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Shear-driven two colliding motions of binary double emulsion droplets

Xiangdong Liu [a], Chengyao Wang [b], Yuanjin Zhao [c], Yongping Chen [a,b,d,*]

[a] School of Hydraulic, Energy and Power Engineering, Yangzhou University, Yangzhou, Jiangsu 225127, PR China
[b] Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing, Jiangsu 210096, PR China
[c] State Key Laboratory of Bioelectronics, Southeast University, Nanjing, Jiangsu 210096, PR China
[d] Jiangsu Key Laboratory of Micro and Nano Heat Fluid Flow Technology and Energy Application, School of Environmental Science and Engineering, Suzhou University of Science and Technology, Suzhou 215009, PR China

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ABSTRACT

We combine experimental visualization with numerical simulation to explore the hydrodynamic shear-driven binary collision of double emulsion droplets. Two typical colliding motions, passing-over motion and reversing motion, are found and identified by quantitatively characterizing the corresponding detailed motion trajectory and morphology development. Compared with the ordinary single-phase droplets, double emulsion droplets are demonstrated to exhibit similar motion trajectories but different deformation development during the binary collision process, which arise from an additional interaction induced by the inner droplet. Especially, we clarify that two typical colliding motions are determined by the competitions among the drag of passing-flow region and the entrainment from reversing-flow and vortex regions in the matrix fluid, which are significantly affected by the dimensionless shear stress (*Ca*) and confinement degree of shear flow (*Co*). With the increasing *Co*, the colliding motion of binary double emulsion droplets transits from the passing-over to reversing, owing to that the entrainment of the reversing-flow region turns to play a dominant role. The drag of the ambient passing-flow in the matrix fluid is increased by enlarging *Ca*, resulting in the emergence of passing-over motion of the colliding droplets. Accordingly, a regime diagram is provided to quantitatively recognize the corresponding regime of these two typical colliding motions, as a function of *Ca* and *Co*.

1. Introduction

Double emulsion droplet is a complex multiphase object that contains smaller droplet inside. Due to the unique nested structure, it is often used as a liquid template for preparation of the core-shell structure material which has significant potential in micro-chemical technology [1–3], biomedical applications [4,5], thermal energy storage capsules preparation [6], etc. The microscopic morphology of the double emulsion droplet, which is developed during the droplet-based processing and finally frozen in the final core-shell structure material, is essential for determining the material properties, such as optical characteristics [3], permeability [4], and mechanical strength [5]. Significantly, microfluidic technology offers many advantages over manipulating the microscopic morphology of the double emulsion droplet due to its excellent control of fluid flow. Therefore, it provides a promising alternative way for fabricating the core-shell structure material with required properties [7,8]. It is worth noting that during the droplet-based processing by the microfluidic technology, the morphology development of the double emulsion droplet is deeply affected by the collision under external flow (e.g. shear flow, extensional flow, and hyperbolic flow). Especially, owing to the unique nested structure, double emulsion droplets always collide with more complicated interface topologies and hydrodynamics than the ordinary single-phase droplets [3–7], resulting in challenges in regulating the morphology development of double emulsion droplets via the microfluidic technology [8–10]. In this context, a thorough understanding of the morphology development and hydrodynamics of double emulsion droplets collision under the external flow is fundamental to precisely manipulate the microscopic structures of the droplets using the microfluidic technology, which is thus necessary for controllable preparation of the core-shell structure material.

Since the pioneering studies by Mason's group [11–13], there have been several efforts concentrated on the hydrodynamic colliding behaviors of traditional single-phase droplets in the external flow, including colliding motion trajectories [14,15], deformation development [14–16], and self-rotation evolution [16–19], etc.

* Corresponding author at: School of Hydraulic, Energy and Power Engineering, Yangzhou University, Yangzhou, Jiangsu 225127, PR China.
E-mail address: chenyp@yzu.edu.cn (Y. Chen).

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Nomenclature

B	half-breadth of deformed droplet
D	deformation parameter
e_r	random uncertainty
e_s	system uncertainty
$\vec{e}_n$	unit normal vector
$\vec{e}_x$	unit vectors in the x-direction
$\vec{e}_y$	unit vectors in the y-direction
F_x	component force in the x-direction
F_y	component force in the y-direction
$\vec{F}_S$	interface tension
G	shear rate
$\vec{g}$	gravitational acceleration
h	spacing gap
k	radius ratio
L	half-length of deformed droplet
l	length
$\hat{n}$	unit vector normal to interface
p	pressure
R	radius
S	surface
t	real time
t^*	dimensionless time
$\vec{U}$ (u)	velocity
w	width
x, y, z	x, y, z-directions

Greek symbols

α	volume fraction
κ	interface curvature
σ	interface tension coefficient
μ	viscosity
ρ	density
σ	interface tension coefficient
$\vec{\tau}$	viscous stresses

Subscripts

c	continuous phase
i	inner droplet of double emulsion
i	index of phase and droplet
o	outer droplet of double emulsion
s	single-phase droplet
0	initial parameter

Guido and Simeone [14] previously performed a visualization experiment to investigate collision between two equal-sized droplets under simple shear, and characterized the collision behaviors via depicting the colliding motion trajectories and temporal deformation of the droplets. It was found that, two droplets slide over each other during the collision, with their distance increasing irreversibly along the velocity gradient direction. Following the work by Guido and Simeone, Chen et al. [15] further experimentally studied the pairwise interaction between drops in confined shear flow. Their results indicated that the confinement of shear can increase the interaction time and affect the drainage of matrix film between the colliding droplets. Besides the experimental studies, numerical researches have also been taken to explore the hydrodynamics underlying the binary collision of droplets. Based on boundary integral method, Loewenberg and Hinch [16] made an early numerical simulation of binary collision between droplets in a simple shear flow. The numerical simulation successfully predicted the sliding motion of colliding droplets, and further demonstrated that slight deformation can endow the drops with a short-range repulsive interaction. Via the numerical simulation based on front-tracking method, Doddi and Bagchi [17] introduced a new reversed colliding motion trajectory under shear in presence of inertia. Especially, they pointed out that the increasing inertia induces the reversed colliding motion trajectory and makes it occur progressively earlier in time. This reversed trajectory under simple shear was also demonstrated by Olapade et al. [18]. Moreover, their numerical work indicates that the competing hydrodynamic effects between shear and finite inertia. Except for the binary collision, multiple collisions of more than two droplets were also numerically studied by Bayareh and Mortazavi [19]. Differing from the motions of binary collision, several clusters of droplet are triggered by the external shear flow and collisions, which is closely related to Capillary number and volume fraction of droplets.

As mentioned above, until now, the previous studies on droplets collision have been focused on traditional single-phase droplets. Significantly, it has been documented that [20], compared with the single-phase droplet, more hydrodynamic interactions and topologies are involved in the hydrodynamic behaviors of the nested double emulsion droplet. Consequently, with respect to the single-phase droplets, different morphology development emerges during manipulation of the double emulsion droplets. For examples, the explorations on hydrodynamic behaviors of a single double emulsion droplet in extensional flow indicated that double emulsion droplet exhibits easier break-up than the single-phase droplet [21,22]. It has been also demonstrated by Smith et al. [23] and our group [24] that more intense transient deformation oscillations appears during the temporal deformation of a double emulsion droplet than the single-phase droplet. In addition, via the numerical simulations, Wang et al. [25] and Zhou et al. [26] both found that, owing to the interaction between the inner and outer interfaces, a double emulsion droplet has more wavy transient outer profile than a single-phase droplet when it passes through a constricted tube, However, it must be noted that, these available investigations are mainly concentrated on the individual behaviors of the single double emulsion droplet without any interaction from the other droplets. Consequently, a clear sense of detailed dynamic behaviors and morphology development of the colliding double emulsion droplets under the external flow is still lack. Particularly, the fundamental hydrodynamics underlying the colliding double emulsion droplets is even less understood.

Therefore, herein, via the combination of experimental observation and numerical simulation, we explore the hydrodynamic binary collision between double emulsion droplets driven by the external shear flow. Two typical colliding motions, passing-over motion and reversing motion, are identified by quantitatively characterizing the corresponding detailed motion trajectory and morphology development. Compared with the ordinary single-phase droplets, double emulsion droplets are found to exhibit similar motion trajectories but different deformation development during the binary collision process, which arise from the additional interaction induced by the inner droplet. In particular, we demonstrate that two typical colliding motions are dominated by the competitions among the drag of passing-flow region and the entrainment from reversing-flow and vortex regions in the matrix fluid, which are significantly affected by dimensionless shear stress (Ca) and confinement degree of shear flow (Co). Accordingly, a regime