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A level-set method for droplet impact and penetration into a porous medium

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ABSTRACT

A level-set method is presented for computation of droplet impact and penetration into a porous medium. The volume averaged conservation equations of mass and momentum are employed for the porous region including the effects of porosity and drag force caused by the porous solid matrix. They are coupled to the conservation equations in the external fluid region through the matching conditions of velocity and stress on the porous surface. Computations are conducted to investigate the effects of initial droplet radius, impact velocity, contact angles, particle size and porosity on the droplet spreading and penetration. A simple analytical formulation is developed for the initial droplet penetration depth and compared with the numerical results. The present level-set method is also applied to the computation of droplet-droplet interaction in the porous medium.

1. Introduction

Droplet impact and penetration into a porous medium has received increasing attention in application of inkjet printing on porous surfaces, such as papers, fabrics and bio materials, and in treatment of chemical agents absorbed in porous soil and biological tissues. Experiments related to the droplet motion were reported in the literature [1–3], but the experimental data were mostly limited to the droplet shapes outside the porous medium. Reis at al. [4] first obtained visual data of droplet deformation inside a porous medium using magnetic resonance imaging (MRI) techniques. The droplet absorbed into the porous medium was found to have a semi-spheroidal shape. However, these experimental studies had inherent limitations in obtaining detailed measurements of the two-phase flow characteristics in the porous region. An alternative way to further clarify the droplet motion in the porous medium is numerical simulation based on the conservation equations of mass and momentum.

Numerical formulations for macroscopic flow characteristics in a porous medium, which consists of microscale solid structures and pores, were developed by several researchers [5–7] averaging the microscopic conservation equations over a small local volume. The averaged conservation equations include the effects of porosity and drag force caused by the solid matrix. Efforts were also made to develop the appropriate matching conditions of the pressure and viscous stress at the interface between the porous region and the external fluid region. Different formulations of the matching conditions were proposed depending on how to treat the pressure and viscous stress over the solid section of the porous medium [8–10], which were reviewed in detail by Alazmi and Vafai [11] and Yu et al. [12]. However, most of the numerical formulations for the porous medium were limited to single-phase flows.

Numerical simulations of droplet impact on a non-porous substrate were performed in a number of studies using a marker-and-cell (MAC) method [13], the volume-of-fluid (VOF) method [14–16], a finite-element method (FEM) [17], a level-set (LS) method [18–21], and a front-tracking method [22]. However, only a few computations were made for droplet motion on a porous substrate. Alleborn and Raszillier [23] investigated the spreading and sorption of a droplet on a porous substrate numerically solving the evolution equations for the droplet height and the wetting front in a porous medium, which were based on the lubrication approximation that the vertical length scale is much smaller than the horizontal length scale.

Reis et al. [24,25] performed more general numerical simulations of droplet impact and penetration into a porous medium by solving the conservation equations of mass and momentum for the free-surface flows inside and outside the porous medium. The conservation equations were coupled through the matching conditions of pressure and viscous stress at the interface, which were derived under the assumption that the pressure and viscous stress over the solid section of the porous medium are zero. The MAC method was

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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	domain height
$\mathbf{n}$	unit normal vector
p	pressure
r, y	cylindrical coordinates
R_o	initial droplet radius
Re	Reynolds number, $\rho_l R_o V_o/\mu_l$
t	time
$\mathbf{u}$	flow velocity vector, (u, v)
V_o	droplet impact velocity
W	domain width
We	Weber number, $\rho_l R_o V_o^2/\sigma$

Greek symbols

α	step function
ϵ	porosity
θ_{pore}	contact angle in a porous medium
θ_s	contact angle at the porous-fluid interface
θ_{sa}	advancing contact angle at the porous-fluid interface
θ_{sr}	receding 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

g, l	gas, liquid
I	liquid-gas interface
o	initial
s	porous-fluid interface

used to track the position of the liquid region and the free surface (or liquid-gas interface). Their method was validated through the comparison with their experimental data. However, the Lagrangian treatment of the interface particles is generally not straightforward to implement for merging and breaking of the interface.

Very recently, Kim and Lee [26] applied the VOF method to computation of droplet impact on a porous substrate. In their VOF advection equation, a compression term was included for accurate estimation of the VOF function. The matching conditions at the interface between the porous and external fluid regions were different from those used by the Reis et al. [24,25]. They included the effect of dynamic contact angle on the droplet motion, but the VOF method is not simple to accurately implement for the geometric condition for contact angle hysteresis, as indicated by Fang et al. [27], and the surface tension force term.

In this work, a sharp-interface LS method is extended for analysis of droplet impact and penetration into a porous medium. The LS formulation based on a smooth distance function has advantages in accurately imposing the contact angle hysteresis condition as well as the surface tension force term. The different formulations of the matching conditions at the porous-fluid interface are compared in the computations of droplet motion.

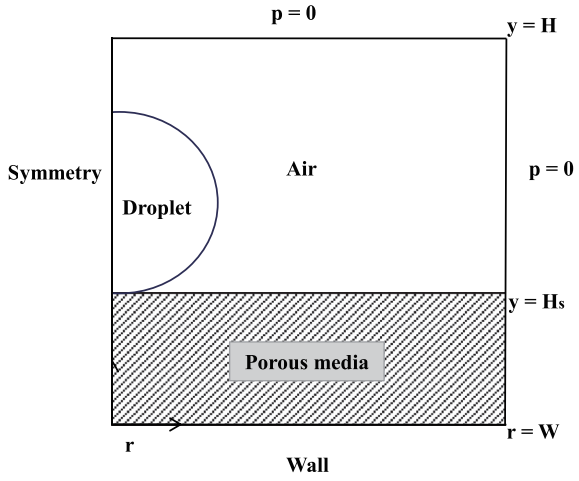

Fig. 1. Configuration used for simulation of droplet impact and penetration in a porous medium.

2. Numerical analysis

The present numerical approach is based on the sharp-interface LS formulation developed by Suh and Son [20] for a piezoelectric inkjet process and Lee and Son [21] for droplet impact and coalescence on a non-porous surface. The LS method is extended for computation of droplet impact and penetration into a porous medium, as depicted in Fig. 1. 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 axisymmetric, incompressible and laminar; (2) the porous medium consists of spherical solid particles with the same diameter, which are uniformly distributed in the porous region; (3) the liquid, gas and solid properties are constant in each phase.

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

The conservation equations of mass and momentum in the external fluid region can be expressed as

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\hat{\rho}\frac{\partial \mathbf{u}}{\partial t} = -(\nabla p + \sigma\kappa\nabla\alpha_\phi) + \nabla\cdot\hat{\mu}\nabla\mathbf{u} + \mathbf{f} \tag{2}$$

where

$$\mathbf{f} = -\hat{\rho}\mathbf{u}\cdot\nabla\mathbf{u} + \hat{\rho}\mathbf{g} + \nabla\cdot\hat{\mu}(\nabla\mathbf{u})^T \tag{3}$$

$$\alpha_\phi = 1 \qquad \text{if } \phi > 0 \tag{4}$$

$$\alpha_\phi = 0 \qquad \text{if } \phi \le 0 \tag{5}$$

$$\mathbf{n} = \nabla\phi/|\nabla\phi| \tag{6}$$

$$\kappa = \nabla\cdot\mathbf{n} \tag{7}$$