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Investigation of effects of receding contact angle and energy conversion on numerical prediction of receding of the droplet impact onto hydrophilic and superhydrophilic surfaces

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ABSTRACT

The aims of this paper is to investigate the influential factors on numerical prediction of the receding of a droplet impact onto the hydrophilic and superhydrophilic surfaces. In order to accomplish this target, the hydrophilic and superhydrophilic copper surfaces are fabricated and the droplet impacts onto the fabricated surfaces are recorded by the experimental observation system. Using the volume-of-fluid(VOF) method with the smooth function, the impacts of the droplet onto the hydrophilic and superhydrophilic surface are predicted. Associated with the experimental data and the numerical results, from two aspects of the dynamic contact angle and energy conversion among the kinetic energy, static pressure, surface energy and viscous dissipation, the characteristics of the receding of the impacting droplet are summarized. It is found that the numerical extra viscous dissipation induced by the parasitic currents have an obvious influence on the height of the apex of the receding droplet for the three dimensional computational domain, and the receding dynamic contact angle play an important role on the moving direction of the triple-phase contact line in the receding. Finally, considering both the space dimensional and dynamic contact angle effects, the 2d axisymmetric computational domains and proper dynamic contact angles are used to present the local energy distributions of the droplet impact on hydrophilic and superhydrophilic surfaces, and the mechanism of the energy conversion inside the droplet is discussed.

1. Introduction

The impact of a droplet onto a solid surface is a general process that appears in nature and industrial applications, and the surfaces impacted on comprise macroscopically flat ones (Liao et al., 2008, Liang et al., 2013, An and Lee, 2012, Vaikuntanathan et al., 2010, Šikalo et al., 2005, Roisman et al., 2008, Lee et al., 2016–, (Yokoi et al., 2009) or rough ones with superficial natural or artificial microstructures (Zu et al., 2010, Merlen and Brunet, 2009, Yan, 2007, Moita et al., 2016, Yuan and Zhao, 2013, Lv et al., 2010, Yuan and Zhao, 2015, Chen et al., 2016, Singh and Dandapat, 2013, Bird et al., 2013, Liu and Kim, 2014, Wang et al., 2015, Liu et al., 2014, Zhang et al., 2016–, (Chamakos et al., 2016). Due to the huge potential application of the wetting and non-wetting surfaces in anti-fogging (Han et al., 2018), anti-icing (Mishchenko et al., 2010, Wang et al., 2016, Lv et al., 2014–, (Wang et al., 2016), inkjet printing (Tan, 2016), water collection (Parker and Lawrence, 2001, Zhai and M.C.Berg, 2006–, (Hou et al., 2015), drag reduction (Lee and Kim, 2011, Xu et al., 2014), self-cleaning, water or oil repellent (Liu and Kim, 2014, Hensel et al., 2013, Moevius et al., 2014), enhanced heat transfer (Betz et al., 2013, Shen et al., 2018), etc., the impact phenomenon of droplet onto the wetting surfaces becomes one of the hottest research topics.

Similar as biological multilevel surfaces, the rough surfaces with microstructures can enhance the water wetting or repellent effects, which correspond to the Wenzel wetting state and the Cassie-Baxter non-wetting state, respectively. Moreover, with the development of the microstructure processing technology, more and more surfaces with microstructures can be fabricated easily, and the impact of the droplet on the surface with microgrooves (Malla et al., 2017, Vaikuntanathan and Sivakumar, 2016, Kannan and Sivakumar, 2008–A.Yagub and S.Kondaraju, 2015), pillar-array (Tan, 2017, Wang and Chen, 2015, Moqaddam et al., 2017, (Wang et al., 2017), microcavities (Kim et al.,

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Nomenclature

a/b	parameters for the formula to get the normal vector of the interface
Ca	capillary number
c_p	specific heat(J•kg^{-1}•K^{-1})
C_γ	adjustable coefficient
D_{ini}	the diameter of the impacting droplet(m)
E_h, E_k, E_p, E_s	global gravitational energy, surface energy, static pressure head and surface energy of the whole droplet(J)
$\boldsymbol{F}_\sigma$	surface tension form term in the momentum equation
f_{Hoff}/f_{Hoff}^{-1}	Hoffman's function/inverse function of the Hoffman's function
$\boldsymbol{g}$	gravitational acceleration vector(m/s^2)
$\boldsymbol{n}_\text{f}$	normal vector of the interface
$\boldsymbol{n}_{\text{f},\ 0}$	current normal vector of the liquid-vapor interface at the wall
$\boldsymbol{n}_{wall}$	normal vector to the wall
p	pressure(Pa)
p_{rgh}	modified pressure(Pa)
∇p_{rgh}	gradient of the modified pressure
r	r-axis in the cylindrical coordinate(m)
r_{cl}	wetting radius of the impacting droplet at the current moment(m)
S_f	area of the cell surface(m^2)
s	slip coefficient at the wall
t	time(s)
T	temperature(K)
$\boldsymbol{u}$	velocity vector(m•s^{-1})
u_i	velocity at the center of the cell adjacent to the wall (m•s^{-1})
$\boldsymbol{u}_\text{r}$	artificial compression velocity(m•s^{-1})
$u_{t,\ wall}$	velocity at the wall(m•s^{-1})
$\nabla \boldsymbol{u}$	gradient of the velocity vector
U_{CL}	velocity of the triple contact angle(m•s^{-1})
$\boldsymbol{x}$	vector of the coordinate point which starts from the origin corresponding to the coordinate point(m)

Greek symbols

θ	apparent contact angle/θ-axis in the cylindrical coordinate (°)
θ_0	current contact angle of the interface(°)
θ_{adv},θ_{rec},$\theta_{\text{rec, min}}$	limited advancing, receding and minimum receding dynamic contact angle(°)
θ_D	dynamic contact angle(°)
θ_e	static equilibrium contact angle(°)
μ	dynamic viscosity(Pa•s)
λ	thermal conductivity(W•m^{-1}•K^{-1})
φ	local viscous dissipation
ρ	density(kg•m^{-3})
$\nabla\rho$	gradient of the density
α	volume fraction
$\tilde{\alpha}_P$	smooth function of volume fraction
$\nabla\alpha$	gradient of the volume fraction
ϕ	mass flux across the cell surface(kg•m^{-2}•s^{-1})
Φ	global accumulation viscous dissipation over the time and space
δ	coefficient of the surface tension(N•m^{-1})
κ	curvature of the interface(m^{-1})
π	circumference ratio

Subscripts

1/2	phase-1/phase-2
f	cell surface
P	cell index
wall	wall surface

Superscripts

T	transposition of matrices

2014), etc., draws much attentions of researchers. The relating dynamic mechanism for the spreading, receding, rebound and splashing, etc., during the process of these droplet impact on these surfaces with microstructures is illuminated (Josserand and Thoroddsen, 2016, Khojasteh et al., 2016). So far, the works to study the impact processes that droplets impact on hydrophobic and superhydrophobic surfaces are much more, whereas to the authors' knowledge, the processes that the droplet impact on hydrophilic surfaces, especially on superhydrophilic surfaces with microstructures re less focused on.

The movement of the triple-phase contact line common to gas, liquid and solid phases (Sui et al., 2014) happens at all dynamic stages for the impact of a droplet onto the surface, and it's a typical multiscale problem involving interaction at the microscale, mesoscale and macroscale. In general the joint manner combining of the experimental test and the theoretical numerical simulation are used to analyze the impacting process (Šikalo et al., 2005, Lee et al., 2016, Liu et al., 2014, Moevius et al., 2014, Fink et al., 2018, Bai et al., 2017). Associated with the key value of the dynamic contact angle obtained from the experimental data (Yokoi et al., 2009, Kistler, 1993, Tanner, 1973), the dynamic spreading and receding process of the droplet impact could be reproduced macroscopically by the typical interface-capturing/tracking methods, such as level-set methods, volume-of-fluid(VOF) methods, diffuse interface methods, front-tracking methods etc. (Sui et al., 2014, Ding and Spelt, 2007, Ding and Spelt, 2007, Sui and Spelt, 2013, Yokoi, 2013–, (Hoang et al., 2013).

However, until now, the receding process, including the receding droplet shape, radius from the center to the triple line and height of apex of the receding droplet, can't be predicted by the numerical method as accurately as the spreading process in most conditions (Šikalo et al., 2005, Fink et al., 2018). Therefore, in this paper the influential factors on the numerical prediction of the receding of the droplet impact onto the hydrophilic(HPi) and superhydrophilic(sHPi) surfaces are investigated, based on both the experimental data and the typical interface-capturing numerical method, i.e. VOF.

The dynamic contact angle is an important measure for the moving contact line problem (Šikalo et al., 2005, Lee et al., 2016, Yokoi et al., 2009, Sui et al., 2014, Kistler, 1993, Tanner, 1973). In addition, the conversion among various inherent energies, including the dynamic and static pressure, surface energy and viscous dissipation, is the inherent driving source for the droplet impact, and naturally have an influence on the dynamic wetting status of the droplet impact (Lee et al., 2016, Lee et al., 2015). Thus, the receding dynamic contact angle at the triple line and the internal energy conversion inside the droplet are taken as the primarily influential factors on the receding of the droplet impact to be discussed in this paper.

In order to accomplish the research target, i.e. revealing the primarily influential factors on the numerical prediction of the receding of the droplet impact, the specific contents in this paper are organized in the following sections. Firstly, the HPi flat copper surface is fabricated by polishing, and the sHPi surface based on the Wenzel wetting theory (Chen et al., 2016, Liu and Kim, 2014, Mishchenko et al., 2010, Wang et al., 2016, Lv et al., 2014, Wang et al., 2016, Lee and Kim, 2011, Xu et al., 2014) is fabricated by the laser ablation and redox reaction. Next, the droplet spreading and receding processes during the impact onto