Stokes equations with the divergence-free constraint. We render the equations of motion dimensionless by choosing a, U and $\tau(= a/U)$ as the characteristic length, velocity and time scales, respectively.

$$\bar{\rho}(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}) = -\nabla p + \frac{Oh}{\sqrt{We}}\nabla\cdot[\bar{\mu}(\nabla\mathbf{u} + \nabla\mathbf{u}^T)] + \frac{\mathbf{f_s}}{We}, \tag{1}$$

$$\nabla\cdot\mathbf{u} = 0, \tag{2}$$

where the dimensionless viscosity and density are $\bar{\mu} = C + (1-C)\lambda_\mu$ and $\bar{\rho} = C + (1-C)\lambda_\rho$, respectively, and C is the volume fraction of one of the fluids ($0 \le C \le 1$). Dimensionless groups are the Ohnesorge number $Oh = \mu/\sqrt{\rho a \sigma}$, Weber number $We = \rho U^2 a/\sigma$. The symbol $\mathbf{f_s}$ denotes the dimensionless surface tension force. All calculations are carried out in the axisymmetric plane (r, z). The implementation of boundary conditions such as the no-slip and the far-field can be found in []. The initial velocity field inside the drop is set to -1, whereas outside the drop it is set to zero.

Diffuse interface method and wetting conditions

We use volume fraction C to describe the interface and its evolution in the framework of a diffuse-interface model [6]. The time evolution of C field is governed by the convective Cahn-Hilliard equation

$$\frac{\partial C}{\partial t} + \nabla\cdot(\mathbf{u}C) = M\nabla^2\psi, \tag{3}$$

where M is the mobility, ψ $(= \phi'(C) - \epsilon^2\nabla^2 C)$ the chemical potential; ϵ represents a dimensionless measure of the thickness of diffuse interface, and $\phi = C^2(1-C)^2/4$ is the bulk energy density. Then, the surface tension force $\mathbf{f_s}$ in the

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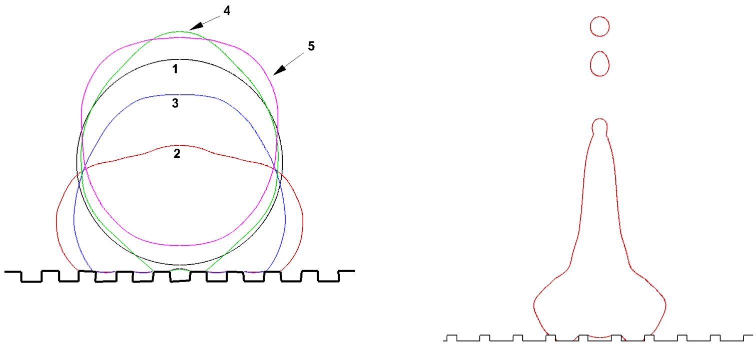

Figure 1. a) Time evolution of a bouncing-off droplet from the rough surface, at $We = 1$, $Oh = 0.003$ and $\theta = 130°$. The numbers indicate the time sequence. b) A sticky drop with pinch-offs. $We = 16$, $Oh = 0.005$ and $\theta = 130°$.

momentum equation (1) can be written as $\mathbf{f_s} = 6\sqrt{2}\psi\nabla C/\epsilon$. The model allows for moving contact lines and by the use of diffusive fluxes it alleviates the related non-integrable stress singularity [7]. The wettability of the grooves is assumed to be the same as the solid substrate, and is prescribed by a Young contact angle θ. A geometric formulation is used for a prescribed contact angle θ [5], leading to boundary conditions for C at the solid walls.

RESULTS AND DISCUSSION

The codes used for the present study are the essentially same as those have been used to study the inertial effects in the droplet spreading [4] and in the drop impact on an anisotropic porous substrate [8]. Two typical results are shown in Fig.1, including a bouncing-off drop from and a sticky drop with pinch-offs at its top. In the former case, the spreading and recoiling of the drops proceed in the Cassie-Baxter state. The presence of the sharp edges of the grooves leads to an effective contact-angle hysteresis, resulting in an energy barrier for the moving contact line. Therefore, the contact line is often seen to reside at the edges of the grooves until the energy barrier is overcome by inertia. However, Fig.1(b) shows a very different case — a sticky drop — on a rough surface that is supposed to be superhydrophobic. The main reason for the difference between the two cases lies in that the groove of the latter is three times as wide as the former. With high impact inertia, the drop in the latter case impales the groove during the spreading process, touches the groove bottom and drives the gas out of the groove. When it recoils after reaching the maximum wetting area, the drop cannot bounce off completely from the rough substrate like the case in Fig.1(a). Instead, it ends up with leaving a relatively large amount of liquid on the substrate and inside the grooves. More results and detailed analysis will be reported in the conference.

CONCLUSIONS

Using droplet impact on a substrate with circular grooves as a model problem, we numerically investigate the transition from the Cassie-Baxter to the Wenzel state, which occurs during the drop spreading on a rough surface in experiments. The sharp edges of the grooves appear to result in an effective contact-angle hysteresis, which pins the contact line and allows for the occurrence of meniscus over the grooves. It is also found that the Cassie-Baxter state can coexist with the Wenzel state.

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