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Multimodal shape oscillations of droplets excited by an air stream

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HIGHLIGHTS

- Drop oscillation was analyzed using optical diagnostics and anemometry.
- Viscous time scale imposes a threshold on frequency response of glycerol drop.
- Correlation of droplet aspect ratio in terms of Weber number and Ohnesorge number.

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ABSTRACT

The shape dynamics of droplets exposed to an air jet at intermediate droplet Reynolds numbers is investigated. High speed imaging and hot-wire anemometry are employed to examine the mechanism of droplet oscillation. The theory that the vortex shedding behind the droplet induces oscillation is examined. In these experiments, no particular dominant frequency is found in the wake region of the droplet. Hence the inherent free-stream disturbances prove to be driving the droplet oscillations. The modes of droplet oscillation show a band of dominant frequencies near the corresponding natural frequency, further proving that there is no particular forcing frequency involved. In the frequency spectrum of the lowest mode of oscillation for glycerol at the highest Reynolds number, no response is observed below the threshold frequency corresponding to the viscous dissipation time scale. This selective suppression of lower frequencies in the case of glycerol is corroborated by scaling arguments. The influence of surface tension on the droplet oscillation is studied using ethanol as a test fluid. Since a lower surface tension reduces the natural frequency, ethanol shows lower excited frequencies. The oscillation levels of different fluids are quantified using the droplet aspect ratio and correlated in terms of Weber number and Ohnesorge number.

1. Introduction

Injection of droplets in a convective gas flow is a practical scenario encountered in different natural and industrial areas such as falling raindrops, spray driers, gas turbine engines, premixers and solution precursor plasma spray process (SPPS). In the practical situations, the hydrodynamic interaction between the liquid and gaseous phases can become very complicated. The growth of shear inabilities at the droplet interface can lead to the disintegration of the parent droplet into daughter droplets. This secondary droplet breakup has paramount influence in determining the final droplet size in addition to dispersion level and thereby the end result of the process, whether it is the emission level in combustion, the final powder quality in spray drying or the coating efficiency in SPPS. The droplets usually exhibit high amplitude shape oscillations as a precursor event to secondary atomization. Hence it is essential to understand the dynamics of droplet shape oscillation for optimizing the performance of these industrial processes. Normal spray models as used in commercial solvers use simple models like TAB (Taylor Analogy Breakup) to approximate the droplet breakup processes and daughter droplet sizes. However, these models fail to address the physics of multimodal shape oscillations that lead to the ultimate droplet breakup.

In his seminal work, using linear energy analysis, Rayleigh (1879) expressed the shape of a droplet freely oscillating in a quiescent medium as an infinite series of Legendre polynomials and derived an expression for the fundamental angular frequency, ω of the nth mode ($n \geq 2$) of oscillation as

$$\omega_n^2 = \frac{n(n+1)(n-1)(n+2)}{[(n+1)\rho_l + n\rho_g]} \frac{\gamma}{R^3} \quad (1)$$

where γ, ρ and R denote the interfacial tension, density and equilibrium radius of the droplet respectively. Subscripts l and g

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refer to the liquid phase and gaseous phase respectively. Lamb (1932) included the effect of small viscosity into the linear analysis. Later, Reid (1960) studied the damping effect of arbitrary viscosity on the small-amplitude oscillations of unforced droplets. Prosperetti (1980) solved the initial-value problem describing infinitesimal-amplitude oscillations for viscous drops. Nonlinear analysis was carried out for moderate amplitude oscillations of inviscid droplets and bubbles by Tsamopoulos and Brown (1983) using the Poincaré–Lindstedt expansion method. A theoretical inviscid model describing the interaction of modes at large amplitude oscillations was developed by Natarajan and Brown (1987).

Many studies have been focused on the dynamics of forced oscillations of droplets. Feng and Leal (1996) studied the shape oscillation frequencies of a conducting droplet subjected to a time-varying electric field. By means of modulated acoustic field Trinh and Wang (1982) examined the large-amplitude oscillations of droplets levitated in another immiscible liquid. Murray and Heister (1999) employed a Boundary-Element Method to investigate the behavior of an acoustically perturbed liquid droplet. In a recent theoretical work Deepu and Basu (2014) analyzed the oscillation behavior of an isolated droplet subjected to pulsatile external flow field.

Several numerical and experimental studies were reported on oscillations of attached droplet. Through an analytical study, Strani and Sabetta (1984) showed that for a supported droplet there exists an additional mode of oscillation ($n=1$) which represents the motion of the droplet center of mass which is not feasible for an isolated droplet. Wilkes and Basaran (1997) used a finite element method to simulate the dynamics of a liquid droplet pendant from an oscillating rod. Vukasinovic et al. (2007) experimentally examined the atomization induced in an inviscid sessile droplet by exciting its resonant modes through vibration of the substrate. Lyubimov et al. (2006) studied the natural and forced oscillations of a hemispherical droplet on a solid plate. Noblin et al. (2009) based on their theoretical model derived an expression for the resonant frequencies of sessile droplets with pinned contact lines. Chebel et al. (2011) reported experiments to investigate the small amplitude shape oscillations of a buoyant drop attached to a capillary tube and observed that for large drops, the measured resonant frequencies of the lower modes match the corresponding theoretical values of a free neutrally buoyant drop. Prosperetti (2012) theoretically established that a constrained droplet is "stiffer" than an unconstrained one. In other words, the presence of the constraint increases the frequency of the normal modes of oscillation. Using an optical deflection method Sharp (2012) studied the free oscillations of sessile glycerol/water mixture droplets in pinned contact line mode. The free surface of the droplet was perturbed by a puff of air and the effect of contact angle on the resonance frequency and that of viscosity on the width of the resonance peak were reported. In their recent analytical work, Bostwick and Steen, 2013a, 2013b have reported the spectra for linear axisymmetric oscillations of inviscid and viscous drops constrained by a belt support.

Despite the extensive research on the subject, there exist various explanations for the actual mechanism which induces the droplet oscillation in practical cases. While some reports (Gunn, 1949; Beard et al., 1989) suggest that the shedding of vortices in the wake of a droplet placed in a convective gaseous medium excites the droplet oscillation modes, others (Winnikow and Chao, 1966; Saylor and Jones, 2005) have reported a lack of association between the eddy detachments and droplet shape oscillations. It is the purpose of this study to understand the real mechanism of droplet shape excitation induced by aerodynamic interaction at intermediate Reynolds number.

It is rather difficult to experimentally simulate the droplet conditions in the applications mentioned above, explaining the lack of experimental data in the literature to satisfactorily explain the reason for the droplet shape oscillation. To cause a relative motion between a droplet and its surrounding, the most realistic method would be to inject a droplet into a gaseous medium. However, if the temporal oscillations of the droplet shape is to be studied, the droplet needs to be optically accessible to the diagnostic apparatus and even moderate droplet Reynolds numbers will demand huge operational logistics of the setup. Other options are to use electric, magnetic or acoustic levitation techniques to study isolated droplets. But these techniques put a constraint on the nature of the fluid studied or the maximum gas flow rate that can be achieved around the droplet. Furthermore, the external levitation force field itself can induce droplet oscillations and hence to separate the effects of gas flow and levitation field will be difficult. From the above discussion it is abundantly clear that any practically feasible experimental method is intrusive to a certain extent.

After considering all the available options, in the present study the droplet is deployed at the junction of cross-wire at the center of a vertical air jet to simulate the practical scenario. A similar setup was used to experimentally study the heat transfer and droplet regression dynamics in a hot air stream as described by Deepu et al. (2013). However the shape oscillations exhibited by such droplets were not analyzed in any detail. Normally, convective heat transfer in a hot air jet will lead to significant diameter regression, thereby stabilizing the shape oscillations of the pendant droplets. Hence in the present study, to exclusively investigate the role of aerodynamic loading, the setup described in Deepu et al. (2013) with only air jet at room-temperature is used to suppress convective heat transfer. The influence of wake structure, if any, on the observed droplet shape oscillations is investigated. Furthermore, by using different fluids, the effect of fluid properties on the Legendre oscillation modes of the droplets is examined.

Empirical correlations are proposed to describe the droplet aspect ratio oscillations to the droplet physical properties and flow parameters. The experiments were carried out for the Reynolds number (based on droplet diameter) range of 190–650. Since the gravitational bond number, $G \equiv \rho g R^2/\gamma \sim O\,(0.1)$ for all the fluids, the gravitational effects are not taken into account in the present analysis. The sphericity of the initial unperturbed droplet supports this argument. Here g denotes the acceleration due to gravity. The focus of this study is to consider only the dominant mode of oscillation, namely the prolate–oblate droplet mode, and the effect of the external flow field fluctuations on the mode. A more detailed analysis considering the non-linear coupling and energy transfer between the different modes is not considered in the current study.

2. Experimental setup

Fig. 1 illustrates the schematic of the experimental setup. The setup described in Deepu et al. (2013) is used for the present experimental study with a few modifications. Compressed air was passed through a drier to remove unwanted moisture before discharging as a vertical jet from a tube (inner diameter 12 mm). The jet was shielded by glass slabs on all four sides to avoid any external disturbances. The droplet was deployed using a high-accuracy micro-pipette at the junction of a firmly mounted cross-wire made of two quartz fibers (diameter 200 μm each). After deploying the droplet (4.5 ± 0.2 μl volume) at the junction, a swinging deflector is actuated to introduce the moving stream of air around the droplet. The images of the back-illuminated oscillating droplet were recorded at 2000 fps using a Photron Fastcam SA5 camera. Since the steady-state oscillation of the droplet is the subject of interest, the image acquisition was started 5 s after the jet was released. The length of the recorded video was