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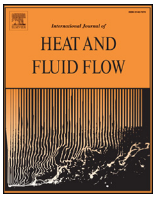

Effects of temperature-dependent contact angle on the flow dynamics of an impinging droplet on a hot solid substrate

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ABSTRACT

A temperature-dependent dynamic contact angle as a function of temperature-dependent surface tension and reference equilibrium contact angle is proposed for modeling of moving contact line flows, in particular, for computations of liquid droplet impingement on a hot solid substrate. The fluid flow in the liquid droplet is described by the time-dependent incompressible Navier–Stokes equations, whereas the heat transfer in the liquid droplet and in the solid substrate is described by the energy equation. The arbitrary Lagrangian–Eulerian (ALE) approach together with the finite element method is used to solve the governing equations in a time-dependent domain. Further, the Marangoni effects are incorporated into the model without evaluating the tangential derivatives of the temperature on the free surface. The effects of temperature-dependent contact angle on the flow dynamics of the droplet and on the heat transfer from the solid substrate into the liquid droplet are studied for different Reynolds numbers, Weber numbers, solid phase Peclet numbers, solid phase initial temperatures and reference equilibrium contact angles. Numerical studies show that the influence of the temperature-dependent contact angle is negligible in partially wetting droplets, whereas the effects on the wetting diameter and on the total heat transfer are 10.79% and 7.36% respectively in the considered highly wetting and non–wetting droplets.

1. Introduction

Understanding the physics involved in cooling and/or temperature regulations of solid substrates using sprays are of fundamental importance in a wide variety of industrial applications such as fuel injection, thin film coating, spray cooling, internal combustion engines, micro/nano material fabrication, etc. Most of these applications involve heat transfer and their computations are of particular scientific interest. Modeling of the heat transfer mechanism involved in the process of a liquid droplet impinging on a hot solid substrate is very complex. Tracking/capturing the moving boundaries and incorporating the dynamic contact angle are the main challenges in the modeling. Further, an accurate approximation of the curvature, precise inclusion of the Marangoni and surface forces and handling the jumps in the liquid and solid material parameters make the computations more challenging.

Apart from all these challenges, handling the moving contact line is one of the main challenges in moving contact line flows (Ganesan, 2013; Ren and Weinan E, 2007; Sui et al., 2014). The choice of an appropriate boundary condition on the liquid-solid interface and a dynamic contact angle are the two challenges associated with the modeling of moving contact line flows. The use of the classical no-slip boundary condition on the liquid-solid interface induces an unbounded stress singularity at the moving contact line, where the liquid, solid and gas phases intersect. Several approaches have been proposed in the literature to alleviate this singularity, see for example, Behr and Abraham (2002); Eggers and Stone (2004); Hocking (1977). Among all, the Navier-slip boundary condition has been widely accepted to ease the singularity at the moving contact line. Nevertheless, the main challenge in using the Navier-slip boundary condition is the choice of the slip coefficient. The slip coefficient is often determined by comparing computationally obtained wetting diameter with experimental results (Ganesan, 2013; Ganesan et al., 2014). A number of expressions have been proposed for the slip coefficient, see for example, Cox (1986); Dussan V (1976); Hocking (1977) for different moving contact line problems. Recently, a mesh-dependent slip relation for impinging droplets has been proposed in Venkatesan and Ganesan (2015), and we use it in this work.

The contact angle is an important property of a liquid droplet that is determined by the interfacial tensions between the liquid, solid and gas phases. It deviates from its thermodynamic equilibrium value when the droplet spreads and recoils. In addition,

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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
$\hat{\gamma}$	surface tension factor
δt	time step length
ζ	contact line
θ_d	dynamic contact angle
θ_e^{ref}	reference equilibrium contact angle
$\mathcal{K}$	curvature
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
σ	liquid–gas surface tension
σ^{sg}	solid–gas surface tension
σ^{sl}	solid–liquid surface tension
σ_{ref}	reference surface tension
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
$\mathbb{D}$	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
$\mathcal{C}_1$	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
T_∞	temperature in surrounding gas
T_F	temperature in fluid
T_G	temperature at solid–gas interface
T_{ref}	reference temperature
T_S	temperature in solid
d_0	initial droplet diameter
d/d_0	dimensionless wetting diameter
u_{imp}	impact speed of droplet
g	gravitational constant
p	pressure
q	pressure space test function
t	time
I	given 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
$\mathbf{n}$	unit outward normal on non-wetting part of solid phase
$\mathbf{u}$	fluid velocity
$\mathbf{v}$	Velocity space test function
$\mathbf{w}$	domain velocity

several experimental studies on the influence of the temperature on the contact angle have been reported in the literature, see for example, Adamson (1973); Bernardin et al. (1997); Chandra et al. (1996); Neumann (1974); Neumann et al. (1971); Petke and Ray (1969); de Ruijter et al. (1998); Schonhorn (1966); Steinke (2001). For instance, two distinct temperature regimes for the static advancing contact angle of water on an aluminium surface have been observed in Bernardin et al. (1997). A relatively constant contact angle of 90° has been observed for temperatures less than 120°C, whereas a fairly linear decrease in the contact angle is observed for temperatures above 120°C. Next, the influence of the temperature on contact angles at low temperatures ($5^\circ - 100^\circ$ C) has been investigated in Adamson (1973); Neumann (1974); Neumann et al. (1971). It has been reported in these studies that $|\partial\theta/\partial T| \approx 0.1$deg K^{-1}. Further, the influence of the temperature on the contact angle for water and several other liquids on six polymeric solids has been studied in Petke and Ray (1969). The authors have found that the value of $|\partial\theta/\partial T|$ varies between 0.03 deg K^{-1} and 0.18 deg K^{-1} for the temperature range $5^\circ - 100^\circ$ C. Since the flow dynamics of the droplet directly depends on the contact angle, it is essential to use a temperature-dependent dynamic contact angle model to accurately capture the flow dynamics during the spreading and recoiling.

A considerable number of numerical studies for a liquid droplet impinging on a hot solid surface using the Volume–of–fluid method have been reported in the literature (Briones et al., 2010; Ghafouri-Azar et al., 2003; Harvie and Fletcher, 2001; Putnam et al., 2012; Strotos et al., 2008). Numerical studies using the Level set method (Y. Ge, 2005; 2006), the Immersed Boundary method (Francois and Shyy, 2003a; 2003b) and the Lagrangian method (Z. Zhao, 1996) have also been reported in the literature. Further, computations using the ALE approach for a liquid droplet impinging on a hot solid substrate have been presented in Ganesan et al. (2014); 2015). In all these numerical studies the contact angle, which is independent of temperature, have been considered. Recently, a dynamic contact angle model that depends on surfactants has been proposed in Ganesan (2015); M.-C. Lai and Huang (2010). However, to the best of the authors' knowledge, a temperature-dependent dynamic contact angle for computations of droplet impingement on a hot solid substrate has not been used in the literature.

In this paper, a temperature-dependent dynamic contact angle using the Young's law which is a function of temperature-dependent surface tension and reference equilibrium contact angle is proposed. Further, the effects of temperature-dependent dynamic contact angle on the flow dynamics of the droplet are studied by comparing the results with temperature-independent contact angle model (Ganesan et al., 2014; 2015). We use the sharp interface ALE finite element approach for computations of a non-isothermal liquid droplet impinging on a hot solid substrate. The inclusion of the contact angle is straightforward in interface resolved numerical schemes and explained in Ganesan et al. (2014). However, the choice of an appropriate contact angle in

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