Mechanics Research Communications 70 (2015) 85–93

Contents lists available at ScienceDirect

Mechanics Research Communications

journal homepage: www.elsevier.com/locate/mechrescom

Motion of non-wetting drop in constricted geometry

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ARTICLE INFO

Article history:
Received 2 August 2014
Received in revised form 24 July 2015
Accepted 21 September 2015
Available online 22 October 2015

Keywords:
Immiscible fluids
Non-wetting fluid
Drop
Constricted geometry
Volume of fluid
Drop breakup

ABSTRACT

This work is a contribution to the study of deformation of a non-wetting drop transported under the combined effect of gravity and permanent fluid motion in a vertical channel. The deformation being caused during passage of the drop through a constriction formed by two spherical obstacles placed opposite in a vertical channel. For this purpose a three-dimensional computation is conducted in order to illustrate the behavior of the drop in the condition of non-wettability. The flow based on Navier–Stokes equation is solved numerically with volume of fluid (VOF) method. The corresponding simulations are carried out in view to analyse the behavior of the drop when it is forced to move between the obstacles for different values gap size until the breakup is obtained.

1. Introduction

Scientific problems concerning the interaction between immiscible fluids and fixed solid particles continue to receive much attention in mechanical engineering, chemical and biochemical processing, environmental engineering or biomechanics. Literature concerning this interaction has primarily considered the motion of a single drop through a constricted tube, including cases where drop breakup occurs [9,13,15,21]. More recently, Davis and Zinchenko [6], Zinchenko and Davis [23,24] presented simulations of a drop through a constriction between solid particles rigidly held in space, including both spheres and disks, and extended to the case of multiphase flow through a granular medium composed by solids spheres. They indicated that the drop becomes trapped in a smaller pore neck when the capillary number is less than a critical value so that the drop is unable to deform enough to squeeze through the constriction. Nguyen [14] and Hellou et al. [8] also carried out a two-dimensional study of the influence of the shape of the pores on the infiltration of a drop of Dense Nonaqueous Phase Liquid (DNAPL) in a porous medium. Their analysis was realised when the solid obstacles bounding the pores have circular shape, square shape or intermediate ones and showed that the retention of the liquid drop decreases as the shape of the solids evolves from the square to the circle. In the present paper, we consider the situation where the retention is week. Thus, we investigate the behavior of a non-wetting drop flowing through a pore formed by two spherical solid particles. In this objective, a computational study that describes the deformation process of this non-wetting spherical drop in viscous fluid immobile or moving with uniform velocity Uc in the direction of gravity is conducted. The fluids are assumed to be Newtonian and the flow based on the Navier–Stokes equation is solved with the volume of fluid (VOF) method. A parametric study highlighting the relevant importance of the gap between the two solid spheres affecting the behavior of the drop is realised.

2. Description of the problem

The flow domain is a parallelepiped container filled with a viscous fluid (called hereafter carrier fluid and designed by the subscript c). This container has a square cross-section a^2 and height h_1 (Fig. 1). Two solid obstacles of spherical shape of diameter D are fixed on two opposite vertical walls of the box thus they form a variable constriction whose the gap at the coordinate z obeys to the following expression:

$$e_z = e_0 + D\left(1 - \sqrt{1 - \frac{4z^2}{D^2}}\right) \quad (1)$$

where e_0 is the gap for $z = 0$.

Note that the position of these obstacles is not at the mid-height of the container (the lower part is longer than the upper part). This disposition permits a sufficient length to track the deformation process and eventually the breakup process of the drop after it passes

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http://dx.doi.org/10.1016/j.mechrescom.2015.09.009
0093-6413/

Nomenclature

a	Cross-section size of the box
h_1, h_2, h_3	Distance
D	Obstacle diameter
d	Drop diameter
U_d	Drop velocity
U_c	Carrier fluid velocity
μ	Dynamic viscosity
ρ	Density
σ	Surface tension
Re	Reynolds number
Bo	Bond number
Ca	Capillary number

the constriction. The narrowest constriction of size e_0 is located in the upper half of the container at a height h_3 from the mid-height of this container. Table 1 presents the values of the geometrical parameters used numerically. This configuration is experimentally reproduced for experiments based on the visualisation of the drop in order to validate the numerical results.

The flow of the carrier fluid is permanent and occurs along the gravity direction with a mean velocity called U_c. A drop of dense fluid of diameter d is located, at the time $t=0$, upstream of the constriction at the distance h_2 from the centre of the constriction (the subscript d is assigned to the drop). The relative distance between the drop and the constriction is $\frac{h_2-D/2}{d}=0.7$ (see Table 1 for the values). This distance seems to be low but we have verified that the influence of the presence of the constriction is not sensitive yet. Furthermore, to avoid the influence of the exterior, we insure at the initial time that the drop is completely immersed. In all the

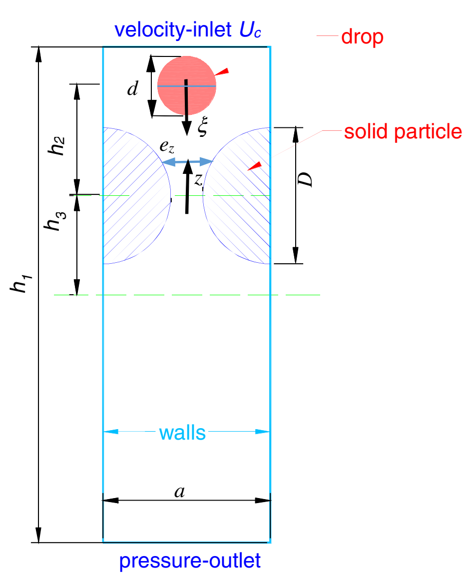

Fig. 1. Sketch of the problem.

Table 1
Values of the geometrical parameters (values in the second column are in mm, in the third column the values are non-dimensioned).

a	19.7	1
h_1	59.1	3
h_2	12.8	0.65
h_3	11.8	0.6
D	15.8	0.8
d	6.9	0.35

Table 2
Physical properties of the immiscible fluids at 20 °C (the properties presented in this table correspond to fluids used in the experiments: silicon oil for the carrier fluid and glycerin oil for the drop).

	drop	carrier fluid
Density ($kg.m^{-3}$)	1245	973
Viscosity ($Pa.s$)	1.5	1.1
Surface tension ($N.m^{-1}$)	0.022	
Contact angle Glass/silicon oil/glycerin oil	130°	
Mobility ($\lambda=\mu_d/\mu_c$)	1.36	

simulations and experiments, the layer of the carrier fluid over the top of the drop is about d/4. The main physical properties (density, viscosity and surface tension) of both the carrier fluid and the drop are assumed to be constant. The static contact angle between the fluids and the walls of the obstacles of value 130° insures the drop to be non-wetting. The values of these physical parameters are summarized in Table 2.

The non-dimensioned numbers related to the flow of these immiscible fluids are the Reynolds number of the carrier fluid (Re_c) the capillary number (Ca) and the Bond number (Bo). They are defined respectively as:

$$Re_c=\frac{\rho_c U_c a}{\mu_c};\ Ca=\frac{\mu_c U_c}{\sigma};\ Bo=\frac{gd^2\Delta\rho}{\sigma}$$

where ρ_c, μ_c represent respectively the density and the viscosity of the carrier fluid; ρ_d and d are the density and the diameter of the drop; the other parameters are the width of the box (a), the interfacial tension σ and the acceleration due to the gravity (g).

The velocity of the continuous fluid U_c is fixed to 5 mm.s^{-1} thus the Reynolds number, and the capillary number are 0.09 and 0.25, respectively. The Bond number is equal to 5.77. In these conditions, the capillary force is neglected in front of viscous and gravitational forces. Furthermore, according to results of Cristini et al. [5] in the case of shear flow, the capillary number outside the constriction ($U_c=5$ mm.s^{-1}, Ca = 0.25) is less than the critical capillary number for the viscosity ratio (mobility) used (for mobility of 1.36 the critical capillary number of Cristini et al. is 0.48). Thus the breakup of the drop can not occur upstream of the constriction.

It is worth noting that the value of the drop velocity settling in an infinite static carrier fluid is given by the following formulae [7,16]:

$$U_{d\infty}=\frac{gd^2\Delta\rho}{2\mu_c}\frac{(1+\lambda)}{(6+9\lambda)};\left(\lambda=\frac{\mu_d}{\mu_c}\right) \quad (2)$$

For the data presented in Tables 1 and 2, this velocity is equal to $U_{d\infty}=7.47$ mm.s^{-1}.

To present the results in a dimensionless form, the following dimensionless parameters are used:

- e_z/d: ratio of the gap at the coordinate z (Eq. (1)) and the drop diameter, useful to examine the influence of the confinement on the deformation of the drop for a fixed drop diameter;
- e_0/d: gap for z = 0, corresponding to the minimal gap size (narrowest constriction);
- ξ/h_2:dimensionless drop position in the fluid relatively to its initial position. The values used for the fluid domain lead to the following range for $\xi/h_2(-0.38, 4.23)$. The value $\xi/h_2=1$ corresponds to the drop position at the narrowest constriction;
- $\frac{u_d-u_c}{u_{d\infty}}$: dimensionless relative velocity of the drop (U_d is the barycentric velocity of the drop).