SIMULATION OF DROP MOVEMENT ON AN INCLINED SURFACE

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ABSTRACT: *Numerical simulations of the dynamics of droplet impact and spreading on inclined surfaces were carried out using the PLIC-VOF method. First, four different surface tension models are examined by simulating a three-dimensional stationary drop in a gas and it is found out that the SGIP model has the best performance as a surface tension model. Then, using SGIP model and applying dynamic contact angle, the deformation and movement of a droplet on inclined surfaces is simulated. The effects of the droplet velocity and inclined angle on the deformation and movement of the drop are studied.*

1. INTRODUCTION

Many engineering and industrial applications involve flow of liquids over solid surfaces, for example in trickle bed reactors, structured reactors and monoliths, packed beds, surface coatings, printing[6]. The experimental investigations of Šikalo *et al.* [9] showed that the drop volume, the surface inclination and impact velocity have significant effects on the drop dynamics and the regimes of drop impact. The regimes of drop the impact observed experimentally by Šikalo *et al.* [9]. Sedev *et al.* [8] carried out an experimental study with the droplets and reported the dependence of the dynamic contact angle (DCA) on the contact line velocity, the surface roughness and the time of solid–liquid contact.

Different numerical methods are available for computations of flows with moving interfaces. The VOF method is more suitable for the simulation of drop spreading. Most of the numerical simulations of drop spreading were carried out for horizontal surfaces and using the static contact angle (SCA) model. Šikalo *et al.* [10] reported a numerical study on the DCA model for drops impact over flat surfaces. Using the VOF method, Bussmann *et al.* [3] successfully simulated the drop spreading on an inclined surface by accounting the time variation of the DCA and the contact line velocities. They investigated the impact and spreading of a 2mm water droplet on a 45∘ inclined steel surface. The experimentally measured DCAs were implemented as a wall boundary condition. Afkhami and Bussmann[1] extended the work of Bussmann *et al.* [3] by discussing the effect of different implementations of the contact angle and the contact line velocity on the predictions of drop spreading. Based on experimental observations, finally they suggested the contact angle model as a function of velocity contact line which is shown in Fig. 1. Lunkad *et al.* [6] carried out the numerical investigations of drop impact and spreading on horizontal and inclined surfaces using the VOF method and using the commercial flow solver (Fluent 6.3). They used SCA and DCA models.

One of the challenges in numerical simulation of interfacial flows with Eulerian approaches is modeling of the surface tension forces. The more commonly used surface tension treatment methods are the Continuum Surface Force method (CSF) and the Continuum Surface Stress method (CSS). The main problem in the numerical modeling of surface tension forces in the capillary dominated flows is the production of so-called “spurious” or “parasitic” currents. They are small but growing flows, which are generated due to the different density of two phases in the interfacial region. Spurious currents affect the interface shape and produce unphysical results. The currents are produced mainly in the light fluid side near the interface, where the fluid with lower density accelerates more than the fluid with higher density.

2. COMPUTATIONAL MODEL

2.1 The VOF method

A volume-of-fluid (VOF) method along with a piecewise linear interface calculation (PLIC) is used to capture the fluid interfaces. In PLIC technique, the interface is approximated a plane of adequate orientation in each cell. In the VOF model, the motion of a moving interface is computed by solving an advection equation for the volume fraction of the secondary-phase:

$$\partial_t c + (\vec{v}.\nabla)c = 0 \tag{1}$$

where c is the volume fraction of one fluid in each cell. The density and the viscosity in each cell are given as follows:

$$\rho = \rho_2 + c(\rho_1 - \rho_2) \tag{2}$$

$$\mu = \mu_2 + c(\mu_1 - \mu_2) \tag{3}$$

2.2 Surface Tension Force Model

Two main approaches to calculate surface tension force are CSF and CSS. Following Brackbill *et al.* [2] CSF model, the surface tension force and the interface curvature may be calculated as

$$\vec{F}_v^{st} = \sigma\kappa\hat{n}\frac{|\nabla\tilde{c}|}{[c]} \tag{4}$$

and

$$\kappa = -\nabla.\hat{n} = -\nabla.\frac{\nabla\tilde{c}}{|\nabla\tilde{c}|} \tag{5}$$

where the tilde denotes the filtered (smoothed) value, the square brackets denote the difference between maximum and minimum values of the function inside the brackets, and $\vec{F}_v^{st}$ is the volumetric surface tension force. The above model produces an artificial acceleration in the lighter fluid when the density ratio of the two fluids is large. This acceleration is the main source of producing spurious currents. Brackbill *et al.* [4], as well as Kothe *et al.* [2] recommended the addition of a density scaling factor in order to reduce the formation of such acceleration. Therefore, they proposed the following equation instead of Eq. (4):

$$\vec{F}_v^{st} = \sigma\kappa\hat{n}\frac{|\nabla\tilde{c}(x)|}{[c]}\frac{\rho(\vec{x})}{\langle\rho\rangle} \tag{4}$$

where

$$\langle\rho\rangle = \frac{(\rho_1 + \rho_2)}{2} \tag{5}$$

and $\rho(x)$ is the local value of the density obtained by Eq. (6). The density correction term (the second fraction in Eq. (4)) is added to correct the force in the momentum equation. In present study this method is called CSF-BKZ.

Another model which is widely used is that of Zaleski's CSS model [5]. In this model we have:

$$\vec{F}_v^{st} = -\nabla.T = \nabla.\left[\sigma\left(|\nabla\tilde{c}|I - \frac{\nabla\tilde{c}\otimes\nabla\tilde{c}}{|\nabla\tilde{c}|}\right)\right] \tag{6}$$

An improved method is used for calculation of surface tension force. This method was developed by Seifollahi, *et al.* 2008 [7] for the application of interface force in the computational modeling of free surfaces and interfaces, and uses VOF-PLIC methods. This method is applied to a staggered grid and it is referred to as Staggered Grid Interfere Pressure or SGIP method. It has been shown in two-dimensional cases that the new method predicts the pressure jump at the interface more accurately and produces less spurious currents compared to the CSF and CSS. In this study we examine SGIP model in a three-dimensional case along with some other methods.

In SGIP method, the volumetric surface tension force in x-direction on the cell $i + 1/2, j, k$ can be calculated from Eq. (2). The result is:

$$F^{st}_{x,i+\frac{1}{2},j,k} = \frac{\sigma\kappa_{i+\frac{1}{2},j,k}A_{x,i+\frac{1}{2},j,k}}{V_{i+\frac{1}{2},j,k}} \tag{7}$$

where $A_{x,i+1/2,j,k}$ is the projection of the interface surface area in $i+1/2, j, k$ cell and in the x-direction (that is on the y–z plane). $A_{x,i+1/2,j,k}$ is given by (see Fig. 2):

$$A_{x,\mathrm{i}+\frac{1}{2},\mathrm{j,k}} = S_{x,i+1,j,k} - S_{x,i,j,k} \tag{8}$$

Here we avoid more details and process of calculation of interface functions S_x. For more information refer to [7].

2.3 Contact Angle

As mentioned in the introduction, for numerical simulations of moving contact lines, contact angles are required to be given as a boundary condition at the contact line. The DCA considered as a function of contact line velocity. In this paper the model that proposed by Afkami *et al*. [6] and is shown in Fig. 1, has been used.

3. RESULTS

First we consider a 1 cm stationary water drop in air at standard conditions and examine four different surface tension models. Results are given for several surface tension models which are mentioned in previous sections. Figs. 3 and 4 show the norm of spurious currents and pressure contours for four cases where the CSS, CSF, SGIP and CSF-BKZ models are used. In these figures although the CSF-BKZ produces less spurious currents but, it does not show correct pressure jump. However the SGIP produces much better results compared to the other models. Thus, we use this model for our simulation of the cases.

Then simulation of a 3mm droplet impact on an inclined surface, with inclination of φ = 30, 45 and 60 degrees and two velocity impact of 0.5 and 1 m/sec, is carried out. Droplet shapes are given in Figs. 5 and 6. It shows that a droplet on a surface with small inclination spreads more rapidly and moves down more slowly. Additionally by increasing of droplet impact velocity, the spreading of the droplet will be increased.

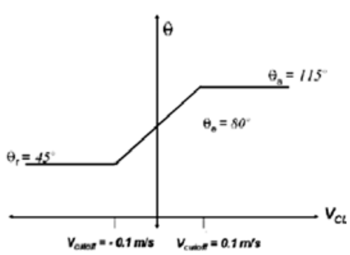


Fig. 1 DCA as a function of contact line velocity [2]

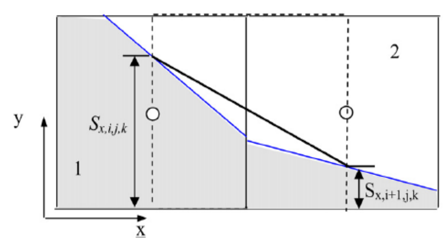


Fig. 2 Interface functions S_x in a x-momentum cell

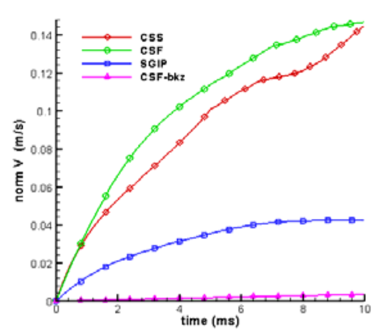
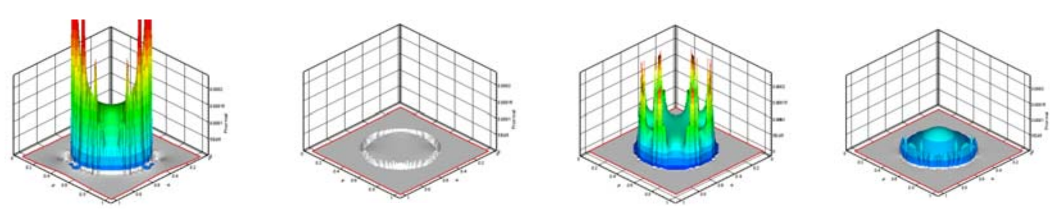


Fig.3 Spurious currents for a stationary droplet



(a) (b) (c) (d)

Fig. 4 Pressure contours at t = 5 ms (a) CSF, (b) CSF-BKZ (c) CSS (d) SGIP.

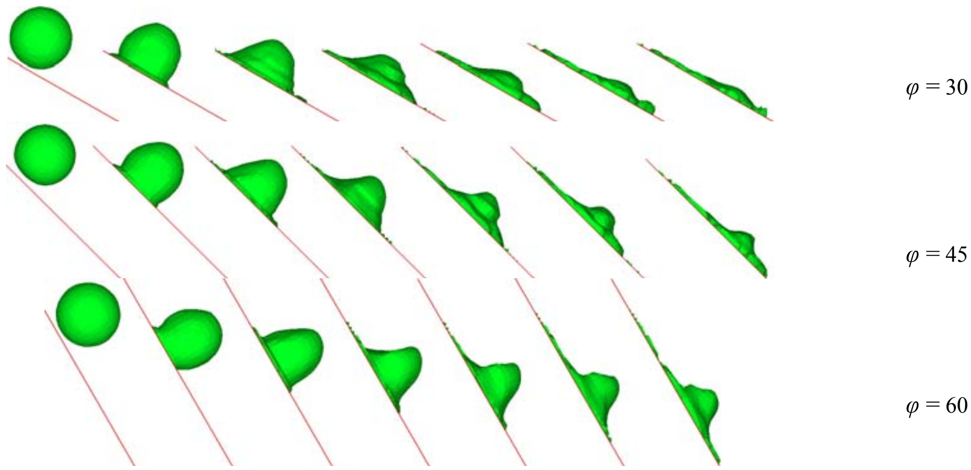


Fig. 5 Impact of 3mm droplet on an inclined surface and 0.5 m/s impact velocity at 0, 2, 4, 6, 8, 10 and 12 ms

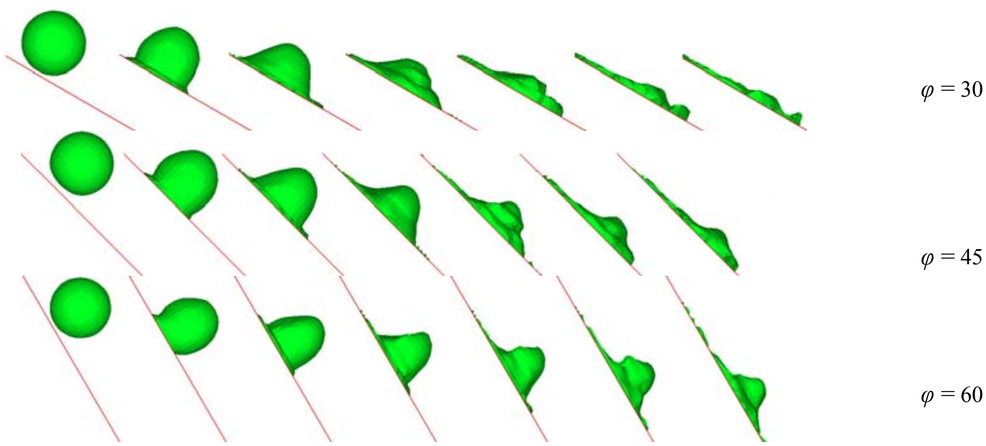


Fig. 6 Impact of 3mm droplet on an inclined surface and 1m/s impact velocity at 0, 1, 2, 3, 4, 5 and 6 ms

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