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Modeling of the non-isothermal liquid droplet impact on a heated solid substrate with heterogeneous wettability

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ABSTRACT

A comprehensive numerical investigation on the impingement and spreading of a non-isothermal liquid droplet on a solid substrate with heterogeneous wettability is presented in this work. The time-dependent incompressible Navier–Stokes equations are used to describe the fluid flow in the liquid droplet, whereas the heat transfer in the moving droplet and in the solid substrate is described by the energy equation. The arbitrary Lagrangian–Eulerian (ALE) formulation with finite elements is used to solve the time-dependent incompressible Navier–Stokes equation and the energy equation in the time-dependent moving domain. Moreover, the Marangoni convection is included in the variational form of the Navier–Stokes equations without calculating the partial derivatives of the temperature on the free surface. The heterogeneous wettability is incorporated into the numerical model by defining a space-dependent contact angle. An array of simulations for droplet impingement on a heated solid substrate with circular patterned heterogeneous wettability are presented. The numerical study includes the influence of wettability contrast, pattern diameter, Reynolds number and Weber number on the confinement of the spreading droplet within the inner region, which is more wettable than the outer region. Also, the influence of these parameters on the total heat transfer from the solid substrate to the liquid droplet is examined. We observe that the equilibrium position depends on the wettability contrast and the diameter of the inner surface. Consequently, the heat transfer is more when the wettability contrast is small and/or the diameter of inner region is large. The influence of the Weber number on the total heat transfer is more compared to the Reynolds number, and the total heat transfer increases when the Weber number increases.

1. Introduction

The dynamic behavior of droplets and sprays impinging on a solid substrate is of great importance in many industrial applications such as spray cooling, spray forming, flow boiling, ink-jet printing, thermo-syphons, fuel injection, engines with internal combustion and jet impingement cooling. Most of the industrial applications involve droplets or spray impact on solid substrate with heat transfer and phase change, which are mainly influenced by the droplet dynamics. The spray-wall interactions and the heat transfer process are very complex and our understanding is far from being complete. The insight into the fundamental mechanisms responsible for the wetting and heat transfer in two-phases is indispensable for optimal results and therefore scientific studies on single droplet impact on hot solid substrate, including heterogeneous wettability are highly demanded.

Although investigations involving a droplet wetting on non-homogenous surfaces are in the early stages of research, droplet impinging on heterogeneous substrate has a variety of potential applications. For example smart surfaces with artificially designed wettability, spatially controlled fluidic transport in microfluidic and lab-on-a chip devices and engines with internal combustion use dynamic wetting properties, see [1] for an overview. In these applications, the droplet has to be confined within a specified area and the interaction with the adjacent droplets has to be avoided when the deposited droplets are in close proximity to each other. To confine the spreading of an impinging droplet within a specified area, chemical surface coating with a pattern of high wettability contrast is often used in industrial applications. In addition, the temperature (also the magnetic or the electric) field can also be used to enhance the control on the dynamics of the droplet [1].

A number of experiments and numerical simulations have been reported in the literature for the equilibrium shape of the droplet on heterogeneous surfaces, see the recent review [1] and the references therein. Most of the numerical simulations have been performed to identify the equilibrium shape of the droplet on a

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Nomenclature

α_F	convection heat transfer coefficient on liquid–gas interface
β_ϵ	slip number
Γ_F	free surface
Γ_N	non-wetting part of the solid phase
Γ_S	liquid–solid interface
γ_{ref}	reference surface tension
$\hat{\gamma}$	surface tension factor
ζ	contact line
θ_c	dynamic contact angle
θ_e^{in}	equilibrium contact angle of inner surface
θ_e^{out}	equilibrium contact angle of outer surface
λ_F	thermal conductivity of fluid
λ_S	thermal conductivity of solid
μ	dynamic viscosity of fluid
ν_F	unit outward normal vector on free surface
ν_S	unit outward normal vector on liquid-solid interface
$\boldsymbol{\nu}_\zeta$	co–normal vector at the contact line
ρ	density of fluid
ρ_S	density of solid
τ_F	unit tangential vector on free surface
τ_S	unit tangential vector on liquid–solid interface
Ω	computational domain for energy equation
Ω_F	fluid domain
Ω_S	solid domain
$\hat{\Omega}$	reference domain of ALE mapping
$\mathbb{D}$	deformation tensor of fluid velocity
$\mathbb{I}$	identity tensor
$\mathbb{S}$	stress tensor of fluid
∇_Γ	tangential gradient operator on the free surface
$\otimes$	tensor product
id_Γ	identity mapping
$\mathcal{A}_t$	ALE mapping
$\mathcal{C}_1$	negative rate of change of surface tension with temperature
tr	trace
Bi	Biot number
Fr	Froude number
Pe_F	fluid Peclet number
Pe_S	solid Peclet number
Re	reynolds number
We	weber number
c_p^F	specific heat of fluid
c_p^S	specific heat of solid
D_p^{in}	pattern diameter of the inner surface
T_∞	temperature in surrounding gas
T_F	temperature in fluid
T_{ref}	reference temperature
T_S	temperature in solid
d_0	initial droplet diameter
d/d_0	dimensionless wetting diameter
u_{imp}	impact speed
g	gravitational constant
p	pressure
q	test function in pressure space
t	time
I	end time
L	characteristic length
Q	pressure space
U	characteristic velocity
V	velocity space
$\mathbf{e}$	unit vector in the direction opposite to gravitational force
$\boldsymbol{n}$	unit outward normal on non-wetting part of solid phase
$\mathbf{u}$	fluid velocity
$\mathbf{v}$	test function in velocity space
$\mathbf{w}$	domain velocity
$\mathbf{X}$	Eulerian coordinate
$\mathbf{Y}$	ALE coordinate

heterogeneous wetting surface by minimizing the free energy with the volume constraint. The equilibrium shape of a three-dimensional (3D) droplet has been computed in [2] using the public-domain software "Surface-Evolver". The authors varied the contact angle in the free energy minimization calculation to incorporate the heterogeneous wettability effect and studied the contact angle hysteresis through the displacement of the contact line by increasing the volume of the droplet. However, the gravitational effect has not been considered in [2]. A similar approach by varying the contact angle through a position dependent interfacial energy model with gravitational effect has been presented in [3]. In particular, the authors extended the earlier model to treat chemically heterogeneous substrates with "mesa" defects. Another numerical study on the contact angle hysteresis using the free energy minimization algorithm has been presented in [4]. Recently, an analytic expression for the equilibrium droplet aspect ratio on a heterogeneous surface has been proposed in [5]. Further, the authors compared the analytically obtained aspect ratio with the numerical solution obtained using the public software "Surface-Evolver". A free energy lattice Boltzmann algorithm has also been proposed in [6] to study the droplet dynamics on chemically patterned surfaces. The authors applied a constant force (Poiseuille flow field) over the droplet to displace it on a heterogeneous surface, and studied the effect of wettability contrast. Molecular dynamics simulations for water droplets with radius of few Angstrom have been presented in [7] to study the wetting effects on a planar surface with heterogeneous wettability and on surfaces with pillars. Recently, phase-field simulations for micro-sized isothermal droplet impinging on a heterogeneous wettability surface have been presented in [8]. Even though many numerical simulations using free energy minimization algorithms have been performed for the equilibrium shape of the droplet, the flow dynamics of impinging droplets on surfaces with heterogeneous wettability has been considered only in [8].

A considerable number of numerical simulations of droplet impinging on heated solid substrates with homogeneous wettability have been reported in the literature [9–17]. The above list of references may not be complete, but to the best of the authors knowledge, simulation of droplet impinging on heated solid substrates with heterogeneous wettability has not been reported in the previous studies.

In the present study, numerical simulations of non-isothermal droplet impinging and spreading on a heated solid substrate with circular patterned heterogeneous wettability are presented. The ALE finite element scheme proposed in [17] is extended for solid substrates with heterogeneous wettability. Moreover, the Marangoni convection is included in the variational form of the Navier–Stokes equations without calculating the tangential derivative of the surface tension. In the ALE approach, the moving boundaries are resolved by moving meshes and thus the boundaries are