Liquid jet breakup in homogeneous and isotropic turbulence without mean flow

G. Charalampous*,[1], P. Chounta[1], Y. Hardalupas [1]

[1]Mechanical Engineering Department, Imperial College London, London, SW7 2AZ, UK

Abstract

The breakup of a laminar water jet and the dispersion of produced droplets under the influence of homogeneous and isotropic turbulence without mean flow are examined. In this flow configuration the atomisation process is influenced only by the fluctuating velocity component of the gaseous environment without the influence of a mean velocity component. Multiple key aspects of the liquid jet breakup process are considered, including the mean value and the fluctuation of the intact liquid jet with the level of turbulence and the momentum of the liquid jet, the generation of satellite droplets in the region very close to the breakup point and their coalescence with the large droplets downstream, and the effect of turbulence on the mean size and dispersion of the droplets from the jet axis.

Introduction

In complex flows, such as those found in combustion environments, where the liquid fuel jet is destabilised by a turbulent gaseous environment, it is difficult to study the breakup process analytically and experimental investigation is often required. While many investigations have been performed on the breakup of liquid jets [1-4], one of the major challenges is to identify how the gas flow turbulence influences the breakup of the injected liquid jet. This is because in atomising flows significant fluctuations are often imposed over the mean velocity. At present, most research is conducted by examining the atomisation of liquids under the influence of high mean velocity and altering the turbulence level[5]. However, in this approach the mean velocity can obstruct the contribution of turbulence. An alternative approach to examine the contribution of turbulence to atomisation that is proposed here is to remove the mean velocity component and examine the breakup of a liquid jet under only a turbulent environment without a mean velocity component. This is possible to accomplish when using a box of turbulence facility [6, 7]. In this approach a stationary volume of homogeneous and isotropic turbulence with selectable levels of turbulence can be generated where the breakup of a liquid stream and the dispersion of the produced droplets can be observed to examine the role of turbulence on the liquid jet breakup process.

Methods

The experimental investigation was conducted in a ‘box of turbulence’ facility where a volume of homogeneous and isotropic turbulence without mean flow was generated ([8]). This is accomplished by 8 loudspeakers placed at the vertices of a cube and pointing at the cube centre. Each loudspeaker cone was covered with a plate with a regular triangular mesh pattern of 6mm holes. The triangle edge of was 20mm and the pattern covered an area of about 160mm in diameter. The loudspeakers were driven with sinusoidal voltages at 50Hz, and 8 synthetic jet arrays where formed that exhausted to the centre of the cube. When the induced flows from the synthetic jet arrays met at the centre of the cube, the mean flow cancelled out while the generated turbulence was homogeneous and isotropic. The level of turbulence was adjustable by controlling the amplitude of the loudspeaker driving voltage. Three levels of turbulence were considered, which correspond to turbulent velocity fluctuations of u´=0.20m/s, u´=0.38m/s and u´=0.53m/s. In addition injection is a quiescent environment was also considered (u´=0.00m/s)

A round water jet was introduced in the volume of homogeneous and isotropic turbulence from a needle with a flat tip. The internal diameter of the needle was D=0.8mm and its length was in excess of 100mm. Therefore, the diameter to length ratio was in excess of 125 and the water jet can be considered to have a fully developed velocity profile as it exits the needle tip. The needle was vertically aligned and exhausted pointing downwards so that the liquid jet was free to develop under the influence of gravity. Four flow rates were considered which correspond to Reynolds numbers

$$\mathrm{Re} = \frac{\rho D U}{\mu} \qquad (1)$$

in the range of 264-661, with ρ being the liquid density, D the nozzle internal diameter, U the cross section average velocity of the liquid jet, which was in the range of 0.3m/s-0.8m/s, and μ the dynamic viscosity of the liquid.

The breakup of the liquid jet and the dispersion of the droplets was visualised using a PCO Sensicam CCD camera using back illumination. The magnification of the imaging lens resulted to a spatial resolution of about 34μm/pixel which is sufficient to spatially resolve the

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[*] Corresponding author: georgios.charalampous@imperial.ac.uk

liquid jet diameter within 5%. The resulting imaged region was about 35mmx45mm. In total 16 combinations of gas turbulence and liquid jet Reynolds number were considered. For each flow condition, 500 images were obtained.

Table 1: Liquid jet flow conditions

Re	
264	529
397	661

Each image was digitally processed, first to remove imaging noise and then a threshold was applied so that individual liquid fragments (continuous jet and droplets) were identified (Figure 1). In the case of the continuous jet, the breakup length was measured and in the case of droplets, the mean droplet diameter and the spatial location of its centre was detected.

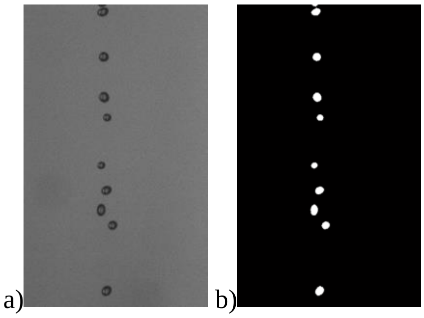

Figure 1: Image processing of the droplet images a) raw image and b) detected droplets

Results

The influence of turbulence on the breakup length of the liquid jet is presented in Figure 2 for liquid jets with Re=529 and Re=661. For the other Re numbers considered the liquid jet broke outside the imaged region for some values of u´ and there were not sufficient data to obtain a trend.

For both Re number where a full set was obtained, when considering the Re number of the liquid jet, it is clear that the jets with higher Re have longer breakup lengths for the same level of turbulence. This is expected, as these jets have higher velocities and will breakup farther under the same level of perturbation.

When keeping the jet Re constant and increasing the amount of turbulent velocity fluctuations, the breakup length is reduced. This is not surprising as the increased level of turbulence is expected to promote the inherent instability of the liquid jet. The effect of turbulence is more profound in the case of Re=661, which is the higher of the two and where the liquid jet has increased momentum. This initially appears to be counterintuitive, as it would be expected that the jet would be less susceptible to perturbation due to the higher momentum. However, the residence time in the turbulent flowfield can account for the observation. The mean time to breakup, was estimated from the ratio of the mean breakup length of the jet and the cross section average velocity of the jet at the nozzle. The liquid jet with Re=661, took about 30% more time to break up. This means that the liquid jet is exposed for longer to turbulence. Consequently, while it is able to resist breakup more due to its higher momentum, it is also more susceptible to increased levels of turbulence. On the other hand, the liquid jet with Re=529, was considerably less affected by the increase in turbulence. Here, it is likely that the inherent jet instability was the dominant mechanism for breakup with a smaller influence from the turbulent velocity fluctuations.

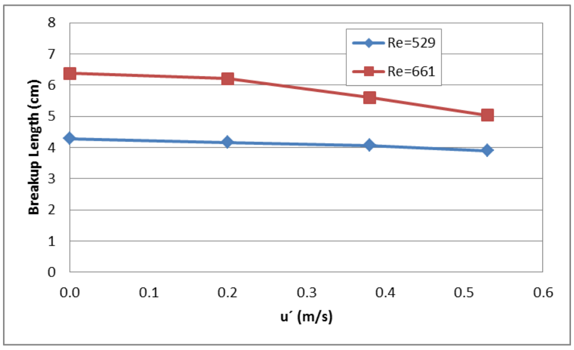

Figure 2: Breakup length for liquid jets with Re=529 and Re=661. Increasing level of turbulence reduces the length of the continuous liquid jet. The effect is more profound for the higher Reynolds number

When the fluctuations of the breakup length are considered, Figure 3, there is little difference between Re=529 and Re=661, when the liquid jet is injected in a quiescent environment. When turbulence is applied, it can be observed that the liquid jet with Re=529 exhibits a greater sensitivity to turbulence. This can be explained as a consequence of the decreased momentum which renders the variability of the liquid jet length more susceptible to the perturbations of the velocity fluctuations even though the average jet length is less affected.

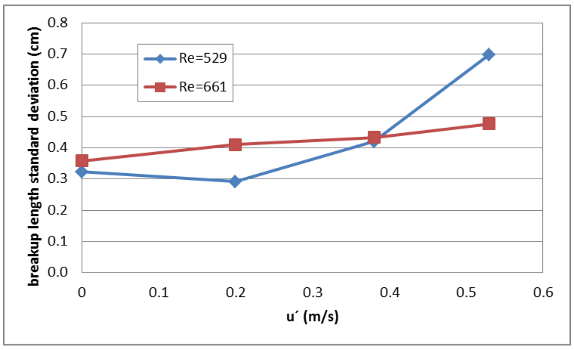

Figure 3: Fluctuation of breakup length for liquid jets with Re=529 and Re=661. Increasing level of turbulence increases the fluctuation of the length of the continuous liquid jet. The effect is more profound for the lower Reynolds number

At the location of the breakup, the liquid jet breaks up in a stream of droplets. When there is no turbulence in the gaseous environment, the droplet spacing is regular among the droplets (Figure 4a). Also, satellite droplets are formed close to the location of the liquid jet breakup, although they appear to merge with the primary droplets downstream. When there is turbulence in the gaseous environment, the spacing of the droplets becomes irregular (Figure 4b). Satellite droplets are also formed in this case and they appear to merge with the primary droplets downstream.

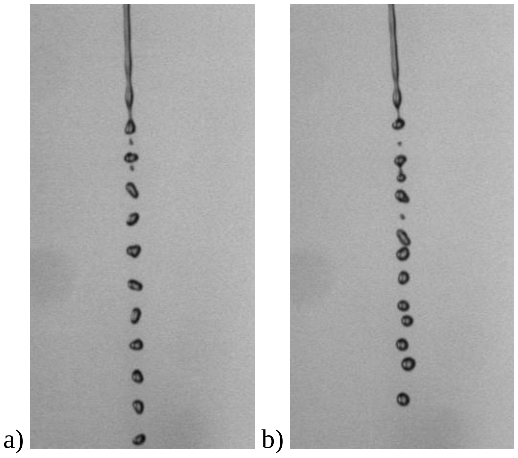

Figure 4: Example images of the jet breakup. Re=529 at a) u´=0m/s and b) u´=0.38m/s

The transverse dispersion of the droplets, estimated as the mean absolute displacement on the imaging plane of the droplets from the needle axis is presented in Figure 5. For each Re on the liquid jet, as the turbulent velocity fluctuations increase, the dispersion of the droplets at a fixed distance from the nozzle increases, while if the amount of turbulence is fixed the dispersion decreases with increasing Re. The droplet dispersion is a function of the distance from the nozzle and for all cases is increasing linearly with the distance from the nozzle. This can be explained from the homogeneous and isotropic nature of the applied turbulence. Since the gas turbulence accelerates and decelerates the droplets equally in the vertical direction, the mean vertical droplet velocity remains unchanged along the height of the image. As the droplets fall with the same mean velocity along the imaged area height and the turbulence is homogeneous and isotropic they disperse equally in all directions.

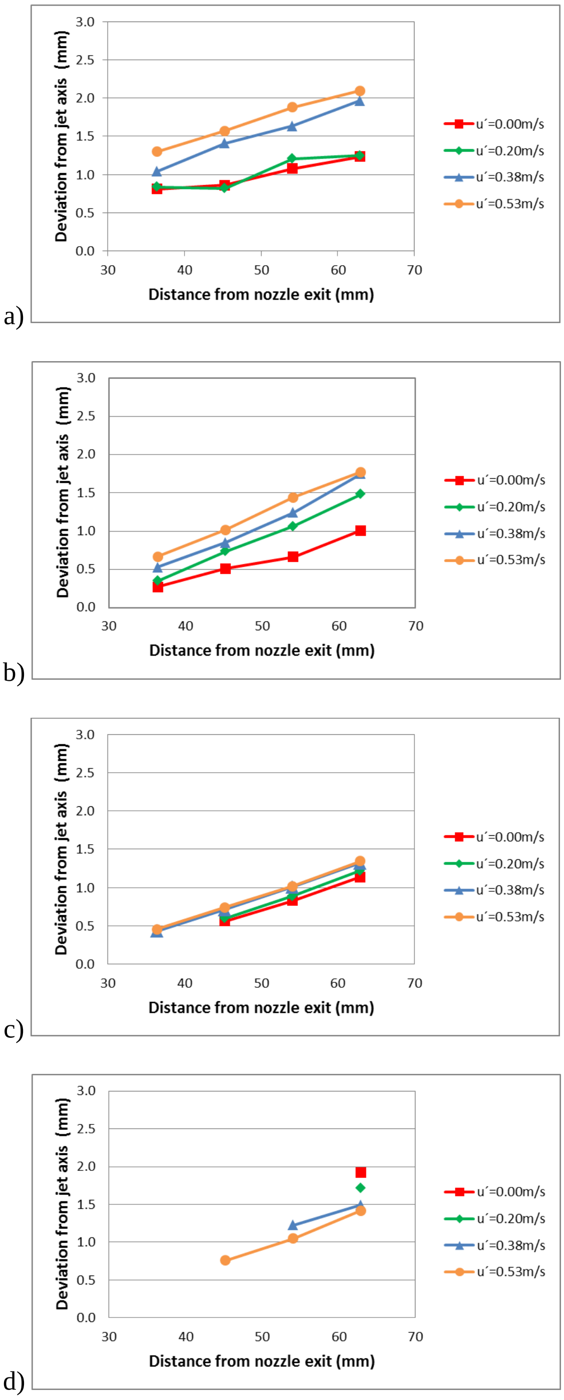

Figure 5: Mean absolute lateral dispersion of droplets from the nozzle axis, as a function of the distance from the nozzle for a) Re=265, b) Re=397, c) Re=529 and d) Re=661.

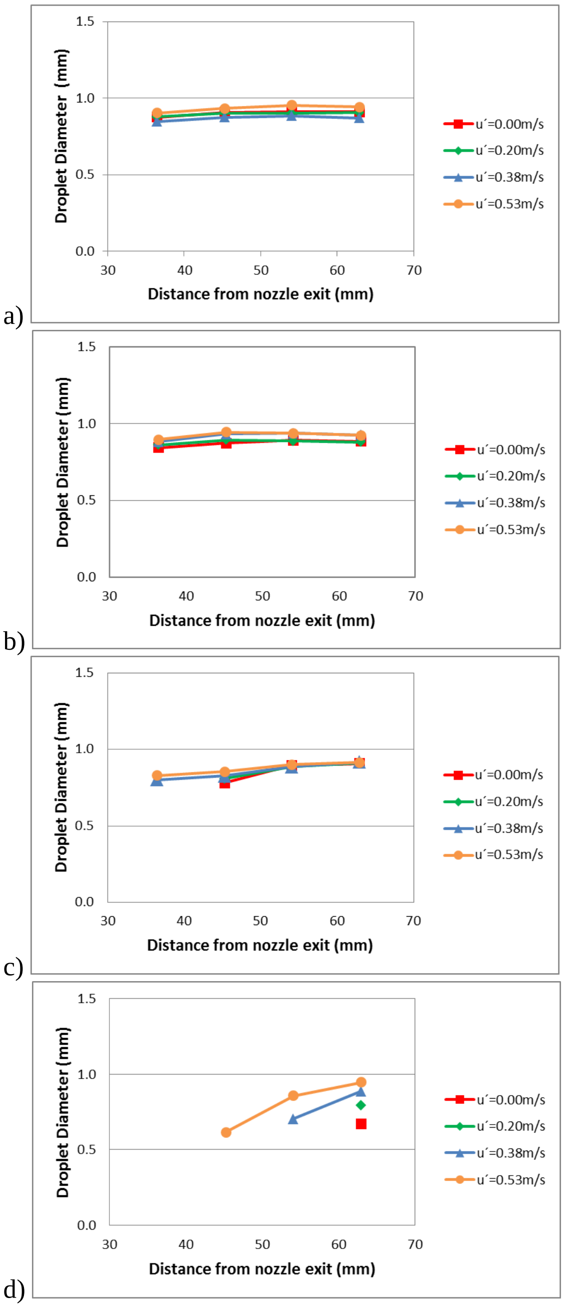

Figure 6: Mean droplet size with vertical distance from the nozzle exit for a) Re=265, b) Re=397, c) Re=529 and d) Re=661.

The evolution of the mean droplet size with the vertical distance from the nozzle exit is presented in Figure 6. There is a tendency for the droplet size to increase downstream, although in most cases the increase is marginal. The increase in the droplet size can be attributed to the merging of the small satellite droplets into the larger main droplets. For the same jet Re number the mean droplet size is slightly greater when the gas turbulence is greater. This can be explained by the increased number of satellite droplets that have been merged with the main droplets, because as the turbulence level increases the breakup of the continuous liquid jet occurs farther upstream. Therefore, at increased turbulence levels, at the same distance from the nozzle the main droplets have absorbed more satellite droplets. This is highlighted in Figure 6c and Figure 6d, which include flow conditions where the breakup of the liquid jet is captured within the imaging region. It can be observed that the growth of the droplets in that location is very fast and it accounts for the majority of collision events that are responsible for increase in the main droplet size. Farther from that location the flow has been depleted from satellite droplets and the droplet diameter stabilises at around 0.9mm for all flow conditions.

Conclusions

The breakup and dispersion of a laminar jet was examined in a volume of homogeneous and isotropic turbulence without mean flow. The purpose was to isolate effects of turbulence in the breakup process. It was found that

1. For fixed liquid jet Re, the liquid breakup length decreased of as the level of turbulence increased.
2. For fixed turbulence level, the breakup length increased with Re.
3. The fluctuations of the breakup length increased with the level of turbulence
4. Satellite droplets are formed in the regions close to the breakup point.
5. The satellite droplets coalesced with the larger droplets downstream from the nozzle exit when Re increased.
6. For lower liquid jet Re greater spatial dispersion of the liquid droplets was observed.
7. The mean droplet dispersion increases linearly with the distance from the nozzle
8. The mean droplet size increases with the level of turbulence and the distance from the nozzle.

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