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Off-centre binary collision of droplets: A numerical investigation

N. Nikolopoulos, A. Theodorakakos, G. Bergeles *

Department of Mechanical Engineering, Nat. Technical University of Athens, 15310 Zografos, Greece

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ABSTRACT

The paper presents results from a numerical investigation of the non-central binary collision of two equal size droplets in a gaseous phase. The flow field is two phase and three dimensional; the investigation is based on the finite volume numerical solution of the Navier–Stokes equations, coupled with the Volume of Fluid Method (VOF), expressing the unified flow field of the two phases, liquid and gas. A recently developed adaptive local grid refinement technique is used, in order to increase the accuracy of the solution particularly in the region of the liquid–gas interface. The reliability of the solution procedure is tested by comparing predictions with available experimental data. The numerical results predict the collision process of the two colliding droplets (permanent coalescence or separation) and in the case of separation the formation and the size of the satellite droplets. The time evolution of the geometrical characteristics of the ligament, for various Weber numbers and impact parameters, is calculated and details are shown of the velocity and pressure fields particularly at the ligament pinch off location not hitherto available. Gas bubbles due to collision are trapped within the liquid phase as it has also been observed in experiments and their volume is calculated.

1. Introduction

Binary droplet collision is appearing in raindrop formation and in various spray processes, especially in internal combustion engines. The first studies on droplet collision, using water droplets in air at atmospheric pressure, have been conducted because of meteorological interest by Adam et al. [1]. They focused attention on the aerodynamic environment of the event and on the outcome of the collisions. Park [2] produced collisions between streams of water droplets traveling in still air and showed pictorially that near head-on collision between pairs of equally sized droplets of 700 μm, resulted in stable coalescence, while off-centre collision at the same relative velocity resulted in a transient coalescence and finally in separation. Brazier-Smith et al. [3] conducted similar experiments to [2] in still air, whilst Ashgriz and Poo [4] developed models for predicting the boundary between the coalescence and separation regimes.

Faeth [5], O'Rouke and Bracco [6] emphasized the importance of droplet collision phenomena occurring within dense sprays and recognized the significance of the rheological properties of the droplets (i.e. hydrocarbons vs. water). As reported by Qian and Law [7] for water droplets, for head-on collisions at atmospheric pressure bounce is not observed; for the same conditions however, the collision outcome between hydrocarbon droplets may result to bouncing.

Jiang et al. [8] provided a comprehensive quantitative assessment of droplet collisions of hydrocarbon droplets (heptane, decane, dodecane, tetradecane and hexadecane), and later Qian and Law [7] extended these investigations to include the effects of ambient pressure, density, viscosity and impact parameter (characterizing off-centre binary collisions). In each of the above studies, mono-disperse streams of droplets were made to collide at various angles. The following collision regimes were found with increasing Weber number; droplet bouncing, stable droplet coalescence, unstable droplet coalescence and droplet stretching separation, [7,8].

Estrade et al. [9] published information about the number of satellite droplets, their sizes and velocities produced by bouncing collisions. Moreover, they also developed a model for predicting the boundary between the bouncing and the coalescence regimes. Brazier-Smith et al. [3] carried out experiments on binary water droplet collisions and developed the threshold of the stability of water droplets against separation, while Arkhipov et al. [11] obtained a relation for the impact parameter separating stable coalescence from stretching separation. Willis and Orme [12] conducted experiments of droplet collisions in a vacuum, devoid of aerodynamic effects, focusing on the role of viscosity in the evolution of the collision phenomenon. Brenn et al. [10] produced a monogram for the various collision regimes and for the number of satellite droplets formed during droplet collision depending on the Weber

* Corresponding author. Address: Department of Mechanical Engineering, Nat. Technical University of Athens, 5 Heroon Polytechniou, Zografos, 15310 Athens, Greece. Tel.: +30 2107721058; fax: +30 2107723616.
E-mail addresses: niknik@fluid.mech.ntua.gr (N. Nikolopoulos), andreas@fluid.mech.ntua.gr (A. Theodorakakos), bergeles@fluid.mech.ntua.gr (G. Bergeles).

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Nomenclature

B	impact parameter, (= x/D_o)
D_o	initial droplet's diameter
f_σ	force due to surface tension
L_1	maximum elongation of coalesced mass
L_2	maximum elongation of ligament or satellite droplet
Re	Re number, (= $\rho_{liq} D_o (2 U_o)/\mu_{liq}$)
t	time
$\vec{T}$	stress tensor
T	non-dimensional time, (= tU_o/D_o)
U_o	initial droplet's impact velocity
$\vec{u}$	velocity
x	the projection of the separation distance between the droplet centres in the direction normal to that of U_o
X	X-axis of computational field
Y	Y-axis of computational field
Z	Z-axis of computational field
We	We number, (= $\rho_{liq} D_o (2 U_o)^2/\sigma$)
w_2	maximum width of ligament or satellite droplet

Greek symbols

α	volume of fluid (also noted as indicator function)
κ	curvature (m^{-1})
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

gas	gas phase
liq	liquid phase
tot	total

number and impact parameter. In the same work results are presented of the characteristics of the formed ligament and satellite droplet diameter. These results have been obtained following a linear stability analysis of the filament formed after collision which agreed quite well with the experimental results of Ashgriz and Poo [4], who showed that for the same *Weber* number of the two colliding droplets, the number of satellite droplets resulting from the droplet separation increases with the increase of the impact parameter.

Studies on the numerical simulation of droplet binary collision are relatively few. The front tracking method for multi-fluid methods developed by Unverdi [13] and discussed by Unverdi and Tryggvason [14–15], was used by Nobari et al. [16] in axi-symmetric formulation for central collision; the method was able to capture the features of bouncing, coalescence and reflexive separation with up to one satellite droplet formed, by prescribing the rupture time of the inter-drop film. The methodology was extended by Nobari and Tryggvason [17] for three dimensional simulations of droplet collisions, but for a low density and viscosity ratio between surrounding gas and droplet 40 and 20 and on a fixed numerical grid ($32 \times 32 \times 64$). In the present simulations the density ratio of liquid to gas phase is much higher and equal to 610 with a viscosity ratio of 129.

Mashayek et al. [18] studied the coalescence collision of two droplets in axi-symmetric coordinates, using a Galerkin finite element method coupled with the spline-flux method for the free surface tracking. Lafaurie et al. [19] used the SURFER method, lattice gas models were used by Drtina et al. [20], Schelkle and Frohn [21,22] in three dimensions, whilst Rieber and Frohn used VOF methodology [23].

Inamuro et al. [24] neglecting the effect of the gas on the droplet collision, presented a lattice Boltzmann simulation of binary droplet collisions in a system with a density ratio of 50 and compared the numerically predicted collision consequences with the inter-regime boundaries given by the model developed by Ashgriz and Poo [4]. In addition they simulated the mixing process of equal-sized droplets, during separating collisions for various impact parameters at We = 80, for the given density ratio. Recently, Pan and Kazuhiko [25] using the implicit continuous-fluid Eulerian method coupled with the level set methodology for a single phase in a fixed uniform mesh system, simulated the three major regimes of binary collision (bouncing, coalescence and separation), both for water and hydrocarbon droplets. Their numerical results suggest that the mechanism of bouncing collision is governed by the macroscopic dynamics while the mechanism of coalescence is related to the microscopic dynamics. By their simulations, it is confirmed that in the case of large impact parameter cases, the capillary-wave instability is the controlling mechanism for the satellite droplets formation, whereas in the case of an intermediate impact parameter, the effects of twisting and stretching due to the angular momentum and the inertia of the colliding droplets are significant for the satellite droplet formation.

Finally, a methodology for the prediction of the borders between the various collision outcome regimes has been undertaken by Munnannur and Reitz [26]. They recently formulated a new model, including bouncing, coalescence and separation as outcomes. This model predicts not only the outcome of the collision, but also the post-collision characteristics such as droplet sizes, velocities and spatial distribution of droplets in the case of polydisperse streams of droplets, under the assumption that the satellite droplets resulting from fragmentation are uniform in size and velocity.

The present investigation studies numerically the off-centre collision of hydrocarbon droplets for various Weber and Reynolds numbers. The Navier–Stokes equations with the introduction of a volumetric force due to surface tension effects are solved numerically by the finite volume methodology; the numerical solution employs a new adaptive local grid refinement technique, whilst VOF methodology is used for the tracking of the liquid–gas interfaces.

Results are presented in which first the reliability of the methodology is established by comparing predictions with reliable published experimental data. After that, new findings are presented regarding the collision mechanism (coalescence or separation) of the two colliding droplets.

2. The mathematical problem

The flow induced by the non-central binary collision of two equal sized droplets is considered as three-dimensional, incompressible and laminar; the two-phase flow (phase 2 is the liquid phase, and phase 1 is the surrounding gas phase) is mathematically expressed by the Navier–Stokes equations and the continuity equation. For identifying each phase separately a volume fraction, denoted by α, is introduced following the Volume of Fluid Method (VOF) of Hirt and Nichols [27]. In the VOF method the volume fraction α is defined as:

$$\alpha = \frac{\text{Volume of liquid phase}}{\text{Total volume of the control volume}} \quad (1)$$