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Numerical simulation of droplet impact and evaporation on a porous surface

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ABSTRACT

Numerical simulation is performed for the evaporation of a droplet impacted on a porous surface. A level-set formulation for tracking the droplet deformation is extended to include the effects of evaporation coupled to heat and mass transfer, porosity and porous drag and capillary forces. The local volume averaged conservation equations of mass, momentum, energy and vapor fraction for the porous region are simultaneously solved with the conservation equations for the external fluid region. The computations demonstrate not only the evolution of the liquid-gas interface during the whole period of droplet penetration and evaporation in a porous medium, but also the associated flow, temperature and vapor fraction fields. The effects of impact velocity, porosity and particle size on the droplet deformation and evaporation are quantified.

1. Introduction

The evaporation of a droplet impacted on a porous surface is of significant importance in various applications such as inkjet printing on papers or bio materials and treatment of hazardous chemicals in soil or fabrics. However, its prediction model has not yet been developed to simultaneously analyze the interfacial motion and evaporation coupled to heat and mass transfer inside as well as outside the porous medium.

A number of numerical simulations were performed for droplet impact and evaporation on a non-porous surface using a marker-and-cell (MAC) method [1], the volume-of-fluid (VOF) method [2– 5], a finite-element method (FEM) [6–9], a body-fitted moving-grid method [10], a level-set (LS) method [11–17] and a front-tracking method [18]. However, only a few numerical studies were extended to the evaporation of a droplet impacted on a porous surface.

Reis et al. [19, 20] conducted numerical simulations of droplet impact on a porous surface by solving the conservation equations of mass and momentum inside and outside the porous medium. The conservation equations inside the porous medium were based on the local volume averaged formulation including the effects of porosity and drag force due to the solid matrix [21–23]. The droplet shape was tracked by the MAC method. The numerical results were comparable to their experimental data of droplet deformation, which were obtained with magnetic resonance imaging (MRI) techniques [24]. Kim and Lee [25] also used a similar form of conservation equations for analysis of the droplet motion in a porous medium. They incorporated the effect of dynamic contact angle into the VOF formulation with a compression term. Choi et al. and Son [26] employed the LS method to investigate the effects of initial droplet radius, impact velocity, contact angle, particle size and porosity on the droplet spread and penetration in a porous medium. The different formulations for the matching conditions of the pressure and viscous stress at the porous-fluid interface were compared in the computations of droplet motion. The LS method was also applied to the computation of droplet-droplet interaction in the porous medium.

Roberts and Griffiths [27, 28] presented an analytical model for predicting droplet evaporation from a porous surface. The model was based on a one-dimensional shape of the droplet embedded in a porous medium. During the early period, the evaporation rate is constant and depends on the vapor transport into the air. As the upper evaporating surface of the embedded droplet further recedes in the porous medium, the evaporation rate decreases depending on the vapor transport inside as well as outside the porous medium. Westin et al. [29] developed a more comprehensive model for predicting the

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Nomenclature

B	drag coefficient of a porous solid matrix
d_p	particle diameter
d_{pore}	pore diameter
F	fraction function
h	grid spacing
H_s	height of a porous medium
M	molecular mass
$\mathbf{n}$	unit normal vector
p	pressure
r, y	cylindrical coordinates
R_o	initial droplet radius
t	time
$\mathbf{u}$	flow velocity vector, (u, v)
v_o	droplet impact velocity
Y_v	vapor mass fraction

Greek symbols

α	step function
β	$\rho_g^{-1} - \rho_l^{-1}$
ϵ	porosity
θ_a	advancing contact angle
θ_{pore}	contact angle in a porous medium
θ_r	receding contact angle
θ_s	contact angle at the porous-fluid interface
κ	interface curvature
μ	dynamic viscosity
ρ	density
σ	surface tension coefficient
τ	artificial time
ϕ	distance function from the liquid-gas interface
ψ	distance function from the porous-fluid interface

Subscripts

a, v	air, vapor
g, l	gas, liquid
o	initial
p	particle
s	solid or porous medium

spreading and absorption of a droplet impacted on a porous surface. The subsequent evaporation and redistribution of the droplet embedded in the porous medium were computed from a vertical one-dimensional diffusion equation. Figus et al. [30] studied the phase-change heat transfer in the porous medium of a capillary evaporator using two numerical methods: a continuum (Darcy) method based on a body-fitted moving FEM and a pore network method. When the porous medium was assumed to have a single pore size, the results from both methods were almost identical and the vaporizing interface was smooth. However, when the pore size was not uniform, the pore network simulations resulted in irregular liquid-gas interface configurations. The pore network method was also applied to droplet evaporation in a porous medium [31, 32], but it was not extended to computation of the whole process of the evaporation of a droplet impacted on a porous surface.

In this work, we extend the LS method to computation of droplet impact and evaporation on a porous surface and perform a simultaneous analysis of the interfacial motion and evaporation inside as well as outside the porous medium. The effects of impact velocity, porosity and particle size on the droplet evaporation are quantified.

2. Numerical analysis

The present numerical approach is based on the sharp-interface LS formulation developed by Son [16] and Lee and Son [17] for droplet evaporation on a non-porous surface and Choi et al. [26] for droplet impact on a porous surface. The LS method is extended for the evaporation of a droplet impacted on a porous surface. The droplet surface is tracked by the LS function ϕ, which is defined as a signed distance from the liquid-gas interface. The positive sign is chosen for the liquid phase and the negative sign for the gas phase. We introduce another LS function ψ, which is defined as a signed distance from the interface between the porous and external fluid regions. The positive sign is chosen for the external fluid region and the negative sign for the porous region. In this work, the following assumptions are made: (1) the flow is incompressible and laminar; (2) the gas phase is an ideal mixture of air and vapor; (3) the liquid phase is a pure substance; (4) the porous medium consists of spherical solid particles with the same diameter, which are uniformly distributed in the porous region; (5) the liquid-gas interface is sharp inside and outside the porous medium; (6) the porous medium is at local thermal equilibrium between its solid and fluid portions; (7) the liquid, gas and solid properties are constant in each phase; (8) the interface temperature is below the boiling temperature.

2.1. Governing equations in the external fluid region ($\psi > 0$)

The conservation equations of mass, momentum and energy for the liquid and gas phases and vapor mass fraction (Y_v) for the gas phase can be expressed as

$$\nabla \cdot \mathbf{u} = \beta \dot{m} \mathbf{n} \cdot \nabla \alpha_\phi \tag{1}$$

$$\hat{\rho} \frac{\partial \mathbf{u}}{\partial t} = -\left[\nabla p + \left(\sigma\kappa - \beta \dot{m}^2\right) \nabla \alpha_\phi\right] + \nabla \cdot \hat{\mu} \nabla \mathbf{u} + \mathbf{f} \tag{2}$$

$$(\rho c)_f \frac{\partial T}{\partial t} = -(\rho c)_f \mathbf{u} \cdot \nabla T + \nabla \cdot \hat{\lambda} \nabla T \quad \text{if} \quad \phi \neq 0 \tag{3}$$

$$T = T_I \quad \text{if} \quad \phi = 0 \tag{4}$$

$$\frac{\partial Y_v}{\partial t} = -\mathbf{u} \cdot \nabla Y_v + \nabla \cdot \hat{D}_v \nabla Y_v \quad \text{if} \quad \phi < 0 \tag{5}$$

$$Y_v = Y_{v,I} \quad \text{if} \quad \phi = 0 \tag{6}$$

where

$$\beta = \rho_g^{-1} - \rho_l^{-1} \tag{7}$$

$$\alpha_\phi = 1 \quad \text{if} \quad \phi > 0 \tag{8}$$

$$\alpha_\phi = 0 \quad \text{if} \quad \phi \leq 0 \tag{9}$$

$$\mathbf{n} = \nabla\phi / \left|\nabla\phi\right| \tag{10}$$

$$\kappa = \nabla \cdot \mathbf{n} \tag{11}$$

$$\mathbf{f} = -\hat{\rho} \mathbf{u} \cdot \nabla \mathbf{u} + \hat{\rho} \mathbf{g} + \nabla \cdot \hat{\mu} (\nabla \mathbf{u})^T \tag{12}$$

$$\hat{\rho} = \rho_l F_\phi + \rho_g \left(1 - F_\phi\right) \tag{13}$$

$$\hat{\mu}^{-1} = \mu_l^{-1} F_\phi + \mu_g^{-1} \left(1 - F_\phi\right) \tag{14}$$

$$(\rho c)_f = (\rho c)_l \alpha_\phi + (\rho c)_g \left(1 - \alpha_\phi\right) \tag{15}$$