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A numerical investigation of the evaporation process of a liquid droplet impinging onto a hot substrate

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Abstract

A numerical investigation of the evaporation process of *n*-heptane and water liquid droplets impinging onto a hot substrate is presented. Three different temperatures are investigated, covering flow regimes below and above Leidenfrost temperature. The Navier–Stokes equations expressing the flow distribution of the liquid and gas phases, coupled with the Volume of Fluid Method (VOF) for tracking the liquid–gas interface, are solved numerically using the finite volume methodology. Both two-dimensional axisymmetric and fully three-dimensional domains are utilized. An evaporation model coupled with the VOF methodology predicts the vapor blanket height between the evaporating droplet and the substrate, for cases with substrate temperature above the Leidenfrost point, and the formation of vapor bubbles in the region of nucleate boiling regime. The results are compared with available experimental data indicating the outcome of the impingement and the droplet shape during the impingement process, while additional information for the droplet evaporation rate and the temperature and vapor concentration fields is provided by the computational model.
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Keywords: Droplet evaporation; Volume of Fluid Method; Kinetic theory; Leidenfrost temperature

1. Introduction

The liquid–vapor phase change process, plays a significant role in a number of technological applications in combustion engines, cooling systems or refrigeration cycles. In all the aforementioned applications, the dynamic behavior of the impinging droplets and the heat transfer between the liquid droplets and the hot surfaces are important factors, which affect the mass transfer associated with liquid–vapor phase change.

The mechanism of the droplet spreading and the accompanying heat transfer is governed not only by non-dimensional parameters as the droplet Weber (We), the Reynolds (Re) number, Eckert (E_c) number, and Bond (Bo) number, but also by the temperature of the surface. As the droplet impacts upon the hot solid surface, heat is transferred from the solid to the liquid phase. This energy transfer to the droplet increases its mean temperature, while liquid vaporizes from the bottom of the droplet. If the heat transfer rate is large enough during the impact, liquid vaporized from the droplet forms a vapor layer between the solid and the liquid phase, which repels the droplet from the solid surface. In this case the heat transfer reaches a local minimum and the evaporation lifetime of the droplet becomes maximum. This phenomenon was first observed by Leidenfrost [1] in 1756 and hence the behavior is known as the Leidenfrost phenomenon. Based on the evaporation lifetime of a droplet, mainly four different evaporation regimes can be identified depending on the wall temperature; film evaporation, nucleate boiling, transition boiling and film boiling. This work contributes to the study of transition and film boiling impact regimes only.

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Nomenclature

Bo	Bond number, $(=\rho_{\text{liq}} g D_{\text{o}}^2/\sigma)$
C_p	non-dimensional pressure, $\left(=\Delta P/\frac{1}{2}\rho_{\text{liq}} U_{\text{o}}^2\right)$
c_p	heat capacity (J/kg K)
D_{AB}	diffusivity of gas A to gas B, $(=\mu/(Sc\cdot\rho))$
E_c	Eckert number, $(=U_{\text{o}}^2/(c_p(T_{\text{liq}}-T_{\text{w}})))$
D_{o}	initial diameter of droplet
E_{sur}	surface energy
E_{kin}	kinetic energy
k	thermal conductivity (W/mK), $(=c_p\cdot\mu/Pr)$
MB	molecular weight (kg/kmol)
$\vec{n}$	vector normal to interface of the two phases
Oh	Ohnesorge number, $(=\mu_{\text{liq}}/(\sigma\rho_{\text{liq}} D_{\text{o}})^{0.5})$
P	pressure
Pr	Prandtl number, $(=\mu c_p/k)$
$\overline{R}$	universal gas constant (J/kmol K)
R	computational radius
R_{o}	radius of initial droplet
Re	Reynolds number $(=\rho_{\text{liq}} D_{\text{o}} U_{\text{o}}/\mu_{\text{liq}})$
Sc	Schmidt number $(=\mu/(\rho D_{AB}))$
SYG	vapor concentration (mass of vapor (kg)/mass of gas phase (kg))
T	temperature
t	time
$\vec{T}$	stress tensor
$\vec{u}$	velocity
U_{o}	initial velocity of droplet
U_1	velocity of an equivalent droplet of the ring
V	volume
X	X-axis of computational field
Y	Y-axis of computational field
Z	Z-axis of computational field
Z_h	height of spreading droplet
We	Weber number, $(=\rho_{\text{liq}} D_{\text{o}} U_{\text{o}}^2/\sigma)$

Greek symbols

α	volume of fluid (also noted as indicator function)
δ	vapor height
κ	curvature (m^{-1})
μ	dynamic viscosity
ρ	density
σ	surface tension
$\bar{\sigma}$	thermal accommodation coefficient

Subscripts

gas	gas phase
liq	liquid phase
b	base
vap	vapor
cell	computational cell
sat	saturation point
w	substrate or wall

The collision dynamics of a liquid droplet impinging on a hot surface has been investigated mainly experimentally. Researchers have presented a sequence of photographs showing the deformation process of liquid droplets impacting on a hot surface. Wachters and Westerling [2] were among the first to investigate the impact of a saturated water droplet of about 2 mm in diameter impinging on a polished gold surface heated to 400 °C, while Akao et al. [3] inspected the deformation behavior of various liquid droplets of 2 mm diameter on a chromium-plate copper surface heated to the same temperature. Xiong and Yuen [4] measured the time history of a n-heptane droplet impinging on a stainless-steel surface heated to temperatures between 63 °C and 605 °C. Chandra and Avedisian [5] performed the same experiment with a temperature range from 24 °C to 205 °C keeping a constant Weber number $We = 43$ while the same authors in [6] have presented results for the deformation process of a droplet impinging onto a porous ceramic surface. Naber and Farrell [7] examined the deformation process of liquid droplets of 0.1–0.3 mm in diameter impinging on a hot stainless-steel surface, while at the same time Anders et al. [8] investigated the rebounding phenomenon of ethanol droplets impacting obliquely on a smooth chromium-plated copper surface at 500 °C.

Ko and Chumg [9] investigated experimentally the effect of wall temperature on the break-up process of n-decane fuel, in the Leidenfrost temperature range of 220–330 °C, and demonstrated that wall temperature variation shows a peculiar nonlinear behavior in the droplet break-up probability, especially near 250 °C, which corresponds to the temperature of local maximum droplet lifetime. Manzello and Yang [10] examined the effect of an additive in a water droplet on its collision dynamics on a stainless-steel surface with the wall temperature varying from film evaporation to film boiling regime for three *Weber* number impacts.

Bernardin et al. [11,12] realizing that the impact parameters can alter the collision outcome, conducted a thorough series of experiments, concerning water droplets impinging on a polished aluminium surface, with the main controlling parameters of the phenomenon being droplet velocity, resulting in We number from 20 to 220 and surface temperature from 100 °C to 280 °C. They constructed droplet impact regime maps, which distinguish between the various boiling regimes for each of the three experimental We numbers investigated. Moreover, the heat flux from the surface was measured, for different We numbers, drop impact frequency and surface temperature, determining the two very important points in the regime map, the Leidenfrost point (LFP) and the critical heat flux point (CHF). The first

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