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Short Communication

Effect of evaporation and agglomeration on droplet shape oscillations

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HIGHLIGHTS

- Wavelet transform reveals non-linear signatures in water droplet oscillation.
- Continuous increase in natural frequency of evaporating ethanol droplet.
- Drastic reduction in oscillation level due to particle aggregation.

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ABSTRACT

The effects of evaporation and the presence of agglomerating nanoparticles on the oscillation characteristics of pendant droplets are studied experimentally using ethanol and aqueous nanoalumina suspension, respectively. Axisymmetric oscillations induced by a round air jet are considered. Wavelet transform of the time evolution of the 2nd modal coefficient revealed that while a continuous increase in the natural frequency of the droplet occurs with time due to the diameter regression induced by vaporization in the case of ethanol droplet, no such change in resonant frequency occurs in the case of the agglomerating droplet. However, a gradual reduction in the oscillation amplitude ensues as the agglomeration becomes dominant.

1. Introduction

Droplet oscillation has received a lot of attention in the literature for more than a century because of its technological relevance in applications like spray drying, combustors, thermal barrier coating and ink-jet printing. Rayleigh (1879) showed that the natural frequency of the nth mode of an isolated inviscid droplet (with equilibrium radius R, density ρ and surface tension γ) is given by

$$f_n = \sqrt{\frac{\gamma n(n-1)(n+2)}{\rho R^3}}, \tag{1}$$

where the droplet shape is represented in a spherical coordinate system (with origin set at the centre of the undeformed drop) as a summation of infinite modes:

$$r(\theta, t) = R + \sum_{n=2}^{\infty} a_n(t) P_n(\cos\theta) \tag{2}$$

with P_n denoting the nth order Legendre polynomial, t time, and θ polar angle. For a discussion of the subsequent developments that have been made in the field, see Ashgriz and Movassat (2011).

This short communication is an extension of our previous work (Deepu et al., 2014) which deals with the oscillation behavior of a droplet placed in an external convective flow field. Detailed modal analysis showed that the lower Rayleigh modes ($n=2$ to 4) get excited by the free stream pressure fluctuations and each mode shows a sustained non-linear (high amplitude) response at the corresponding natural frequencies. However the external air jet used was at ambient temperature to prevent droplet evaporation. The droplets in plasma or flame environments mentioned earlier, however, undergo severe deformation due to aerodynamic and thermal loading which can lead to secondary atomization and thus influence the final spray/product quality. Simultaneously the droplets undergo evaporation (e.g. pure fuel drops in a combustor) and/or agglomeration (e.g. precursor droplet in a spray dryer). Hence it is the objective of this study to investigate the effect of these two phenomena on droplet oscillation.

The fundamental mode of oscillation is the one corresponding to $n=2$ in Eq. (2), which carries the highest amount of energy. Physically, this mode represents the prolate–oblate oscillation of the droplet and hence has the same frequency characteristics as

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the droplet aspect ratio (Deepu and Basu, 2014). Thus we select the corresponding temporal coefficient a_2 as the oscillation parameter of the droplet in this work. Using wavelet analysis, we demonstrate the effects of diameter reduction due to vaporization and morphological changes due to agglomeration on the oscillation characteristics of the droplet.

2. Experimental setup and procedures

The current experiments were conducted on the same setup described in our previous study (Deepu et al., 2013) which considered only droplet vaporization by employing very moderate air velocity (so the oscillation levels were too low to influence the vaporization characteristics). The droplet (of $R \approx 1$ mm) was suspended at the junction of a quartz cross-wire (diameter of wire is 200 μm) placed at the centre of a free circular air jet. The temperature, T and velocity, U_∞ of the air jet at the droplet location were controlled. These were measured using a thermocouple and a constant temperature hot-wire anemometer, respectively. A high-speed camera recorded the images of the back-illuminated oscillating droplet at a frame rate of 500–2000 fps (fixed depending upon the duration of the observation). Edge-detection technique was employed to trace the co-ordinates of the droplet contour in each frame of the videos and subsequently a_2 was evaluated. More detailed description of the setup and image analysis procedure can be found in Deepu et al. (2013, 2014). The droplet Reynolds number is defined as $Re = 2U_\infty R/\nu_{\text{air}}$, where ν_{air} denotes the kinematic viscosity of air. Three cases were considered: (1) distilled water droplet at $T = 30\,^\circ$C (ambient jet) and $Re = 639$, (2) pure ethanol droplet at $T = 100\,^\circ$C and $Re = 200$ and (3) NA10 droplet (aqueous nanoalumina suspension with average particle diameter = 21 nm and particle volume fraction = 0.1) at $T = 30\,^\circ$C and $Re = 639$. Case 1 represents the benchmark case (no evaporation/agglomeration), while cases 2 and 3 enabled us to study the individual effects of evaporation and agglomeration, respectively. The values of Re chosen for the different cases are roughly the highest that could be achieved without causing vigorous droplet oscillations leading to loss of axisymmetry. Likewise, 100 °C is the maximum safe temperature we could achieve without causing oxidation at the hottest point of the copper tube carrying the hot air flow. The nanofluid (NA10) was procured from Sigma-Aldrich and was used after ultrasonication for 20 min. Nanofluid was stable and showed no agglomeration behavior over extended time periods. Relevant fluid properties are given in Table 1.

Deepu et al. (2014) employed Fourier techniques for spectral analysis of the modal coefficients whose oscillation properties were stationary or non-transient. But for signals that are non-stationary, such as the temporal coefficient a_2 of an evaporating or agglomerating droplet considered here, Fourier transform will lead to the loss of information on the temporal behavior of the spectral characteristics. Hence, in order to reveal the time signature of the frequency characteristics of droplet oscillations, we perform a 1-D continuous wavelet transform (CWT) on the time series data of a_2 which can generate the time-frequency map of the fluctuating data. CWT technique (Farge, 1992) uses a basis of temporally (or spatially, as the case maybe) localized functions called wavelets, which are obtained by translating and dilating a mother wavelet. We used MATLAB to perform the wavelet analysis with Morlet wavelet as the mother wavelet. Since the dilation parameter represents the scale factor by which the mother wavelet is stretched or compressed, it is directly related to the frequency components in the signal (higher scale corresponds to lower frequency and vice versa) and can be converted into an equivalent Fourier frequency, as presented in the wavelet spectrograms (which represents the percentage of energy for each continuous wavelet coefficient) shown later. Because it is a scaled (or normalized) image, the CWT spectrum gives the relative distribution of energy among the different frequency components for a particular case and the amplitude of the frequency components cannot be compared between two cases in an absolute sense.

Table 1
Thermophysical properties of test fluids at 30 °C.

Fluid	Density, ρ (kg/m^3)	Surface Tension, γ (mN/m)	Dynamic viscosity, μ (mPa s)
Water	995	72	0.8
Ethanol	788	22	1.2
NA10 (Basu et al., 2013b)	1295	46	18

3. Results and discussion

Fig. 1 shows the temporal variation of a_2 for the three droplets considered. The negative value suggests that the distorted droplet assumes oblate spheroid shape as the aerodynamic force squeezes the droplet along its streamwise axis. The presence of the horizontal wire passing through the droplet may also contribute to a larger dimension in the cross stream direction of the droplet. Also note the magnitude of a_2 for water reaches 20% of the static droplet radius, indicating that the droplet oscillations are highly non-linear. In the absence of any substantial evaporation, shape oscillation amplitude of pure water drop is found to be constant with time as the external jet velocity and pressure fluctuations continuously provide the energy for the sustained oscillations (Deepu et al., 2014). In comparison, the oscillation dynamics of evaporating or multiphase droplets is quite different; in both cases, the oscillation level diminishes over time. Note that for same value of Re, nanoparticle laden droplets exhibit lower amplitude of oscillation in a_2 (Fig. 1c) compared to water beyond $t = 15$–20 s. We will elaborate on these results in subsequent sections.

3.1. Shape oscillations of a pure non-evaporating droplet

Fig. 2 shows the wavelet spectrogram of a_2 for water where the droplet response is observed in a band of frequency range constituted by peak responses at the fundamental frequency, f_2 (≈ 110 Hz from Eq. (1)) and its subharmonic (≈ 55 Hz). The highest droplet excitations at these two frequencies (marked by the brightest spots) are circled in the zoomed-in image. Such a sub-harmonic excitation and its intercoupling with the harmonic response is a manifestation of the non-linear effects of the droplet oscillation. For linear (small-amplitude) oscillations only the harmonic response is allowed as shown by the theoretical results of Deepu and Basu (2014). Without any overall change in diameter size, the frequency range of excitation of water remains constant with time as shown in Fig. 2.

3.2. Shape oscillations of an evaporating droplet

The CWT spectrum of ethanol droplet (Fig. 3) also shows response around the natural frequency of $n = 2$ mode. However due to the lower Re employed for ethanol droplet, the oscillation amplitude is low (see Fig. 1) and hence the manifestation of the non-linear effects in the form of sub-harmonic response is not as prominent as in the case of water. Another difference to be noted is the constant shift of the resonant frequency response to the higher frequency side with time. The peak responses of $n = 2$ mode obtained from the wavelet spectrum as a function of time are