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Atomization Instabilities in Bubble Induced Break-up

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Abstract

Effervescent atomization, or bubble induced atomization is one of the more uncommon methods of primary jet break-up. As a technique, it offers a substantial degree of atomization at very low mass gas-to-liquid ratios (GLR). This advantage however comes with a significant deficiency being the near-field spray instability which can arise due to bubbles traversing down the liquid jet in discrete packets. These injected bubbles create dominant frequencies in the primary atomization region which are driven by a complex two-phase flow that initiates upstream of the nozzle ejection orifice. There is a severe lack of understanding of bubble dynamics in effervescent sprays. In this paper, using high speed microscopic imaging techniques, and laser Doppler anemometry (LDA), an initial study of the near-field jet break-up is conducted. The LDA system is used in order to measure the physical locations in the spray where dominant frequencies are no longer measurable. These locations represent the portions of the spray where significant entrainment and turbulent mixing has occurred such that dominant bubble frequencies are 'destroyed'. The results presented here allow for an understanding of spray instability in effervescent atomization, which would ultimately facilitate the design of more stable fuel injection systems leading to reduced combustion instabilities in a wide range of applications.

Introduction

An essential requirement of combustion systems, is the production of vapour over a short and ideally controlled time-scale with minimal liquid deposition on the walls of the combustion chamber. Key time-scales related to the spray formation stages are the primary and secondary atomization break-up times followed by the droplet evaporation time-scales. Short break-up times can be achieved using a variety of techniques, where for high pressure injection systems, a pressurized plain orifice atomizer [2, 15] is the most common one.

However, it has been shown that the addition of atomizing gas directly in the fuel (effervescent atomization) drastically reduces the ejected droplet size [18, 11, 19, 7] and also greatly improves dispersion [13, 18]. This is also true with liquid preheated atomization where vapour bubbles form in the fuel [6, 14]. This method of air injection forms a twin-fluid atomization technique which is however distinctly different from other twin-fluid techniques such as air-blast [1, 8] and air assisted swirl atomization [8]. Bubble induced or effervescent atomization involves the 'pre-mixing' of two phases upstream of the ejection orifice. Depending on the ratio of gas to liquid by mass, a number of different flow regimes can exist in the internal atomizer geometry such as 'bubbly flow', 'slug flow' and 'annular flow' [3, 4, 18, 10] where upon exiting the orifice, the air present in the liquid column promotes the creation of liquid shreds that may appear as a 'tree-root' structure [18, 11].

Effervescent atomization is extremely efficient given that useful gas to liquid mass ratios (GLR) can be as low as 0.001 [18]. In contrast, in a typical air-blast atomizer the gas to liquid ratio is typically orders of magnitude higher in order to achieve significant interfacial instabilities [8]. While research in effervescent atomization has shown a very significant droplet size reduction with an increase in GLR, there has been minimal work which has quantitatively examined the instabilities that arise due to the existence of a two-phase mixture upstream of the orifice. The work that has been done in this area has qualitatively examined the separation between packets of atomized liquid and has clearly shown the existence of unsteadiness in the spray [3]. Ghaemi et al. [4] have shown that the size of the bubbles at the exit orifice is directly linked to the atomization mechanism where bubbles smaller than the orifice size are desirable for stable operation. More recent work [16, 9] has also shown substantial temporal variations in droplet size from an effervescent atomizer operating with liquids of varying viscosity. A very comprehensive study by Shepard [17] has shown the quantitative influence of bubble size on atomization, and has also shed some new physical insight on the method of effervescent atomization slightly downstream of the nozzle.

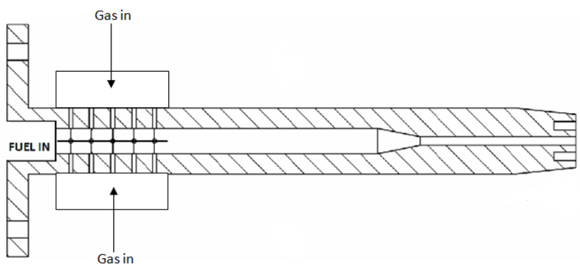

Figure 1. A schematic of the effervescent atomizer showing the gas aeration holes and main fuel line.

The work of Shepard [17] suggests that the atomization is more likely caused by collisions of discrete packets of liquid ejected from the nozzle. These packets originate from intermittency in the flow at the exit plane, where liquid and air mix. This observation seems to be at least qualitatively consistent with much of the images in the effervescent atomization literature, suggesting that 'bubble explosions' may not be the true reason for atomization, but rather the fluctuations in the liquid column void fraction that the air generates. In work by Meier et al [12] axial instabilities (generated using a piston) on the ejected liquid columns were found to yield strikingly similar features to those generated in effervescent atomization.

Despite these studies, there remains a lack of work in the literature that quantitatively examines instabilities in effervescent atomization. If such a mode of spray formation is to become more of a standard in combustion applications then further research is necessary in order to fully understand the generated instabilities thus leading to knowledge on how to remove them. This study makes a contribution in this space by providing qualitative observations of the near field effervescent atomization structure and quantifying the break-up frequencies as a function of the GLR ratio using high speed microscopic imaging along with LDA.

Case	Ef1	Ef5	Ef8	Ef9	Ef10	Ef11
Gas flow rate (g/min)	0.07	0.46	1.16	1.39	1.63	1.97
Injection Pressure P_{inj} (KPa)	40	61	120	138	155	180
GLR	.001	.009	.022	.027	.031	.038

Table 1. Test conditions for cases investigating including the gas mass flow-rate through the aeration holes, the injection pressure and the gas to liquid ratio by mass.

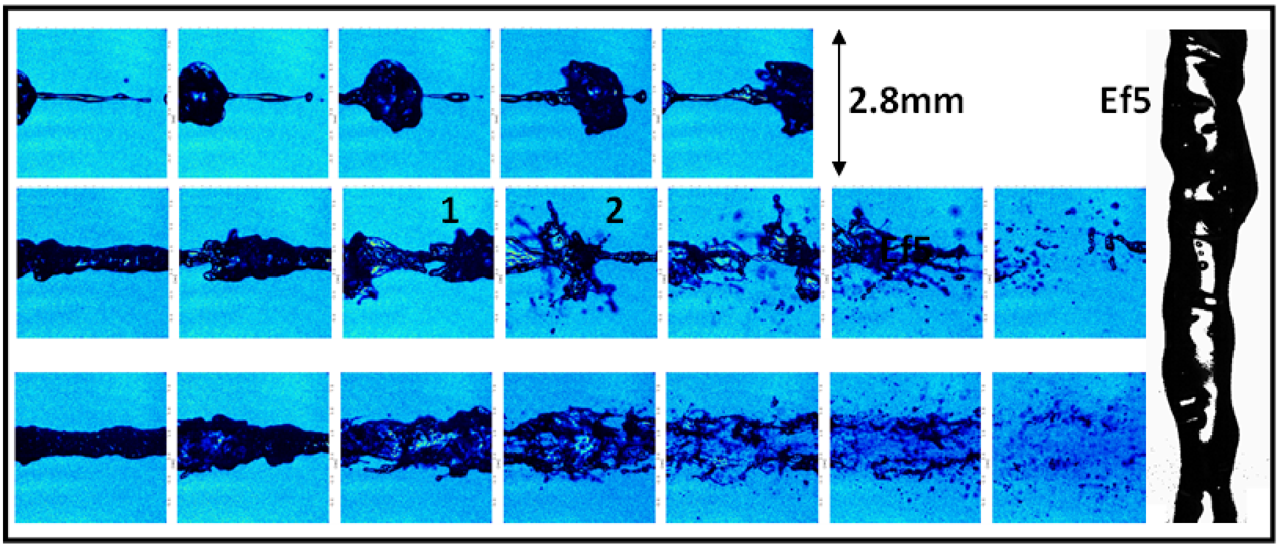

Figure 2. Sequential high speed images separated by 100μs, at the exit plane of the liquid orifice for cases Ef1 (top), Ef5 (middle) and Ef9 (bottom) as well as a zoomed in instantaneous snapshot of the liquid column for case Ef5.

Experimental Methodology

A 2D commercial laser/phase Doppler anemometry system (TSI Model FSA 3500/4000) has been used for characterisation of the spray. The system can measure droplets in the range 2-120μm. The receiver was operated in a 45 degree forward scattering configuration where more details on the uncertainties and calibration of the system are given elsewhere [5].

High speed imaging is achieved using a backlit microscopic imaging system. This consists of a Nd-YAG diode stack laser (Edgewave) operated at 532nm and 10KHz with a nominal power of 2mJ/pulse as a source of illumination. Two glass diffusing optics are utilized to remove coherence from the beam. The detection system consists of a high speed CMOS LaVISION camera with a QM-100 long distance microscope lens. In this experiment the lens was set with a 2.8x2.8mm field of view at a pixel resolution of 768x768.

A schematic of the effervescent atomizer geometry is shown in figure 1 where twenty aeration holes of 0.5mm in size each are used to inject the gas upstream of the discharge nozzle orifice which also has a 0.5mm diameter. The liquid used in these experiments is water and the aeration gas is air at room temperature. Experimental conditions are presented in table 1 which shows a number of different cases with increasing gas to liquid ratio. In all cases the liquid flow-rate was kept fixed at approximately 52 g/min. The injection pressure presented is measured directly upstream of the aeration chamber and is therefore the closest approximation to the pressure drop between the liquid/air mixture and atmosphere. With these choices of GLR the atomization modes should range from bubbly flow to a slug flow mechanism [18].

Qualitative characteristics

Figure 2 shows a selection of high speed acquisition sequences in time (from left to right) for cases Ef1 (top), Ef5 (middle) and Ef9 (bottom) from table 1. Concentrating on the top row, which shows the case for the lowest GLR the image shows a distinct separation between thinned portions of liquid column and large portions of the liquid which have formed a bag like structure which contains air. These bags occasionally detach from the liquid jet but rarely atomize further. In contrast, the middle row shows, for a case of higher GLR a substantial amount of atomization where the time elapsed from an intact liquid core to an atomized jet is approximately 600μs. Many of the small droplets disperse radially outward leaving the core with large unatomized fragments.

Of particular interest are two images labelled as '1' and '2' in the middle row which show what appears to be a collision event going from image 1 to image 2. Such occurences, where liquid is preferentially expelled radially outward, are commonly observed throughout images, and indicate that a significant amount of atomization may not be related to bubble explosion events. The reasoning behind this is the assymetry associated with the atomization which would be unexpected for bubble explosions [17]. This is in direct agreement with the observations of Shepard [17] in that axial perturbations are responsible for the atomization, however further work is required in order to fully confirm this.

The far right of figure 2 shows a zoomed-in portion of the intact liquid column for case Ef5 (middle row). A background threshold is applied for clarity making individual bubbles within the intact liquid jet very clear. The polydisperse nature of these bubbles is evident here with sizes ranging from the order of the orifice diameter D_l to approximately $0.1D_l$. While we do not suggest that these are directly responsible for the atomization

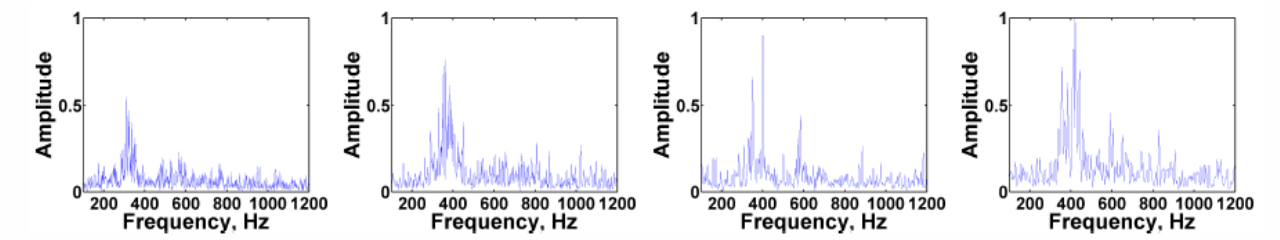

Figure 3. Frequency amplitude normalized by maximum amplitude from Ef11 plotted vs. frequency for cases Ef8, Ef9, Ef10 and Ef11 from left to right at r/D=0, 12 mm downstream from orifice.

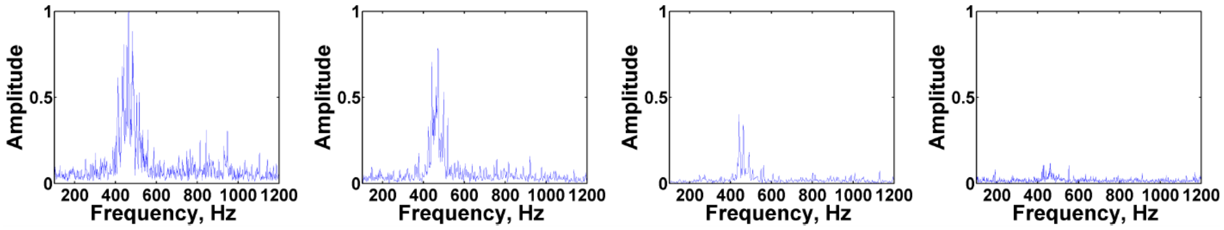

Figure 4. Frequency amplitude from Ef9 normalized by centreline value plotted vs. frequency for r/D_l=0, 1.2, 2.6, and 3.8 from left to right, 12 mm downstream from orifice.

process, coalescence of such bubbles is observable resulting in the bag-like structures of case Ef1. These portions of liquid with thin membranes are then more prone to atomization.

The bottom row shows for case Ef9 more of an annular sheath mode of break-up where a core of air is present within the liquid jet forming a liquid annulus that atomizes. This is quite clear upon observing darker portions of intact liquid which are still present in the periphery of the spray in the late stage of the atomization process (bottom right sub-image of figure 2).

Regardless of the physical atomization mechanism (bubble explosion, collision or axial velocity fluctuations), the effervescent atomization process is extremely intermittent, and this is an undesirable attribute of this liquid break-up mode. In the next section we examine the unstable frequencies in greater detail.

Atomization frequencies

Figure 3 shows the fast Fourier tranform (FFT) of the axial raw velocity signal measured at the centreline from the LDA system. Results from left to right are for cases Ef8, Ef9, Ef10 and Ef11 where the vertical axis is a normalized amplitude. These measurements are made 12mm downstream of the liquid orifice. For all four cases shown here, strong peaks appear in the range between 350 and 450Hz, where the most energetic frequencies for cases Ef8, Ef9, Ef10 and Ef11 equate to 350, 380, 400 and 410Hz respectively. While this is evidence of an increase in frequency with an increase in the GLR ratio such frequencies are also highly dependant on the geometry of the atomizer as well as injection pressures. In addition, all frequency amplitudes are normalized by the maximum for case Ef11 which clearly shows that the spectral density is more concentrated around a narrow frequency band for the highest GLR case when compared to the lower cases.

The reader is reminded that these frequencies are extracted from the velocity measured from the spray which, due to the LDA/PDA system used, is restricted to measuring spherical droplets ranging from 2 to 120μm. Therefore, the measured frequency is an estimate of the 'memory' of the instability contained in the products of the atomization process as opposed to the core instability. However, frequencies measured from the high-speed images are in the same range as those obtained from LDA/PDA though this aspect warrants further investigation. In addition, frequency bands above 500Hz are also observable however it is unclear what the origin of these frequency bands are and this requires further analysis.

Figure 4 shows for case Ef9 the frequency spectrum 12mm downstream as a function of the radial position r/D_l=0, 1.2, 2.6, and 3.8 (from left to right). The spectrum amplitude shown in figure 4 is normalized by the centreline value at the exit plane. Around the periphery of the central liquid core the dominant frequency has dissipated, due to entrainment from the surrounding air. A similar effect is observable as measurements are taken further downstream which generally show that even though these effervescent sprays are extremely intermittent if they are ejected in highly turbulent environments this well known-disadvantage may be outweighed by the improving effect of turbulent mixing.

The dominant frequency which is of the order of 400-420Hz remains unchanged as measurements are taken radially outward, This, however, does not take into account other atomization modes that can be occuring in the periphery of the jet which would stem from the core fragments that cannot be measured using the PDA system. Of further interest is to note that the radial location at which the dominant frequency begins to dissipate equates to the change in gradient in turbulence intensity. This is evident from figure 5 which shows the turbulence intensity plotted vs radial location both for cases Ef5 and Ef9. At r/D_l=3.8 where the frequency has almost dissapeared is the location where substantial shear driven mixing exists showing how efficient turbulence is at destroying the dominant frequencies.

Unfortunately, LDA measurements for case Ef5 were not possible due to the presence of too many ligaments leading to extremely low burst efficiencies from the PDA detector. However, given the very narrow spray core for Ef5 as seen from figure 5, suggests that the dominant instabilities would dissipate very close to the main spray.

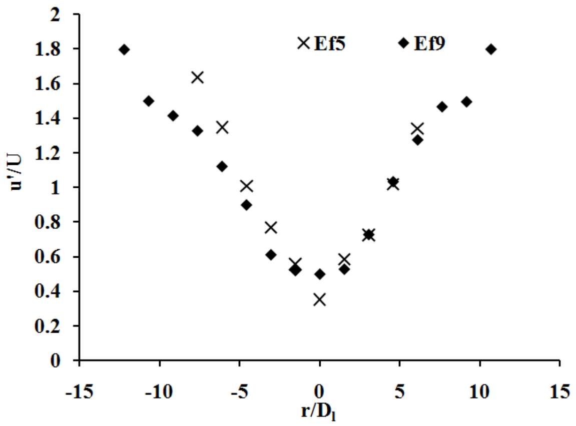

Figure 5. Frequency amplitude normalized by centreline value plotted vs. Frequency for r/D_l=0, 1.2, 2.6, and 3.8 from left to right, for case Ef9, 12 mm downstream from orifice.

Conclusions

A selection of results from a recent study on the instability characteristics of bubble induced (effervescent) atomization has been presented. Qualitative images clearly show an increase in atomization performance with GLR and this confirms earlier findings while also showing large scale collision events. Microscopic images show bubbles in the main liquid core downstream of the orifice which, for some cases, clearly coalesce to form large bag like structures that further promote atomization. The instability modes of effervescent atomization are therefore likely linked both to collision events driven by instabilities as well as bubble coalescence events making this a more complex problem than simpler models would suggest.

The pulsation frequencies of the instabilities increase with GLR. However, shear at the liquid-air interface acts to destroy the dominant frequencies, thereby suggesting that effervescent atomization may suffer from less global intermittency in highly turbulent flows.

Acknowledgements

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