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Drop deformation and breakup in flows with shear

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HIGHLIGHTS

- Droplet breakup is studied in flows with shear by means of the VOF method.
- A regime of bag, shear and intermediate breakup modes is considered.
- The larger the shear rate, the more the deformed drop tilts.
- Breakup approaches shear breakup as the Reynolds nr. and shear rate are increased.
- An empirical model for breakup time is suggested for spray simulation applications.

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ABSTRACT

A Volume of Fluid (VOF) method is applied to study the deformation and breakup of a single liquid drop in shear flows superimposed on uniform flow. The effect of shearing on the breakup mechanism is investigated as a function of the shear rate. Sequential images are compared for the parameter range studied; density ratios of liquid to gas of 20, 40, and 80, viscosity ratios in the range 0.5–50, Reynolds numbers between 20, a constant Weber number of 20, and the non-dimensional shear rate of the flow $G = 0$–2.1875. It is found that while shear breakup remains similar for all values of shear rate considered, other breakup modes observed for uniform flows are remarkably modified with increasing shear rate. The time required for breakup is significantly decreased in strong shear flows. A simple model predicting the breakup time as a function of the shear rate and the breakup time observed in uniform flows is suggested.

1. Introduction

The deformation and breakup of drops have been a problem of longstanding interest due to the common appearance of the phenomenon in various fields of engineering and biomedical applications. It is of fundamental importance in all kind of sprays, printing, food processing, combustion, emulsion formation, aerosols, and drug delivery systems, to mention a few.

Drops in uniform flow have been under investigation in several studies found in literature, such as the works of Krzeczkowski (1980), Pilch and Erdman (1987), Hsiang and Faeth (1992, 1995), Hsiang et al. (1995), Faeth et al. (1995), Han and Tryggvason (1999), Dai and Faeth (2001), Helenbrook and Edwards (2002) and Cao et al. (2007). However, in reality, the flows that drops in the above-mentioned applications are subjected to are rarely simple canonical flows. For example, in combustion processes, more complex flows need to be considered; the drop travels through a rapidly varying velocity field and is subjected to a variety of flow conditions. Therefore, in order to approach a more realistic flow configuration, the superposition of simple flows, such as uniform flow and simple shear, is considered for this study.

A pioneering investigation of steady simple shear flows was performed by Taylor (1932, 1934). In these works, neutrally buoyant drops suspended in sheared viscous liquids were studied both theoretically and experimentally. Taylor found that the deformation of the drop is mainly governed by two non-dimensional parameters, the viscosity ratio of the phases and the capillary number representing the ratio of viscous to interfacial forces. An explicit formula for the deformation parameter was derived by means of small deformation theory. It was also shown that in cases where surface tension dominates, the drop deforms to a spheroid with its main axis at an angle of 45° to the flow, as opposed to cases where viscosity is dominant and a spheroid with its major axis aligning with the flow is observed.

The work of Rumscheidt and Mason (1961) was the first to distinguish the different deformation and breakup mechanisms of droplets in shear flows, presenting three cases leading to breakup and one representing the upper limit of deformation. The three

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cases leading to breakup are characterized by the following. The first is represented by a drop having a sigmoidal shape with pointed ends from which small drops break up. This mode is called tipstreaming breakup in the literature. In the second case, the central part of the droplet forms a neck in the middle that progressively thins. Finally, the drop splits into two larger daughter drops, forming small satellite drops in between. In the third case, the drop extends to a long thread that disrupts after a long time. As concluded by Rumscheidt and Mason (1961), the viscosity ratio of the fluids is the most important parameter in terms of determining the breakup type. Conditions for breakup and critical values for breakup regimes were also studied by Karam and Bellinger (1968), experimentally verifying and summarizing results from earlier studies. It was concluded that there is a minimum ($\mu^* = 0.005$) and a maximum ($\mu^* = 4$) value for the viscosity ratio of the phases beyond which the drop cannot break. Barthés-Biesel and Acrivos (1973) predicted deformation and conditions for breakup in a general linear shear field using a theoretical method. Theoretical studies for Taylor's original and extended small drop deformation analyses (Taylor, 1934; Cox, 1969; Torza et al., 1972; Barthés-Biesel and Acrivos, 1973) are reviewed by Rallison (1980), also investigating the limits of validity for each. Grace (1971) conducted a thorough experimental investigation on the deformation and breakup of droplets accounting for a wide range of viscosity ratios. Results for drop deformation, critical conditions for breakup, breakup time, moreover, the number and size of fragments are presented and compared to data available from earlier studies.

Regarding the different breakup phenomena, some have been studied in more detail. The causes of the tipstreaming phenomenon for example were analysed by De Bruijn (1993), concluding surface tension gradients near the tip of the drop to be the main criteria for breakup. Besides the fact that very small drops are produced, it is also of practical importance that the shear rates required to reach breakup are two orders of magnitude smaller than for other modes. Lin and Guo (2007) studied the dynamic transition during the breakup process itself, analysing the birth of daughter, satellite, and sub-satellite drops. It was shown that depending on the capillary number, drops break via necking mechanism, end pinching, or capillary instability.

Review articles by Acrivos (1983), Rallison (1984), and Stone (1994) provide overviews of the field until the mid-1990s. Most of the works documented in these articles are theoretical or experimental, considering Stokes or low Reynolds number flows. Inertial effects are only briefly mentioned in the paper by Acrivos (1983). With the development of various numerical methods available for simulating two-phase systems the number of studies turning towards higher Reynolds numbers increased as well. One of the first works considering inertial effects was performed by Li et al. (2000). Developing a new VOF method and successfully validating the results with previously established critical values for breakup in low Reynolds number shear flows, an introductory study at higher Reynolds numbers, $Re = 0$–25, is presented. An increase in inertia was concluded to be a criterion for breakup as the increase in inertia alters the flow inside the drop.

Later, several other studies explored the altered critical conditions by investigating flows with Reynolds numbers up to $Re = 100$ (Renardy and Cristini, 2001a,b; Renardy et al., 2002; Khismatullin et al., 2003; Cristini and Renardy, 2006). It was shown that the critical capillary number depends on the Reynolds number according to $Ca_{cr} \sim 1/Re$. Furthermore, regarding the drop fragment distribution, daughter droplet size was concluded to scale with the critical drop size and with the capillary number at high Reynolds numbers. Komrakova et al. (2015) studied the effect of dispersed phase viscosity on the deformation of a drop suspended in simple shear flow as well as on the critical capillary number leading to breakup for a Reynolds number of 10. Renardy (2008) demonstrated the importance of inertia by comparing cases with 'gentle' and 'abrupt' start-up conditions of the shear flow for capillary numbers lower than the critical value. In case of gentle start-up, the drop is placed in a fluid at rest, after which the walls of the channel start to move, and the flow becomes fully developed after a finite time. On the other hand, in case of an abrupt start-up condition, the drop is placed in an established shear flow. It was shown that applying an abrupt start-up flow, the deformation of the drop might overshoot the deformation obtained for gentle start-up conditions of the same shear rate, as capillary forces have no time to counteract deformation. Thus, the drop may break at sub-critical conditions.

Other works on droplets regarding shear flows include investigations of wall effects (Chan and Leal, 1979; Shapira and Haber, 1990; Sibillo et al., 2006; Vananroye et al., 2006, 2007; Janssen and Anderson, 2007; Guido, 2011), time-dependent shear flows (Cox, 1969; Torza et al., 1972; Bentley and Leal, 1986; Stone et al., 1986), the interactions of droplets (Bayareh and Mortazavi, 2011a,b), simulations applying the Lattice Boltzmann method (Haowen and Duncan, 1999; Komrakova et al., 2014), and theoretical works (Fasano and Rosso, 2009). Furthermore, studies on the formation of droplets as a result of external electrostatic fields were presented by Sharma et al. (2014, 2015).

In our previous work, Kékesi et al. (2014), the deformation and breakup of drops were studied in uniform flows for an intermediate Weber number and Reynolds numbers ranging through the entire steady wake regime valid for deformable drops. Density and viscosity ratios were varied as well, accounting for properties typically found in fuel sprays. Results on the deformation process leading to breakup and an analysis regarding breakup times were presented. Besides classical breakup modes, such as bag and shear breakup, several additional modes were observed, and a new regime map was suggested.[1]

The aim of the present paper is to study the breakup of drops in shear flows. It is considered that in complicated flows, such as in combustion for example, there are local velocity gradients present on the small scales around the drops. Thus, the purpose is to study general flows with velocity gradients by imposing shear flows of various shear rates on top of a uniform flow, rather than looking at simple symmetric shear flows used in most studies in literature. Results are compared to previous observations presented in Kékesi et al. (2014). Besides the evolution of the deformation and breakup of drops, a simple model predicting the breakup time as a function of shear rate is suggested for further use in spray simulations employing Lagrangian particle tracking methods.

The paper is structured as follows. In Section 2 the numerical method along with the governing equations and a brief description of the solver are discussed. Section 3 describes the geometry and the mesh. Relevant non-dimensional parameters and a summary of cases considered are provided in Section 4. Sequential images for five breakup modes are shown, and the effect of increasing shear rate on the deformation and breakup process are studied in Section 5. In Section 6 the time required for breakup is investigated, and a simple model for breakup time is suggested.

2. Governing equations and flow solver

Numerical simulations are performed on a two-phase liquid–gas system using the Volume of Fluid (VOF) method. The governing equations describing the flow are the conservation

[1] Note that the definition of the characteristic time in Kékesi et al. (2014) was defined as $t_{char} = 4D/U_0$, and is changed to $t_{char} = D/U_0$ here.