Experimental investigation of multi-scale entrainment processes of a turbulent jet

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The aim of this study is to investigate entrainment mechanisms in the far-field of a turbulent jet. As described by Philip & Marusic (2012) entrainment is a multi-stage process where: (i) the induced inflow draws non-turbulent fluid towards the turbulent jet, (ii) the large-scale eddies generates a large interfacial area that engulfs non-turbulent fluid towards the Turbulent/Non-Turbulent (T/N-T) interface, and (iii) small-scale eddies at the T/N-T transfer enstrophy to the non-turbulent fluid.

Entrainment is a multi-scale process and requires a large dynamic range to fully characterise it experimentally. So far most of the research into this topic has been at relatively low Reynolds numbers. The aim of this work is to understand the entrainment process in a fully developed turbulent jet at higher Reynolds numbers where there is greater scale separation.

To achieve these aims, we implemented simultaneous, time-resolved multi-scale-PIV and PLIF measurements in the far-field of a round, turbulent jet at $Re = 25,300$. Passive dye was used to identify the T/N-T interface whilst the multi-scale PIV allows for the measurement of the velocity field in the vicinity of the interface so that the mechanisms of entrainment can be investigated.

Flow characterisation

A series of experiments were first performed to characterise the behaviour of the turbulent jet. PIV measurements in the near-field showed a top-hat exit velocity profile and the far-field measurements are in full agreement with self-similarity of the jet, - see figure 1. Figure 1 shows the decay of the jet centreline velocity and half-width growth rates are also in good agreement with classical studies on free jets.

![Self-similar axial velocity profile](image)

**Fig. 1** Self-similar axial velocity profile, normalised by local centreline velocity and local jet half-width.

**Simultaneous Multi-scale-PIV/PLIF measurements**

Multi-scale experiments were performed using a high-speed laser with multiple cameras. Filters were positioned in front of each camera to isolate the light from particles and fluorescent dye for PIV and PLIF respectively. The PIV cameras used a notch filter to only allow green light. The PLIF cameras were equipped with a band-pass filter so that only the fluorescent signal was detected. The use of a high-repetition laser allowed for the optimisation of the PIV image separation time ($dt$) for each field of view in the multi-scale set-up. An example of an instantaneous scalar and multi-scale velocity field is shown in figure 2, where the interface is indicated by a thick black line. The T/N-T interface is well detected in the image and the location of the small PIV data is well positioned to capture the velocity data around the interface.

![Instantaneous scalar concentration field](image)

**Fig. 2** An instantaneous scalar concentration field superimposed with multi-scale velocity vectors; vectors down-sampled for clarity.

Van Reeuwijk & Holzner (2014) report that the local instantaneous entrainment velocity and the global mean entrainment velocity scale by the surface areas generated by the respective interfaces. Figure 3 shows that the ratio between the instantaneous and averaged interfacial surface areas remains constant at 2 for a range of scalar thresholds. The aim of this study is to assess if the ratio of local to global entrainment velocities satisfies this area scaling. This is made possible by the time resolved measurements which captured the interface velocity that is necessary to determine the local entrainment velocity.

![Ratio of the average surface area of the instantaneous interface against the averaged interface surface area](image)

**Fig. 3** Ratio of the average surface area of the instantaneous interface against the averaged interface surface area.
