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

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Abstract A combination of particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) experiments were undertaken to study entrainment processes in the far-field of a round, turbulent jet. The experiments were performed using water as the test medium and a passive dye with a Schmidt number $Sc > 1$ to identify the turbulent/non-turbulent interface of the jet. The Reynolds number based on the nozzle exit is 25,300 and the Reynolds number based on the Taylor microscale is $Re_t \approx 360$, which is considerably higher than existing studies of turbulent/non-turbulent interfaces in jets. Independent 2D PIV and PLIF measurements confirmed that the self-similar profiles of velocity and scalar concentration collapse well in the far field. The scaling coefficients of centreline velocity decay and jet half-width also agree well with the classical scaling laws of turbulent jets. Simultaneous, time-resolved multi-scale-PIV/PLIF measurements were performed in the streamwise plane of the jet about the location $z = 50D$. A description of this set-up is given and the multi-scale velocity data is validated. We show that there is a constant ratio between the instantaneous and averaged interfacial surface areas for a range of scalar thresholds, which is analogous to distance from the turbulent jet core.

1. Introduction

The characterisation of entrainment processes has become a widely studied topic, and more specifically, it is the relevance of the turbulent/non-turbulent (T/N-T) interface to the entrainment process that has been the focus of much research. It is important to first distinguish the differences between entrainment processes and T/N-T interfaces because there is much overlap between these topics in the literature. The T/N-T interface was first introduced by Corrsin & Kistler (1955) as a convoluted interface of finite thickness that separates the enstrophy-containing turbulent fluid from the irrotational non-turbulent fluid, where a jump in velocity occurs. Comparatively, entrainment describes the entire mass transfer process that is responsible for the growth of a turbulent region, and in the case of a jet it is the spreading rate.

The velocity jump across the T/N-T that had eluded many early researchers has now been well documented for turbulent jets, Westerweel et al (2005). Similarly, researchers have also observed the predominance of small-scale length and velocity-scales in the T/N-T in both turbulent jets, Mathew & Basu (2002), Westerweel et al (2009), and van Reeuwijk & Holzner (2014), and also in zero-mean-shear flows generated by an oscillating grid, Holzner et al (2007). Thus, much of the published research so far has indicated that “the entrainment process is dominated by small-scale [eddies] at the highly sheared interface,” Westerweel et al (2009). The growing understanding of the T/N-T interface has challenged the classical views of large-scale engulfment in entrainment. However, it should be noted that while small-scale nibbling is important when describing the transfer of vorticity to the non-turbulent fluid at the interface, it alone cannot explain the full entrainment process.

More recent research has described entrainment for turbulent jets as a multi-stage process, Dimotakis (2005) and Philip & Marusic (2012). One interpretation of this process may be described as follows: (i) the induced inflow draws the non-turbulent fluid towards the turbulent jet, (ii) the large-scale eddies generate a large interfacial area to engulf irrotational fluid into the T/N-T, (iii) small-scale eddies at the T/N-T transfer momentum and vorticity to the non-turbulent fluid, and finally (iv) the effects of molecular diffusion mixes
the passive scalar (if present). This description of entrainment captures the roles of the range of scales from the large (induced inflow and engulfment) down to the inertial and small-scales (nibbling and molecular diffusion). It should also be noted that while molecular diffusion is often considered negligible for large Schmidt number flows because the vorticity of the flow dies out long before the scalar is mixed, without molecular diffusion the peak concentrations in the scalar field would never decrease.

When considering the large-scale inflow of fluid into the turbulent jet, it becomes apparent that the global mean entrainment of fluid must balance the entrainment at a local level (i.e. the mean of the instantaneous entrainments). This has recently been validated on a turbulent boundary layer flow in which the mass flux contribution to the mean turbulent boundary growth was shown to balance with the sum of the local instantaneous mass fluxes across the T/N-T, Chauhan et al (2014). van Reeuwijk & Holzner (2014) show that the global entrainment flux may be given by \( \dot{Q}_e = u_e A \), where \( \dot{Q}_e \) is the entrainment flux of ambient fluid into the turbulent region, \( u_e \) is the entrainment velocity in fixed laboratory coordinates, and \( A \) is the surface area given by the mean location of the interface. From a local perspective, the entrainment flux is given by \( \dot{Q}_e = v_n S \), where \( v_n \) is the entrainment velocity in coordinates moving with the interface, and \( S \) is the instantaneous interfacial surface area. Hence, the local entrainment velocities at the fluctuating interface, \( v_n \), must scale with the global entrainment velocity, \( u_e \), at a rate that is proportional to the surface area ratio, \( A/S \).

The focus of this study is to investigate the entrainment processes in a turbulent jet. As previously mentioned, these processes span a large range of scales which demands an equally large dynamic range from the experimental set-up. Moreover, much of the research into this topic has thus far been studied at relatively low Reynolds numbers. The main contribution of this work is the measurement of high Reynolds number and time-resolved data to study T/N-T interface dynamics. To achieve these aims, we implemented simultaneous, time-resolved multi-scale-PIV and PLIF measurements in the far-field of a round, turbulent jet. The use of a passive dye, as measured by PLIF, allows for the identification of an interface that is analogous to the T/N-T. In fact, there is good agreement in ensemble-averaged statistics between interfaces identified by passive scalars and by the enstrophy criterion, Anand et al (2009). The purpose of the time-resolved measurements is to capture the motion of the interface and therefore the instantaneous interface velocity. This is necessary to determine the local entrainment velocity. Achieving time-resolved measurements requires a laser that is capable of high repetition rates (i.e. pulsed laser). Shan et al (2004) and Crimaldi (2008) evaluate the suitability of pulsed-lasers for PLIF measurements and identify non-linearities in the fluorescence intensity; this is the result of the very short laser pulse (high excitation energy) of Nd-YAG lasers. Nd-YLF lasers, however, exhibit much longer pulse durations which reduce the risk of dye saturation. Moreover, Nd-YLF lasers allow for the high repetition rates necessary to capture the dynamics of the entrainment process. The use of multiple PIV cameras in a multi-scale arrangement allowed us to capture a large dynamic range of the flow. This technique has not been widely implemented due to the equipment and calibration requirements. Also, the use of a low-speed pulsed laser results in the same image-separation time (\( \delta t \)) for different fields of view (FOV), which limits the scale separation between the two PIV cameras. This issue is avoided with the use of a high-repetition laser that allows for the optimisation of image-separation time for each FOV. In this paper, a description of this experimental set-up is given and preliminary results are introduced to validate the experimental arrangement of the turbulent jet investigation.

2. Experimental set-up

2.1 Apparatus

The experiments described in this study were undertaken in a 1 m x 1 m x 7 m water tank comprised of an open top section, and PVC plastic walls. The centre section of the tank provides optical access via Perspex sidewalls and floor. The turbulent jet was generated by issuing water (\( v = 1 \times 10^6 \text{ m}^2\text{s}^{-1} \)) from a round nozzle (\( D = 10 \text{ mm} \)) which was centrally positioned 520\( D \) away from the end-wall of the tank. The nozzle unit contained a series of meshes, flow-straighteners, and fifth-order polynomial contraction profile to generate a top-hat velocity profile at the exit, as shown in Figure 1. Two centrifugal pumps positioned in series provided the dynamic head to the jet flow. The jet fluid was drawn from within the tank for the flow velocity characterisation experiments, and was drawn from a separate reservoir containing dyed-fluid.
(rhodamine 6G) for the PLIF measurements. The flow rate of the pump system was controlled using two gate valves and measured using an orifice plate and pressure transducers.

2.2 PIV and PLIF set-up

The PIV measurements were performed using 10 μm silver-coated hollow glass sphere particles (Dantec Dynamics A/S) as the flow tracers. The PLIF measurements were performed using rhodamine 6G (Sigma-Aldrich Co. LLC) as the passive dye, which exhibits maximum light absorptivity at 525 nm and maximum light emissivity at 555 nm. Rhodamine 6G exhibits a Schmidt number Sc ≈ 8000 and therefore the effects of molecular diffusivity of the dye are considered to be negligible. A single high-speed 527 nm Nd:YLF laser (Quantonix Darwin Duo) was used to illuminate the particles and dye, which were recorded using high speed cameras (Photron SA1.1) that were synchronised with the laser pulses. The laser beam passed through a series of beam-collimating spherical optics before passing through plano-concave cylindrical lenses to form a thin light sheet. The thickness of the light sheet was selected to be 1.5 mm thick and this was confirmed by imaging the laser sheet on a white calibration plate. The plate was placed with a 10° incidence to the incoming light sheet; this angle was measured by traversing the plate a known distance and measuring the vertical displacement of the light sheet. The laser intensity profiles were then measured at 3 height positions across the camera field of view (FOV). Three regions across the laser sheet for each height were sampled to generate the mean intensity profile. A Gaussian fit was finally applied to the normalised intensity profiles to estimate the $e^2$ thickness of the laser sheet, as shown in Figure 2.

![Figure 1: Cross-section of jet nozzle nozzle, and nozzle exit velocity profile normalised by nozzle diameter D and nozzle exit velocity $U_e$. Shaded region in velocity profile indicates size of PIV interrogation window.](image)

![Figure 2: Laser sheet thickness measured across the (a) top, (b) middle, and (c) bottom regions within the camera field](image)

A constant time-delay was used between starting the jet and recording the velocity data. The flow was statistically stationary during the recording period of all experiments. This was validated by a comparison of mean velocity fields across the main recording period and a period of time beyond the end of the main recording period. The nozzle-exit velocity profile of the jet is a top-hat profile and is shown in Figure 1.
The measured exit velocity of the jet is 2.53 m/s, in agreement with the volumetric flow-rate measurements, and this produces a turbulent jet with \( \text{Re} = 25,300 \).

A series of 2D experiments were first undertaken to characterise the turbulent jet. The laser (40 mJ/pulse) and cameras were synchronised using a digital timer and a BNC connector block (National Instruments Corporation). In each case, 12-bit uncompressed TIFF images (1024x1024 pixels) were recorded by the high-speed camera and imported into Davis 8.1.6 (LaVision GmbH) for processing. Multi-pass processing with decreasing window size was implemented: the initial particle image correlations were performed with 64 x 64 px\(^2\) interrogation windows (2x passes), then 32 x 32 px\(^2\) windows (2x passes), and finally with 24 x 24 px\(^2\) interrogation windows (2x passes) and 75% window overlap. Every other vector was then removed to give a final vector overlap of 50%.

3. Turbulent jet characterisation

3.1 Far-field jet scaling

The purpose of this experiment was to evaluate the far-field self-similar profiles, the centreline velocity decay, and half-width growth rates to verify that the jet follows classical scaling laws. The far-field behaviour of the jet was first characterised using a 105mm Sigma macro lens (f/4) to achieve a 310 x 310 mm\(^2\) FOV between 35\(D\) and 65\(D\) downstream of the nozzle exit. This downstream range is within the self-similar region of turbulent jet flows, Lipari & Stansby (2011). The in-plane spatial resolution is given by the length of the final interrogation window size and is 7.3 mm for this experiment. A total of 2000 vector fields were captured over 4 separate runs and the vector fields were sufficiently spaced apart in time to ensure statistical independence.

Figure 3: Self-similar axial velocity \( U (a) \) and radial velocity \( V (b) \) profiles of the jet, normalised by the local centreline velocity \( U_c \) and the local jet half-width \( b_u \); the radial location from the jet centreline is given by \( r \).

As shown in Figure 3, excellent collapse of the normalised axial velocity at various \( z/D \) was found. There is greater spread of data for the normalised radial velocity profiles \( V/U_c \) beyond \( r/b_u = \pm 1 \) because the magnitude of radial motion is very small far from the jet centreline. These small fluctuations cannot be captured with the resolution for this field of view. Nonetheless, the profiles agree well with comparable studies of turbulent jets. The plots shown in Figure 4 illustrates the centreline inverse velocity decay and jet half-width growth. The scaling laws for a round, turbulent jet are given by:

\[
\frac{U_e}{U_c(z)} = \frac{z - z_0}{DB}
\]

for the jet centreline velocity decay, where \( z_0 \) is the virtual origin and \( B \) is the velocity scaling coefficient, and
\[ b_L(z) = S(z - z_0) \]

for the jet spreading rate, where \( S \) is the spreading rate scaling coefficient. The inverse velocity decay profile is linear with a scaling coefficient of \( B = 5.84 \) and an estimated virtual origin of \( z_0/D = 2.63 \). This agrees well with the data of Hussein \textit{et al.} (1994) who report a velocity decay scaling coefficient of \( B = 5.8 \) and a virtual origin of \( z_0/D = 4 \). Similarly, the jet half-width growth rate is measured to be \( S = 0.092 \) which is in agreement with published LDA results of Hussein \textit{et al.} (1994) where \( S = 0.094 \). The marginal differences in velocity decay and the narrower jet-spread measured in these experiments compared to the literature may be attributed to the effects of confinement from the side-walls of the tank. This is discussed further below with reference to the momentum flux of the jet.

![Figure 4: (a) Centreline velocity decay, and (b) jet half-width growth. The jet half-width is defined as the distance across the jet at which the mean velocity is half the local mean centreline velocity. Presented data is down-sampled for clarity.](image)

The effects of side- and end-wall confinement on the momentum flux of turbulent jets has been well documented, Schneider (1985), Kotsovinos & Angelidis (1991), and Hussein \textit{et al} (1994). A confined jet cannot entrain fluid through the surrounding walls which results in fluid being drawn upstream in the ambient flow region. The reverse flow draws momentum away from the jet which results in a reduction in the momentum flux, as illustrated in the flux profile in Figure 5. A small momentum loss is inevitable in jets that are not infinitely bounded, as discussed by Hussein \textit{et al} (1994), despite the large water tank using in this study. We estimate the loss to be approximately 10-15% as shown in Figure 5. Note that this does not change the jet behaviour as it still follows the classical scaling for a free jet. The primary aim of this investigation is to consider the instantaneous entrainment processes at the turbulent/non-turbulent interface, and the effects of the mean backflow (~ -0.02\( U_c \)) are considered small in an instantaneous field.
Additional PIV measurements were also performed over a small FOV (38 x 38 mm²) in the far field to capture small-scale statistics on the jet. A 200 mm Nikkor macro lens (f/5.6) was used to capture the flow between 50D and 54D downstream of the nozzle exit. The in-plane spatial resolution is 0.9 mm for this experiment, which equates to 7.4η, where η is the Kolmogorov lengthscale. Further statistical quantities for the turbulent jet are presented in Table 1.

Table 1: Turbulent jet flow statistics at measurement location (50D)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle exit diameter (D)</td>
<td>10 mm</td>
</tr>
<tr>
<td>Measurement location (z)</td>
<td>50D</td>
</tr>
<tr>
<td>Jet exit velocity (U_e)</td>
<td>2.53 m/s</td>
</tr>
<tr>
<td>Reynolds number at exit (Re)</td>
<td>25,300</td>
</tr>
<tr>
<td>Centreline velocity at 50D</td>
<td>0.31 m/s</td>
</tr>
<tr>
<td>Dissipation (ε)</td>
<td>4.6 x 10⁻³ m²s⁻³</td>
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<tr>
<td>Kolmogorov length-scale (η)</td>
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<tr>
<td>Kolmogorov time-scale (τ)</td>
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</tr>
<tr>
<td>Kolmogorov velocity-scale (u_η)</td>
<td>8.25 mm/s</td>
</tr>
<tr>
<td>RMS axial velocity along centreline (u_rms)</td>
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<tr>
<td>RMS radial velocity along centreline (v_rms)</td>
<td>0.064 m/s</td>
</tr>
<tr>
<td>Taylor micro-scale (λ)</td>
<td>4.55 mm</td>
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<tr>
<td>Turbulent Reynolds number (Re_τ)</td>
<td>360</td>
</tr>
</tbody>
</table>

3.2 Scalar concentration measurements

Independent PLIF measurements were performed to capture the scalar field characteristics of the turbulent jet. The PIV arrangement was the same as that described for the large field of view jet velocity characterisation experiment (FOV = 310 x 310 mm²). An example of a PLIF image of the instantaneous scalar concentration field is shown in Figure 6. The turbulent jet at Re = 25,300 well exceeds the mixing transition identified by Dimotakis (2000), and this is also revealed by the absence of unmixed fluid towards the core of the jet.
Fluorescent dyes, such as rhodamine 6G, allow for the identification of the dye within the thin volume defined by a laser light-sheet. The use of PLIF as an effective measurement tool of scalar concentration depends on a linear relationship between concentration and intensity of the fluorescent signal. This may be represented by the relation: $F \propto IC$, where the $F$ is the dye fluorescence, $I$ is the local laser excitation energy, and $C$ is the local dye concentration. To calibrate the measurements a dye cell of known concentration was illuminated at constant laser power. Shown in Figure 7 is the image brightness (fluorescence) as a function of dye concentration; note the linearity of the profile. The image of uniform scalar concentration was also used to normalise the instantaneous PLIF images to account for the Gaussian laser-intensity profile of the light sheet. A black image correction was performed on the camera prior to image acquisition, as suggested by Crimaldi (2008).

The streamwise development of the scalar field of the jet is shown in Figure 8 in the form of centreline scalar concentration decay and jet half-width growth. The inverse concentration decay profile is linear which suggests that the centreline concentration decays as $1/z$, as expected. This profile has been normalised by the maximum centreline concentration in the averaged image and not by the source concentration. Therefore, the virtual origin in the image should not be considered. The scalar jet half-width growth rate is measured to be $S = 0.118$ and an estimated virtual origin of $z_0/D = 2.98$, which is in agreement with the PLIF results of Westerweel et al (2009) where $S = 0.1248$. 

Figure 6: Instantaneous image of the scalar concentration field in the far field of the jet. The colour-bar indicates the intensity counts of the image.

Figure 7: Camera pixel brightness (counts) as a function of concentration of rhodamine 6G; a linear fit to the points is shown by the dashed line. The laser power remained constant for the range of concentrations measured.
Figure 8: (a) Centreline concentration decay, and (b) jet concentration half-width growth. The jet half-width is defined as the distance across the jet at which the concentration is half the local mean centreline concentration.

4. Simultaneous multi-scale-PIV/PLIF experiment

4.1 Experimental set-up

Simultaneous multi-scale-PIV and PLIF measurements at the interface of a turbulent jet provide insight into the interaction between the large- and small-scale eddies and their roles in entrainment. Here the dye provides a robust marker of the T/N-T interface and the PIV provides the local velocity along the interface. The multi-scale experiments were performed using the aforementioned high-speed cameras and high repetition-rate laser to capture the dynamical features of the turbulent flow. Filters were positioned in between each camera and lens 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 to pass, thereby blocking any orange light from the fluorescing rhodamine 6G. The PLIF cameras were equipped with a band-pass filter to block out the green light reflected off the seeding particles in the flow, but allowed the orange fluorescent light to pass through to the camera sensor. The arrangement of the camera FOV’s is presented in Figure 9. Only the bottom half of the jet is captured in these measurements and the small FOV (SFOV) camera was aligned to the mean interface location. The timing sequence of the cameras and laser, shown in Figure 10, was chosen to optimise the PIV $\delta t$ for each of the FOV settings. Each set of velocity and scalar measurements is spaced 1 ms apart and therefore these measurements capture the smallest temporal evolutions of the flow as determined by the Kolmogorov timescale, $\tau = 14.7$ ms. Each run of this experiment captured 5455 vector fields, and 6 runs of the experiment were made. However, the vector and scalar fields were temporally downsampled for analysis.

Figure 9: Location of fields of view for the multi-scale-PIV/PLIF experiment
The multi-scale PIV cameras imaged the same calibration plate and this allowed for greater certainty in the overlap between the two fields of view. This is confirmed by a comparison of averaged and instantaneous velocity plots shown in Figure 12. The self-similar axial velocity profiles collapse well in the overlapped region between the large FOV (LFOV) and SFOV. Similarly, an example of the instantaneous velocity field illustrates the good overlap between the two fields of view. The agreement between the multi-scale measurements indicates that the different cameras are capturing the same flow features, albeit at different spatial resolutions. The advantages of the multi-scale set-up are highlighted in Figure 11 which shows an example of the combined velocity and scalar fields. The LFOV identifies the large-scale flow features of the jet whilst the SFOV identifies the smaller flow features around the interface. The bottom plot of Figure 11 illustrates the local normal vectors to the interface that, in combination with the local velocity field, can give the local entrainment velocities.
Figure 11: Top: Example of instantaneous scalar concentration field with interface shown by white line and superimposed LFOV and SFOV velocity vectors. Middle: Same scalar field as above but zoomed into the SFOV velocity field. All velocity vectors are down-sampled for clarity. Bottom: Same scalar field as above but with interface normals plotted.
4.2 Data processing and analysis

Deriving the T/N-T interface from the scalar concentration fields requires a series of post-processing steps, as depicted in Figure 13. The first steps are to compensate for the shadows in the raw PLIF image that were cast by small scratches in the tank, and to normalise the intensity profile to account for the Gaussian light intensity distribution from the laser sheet. Following this, the interface threshold is determined using the process described in Prasad & Sreenivasan (1989) and Westerweel et al (2002) by considering the inflection point of a plot of averaged-intensity against threshold. The instantaneous scalar image is binarised based on the threshold value given by the inflection point. The binarised image shows results in pockets of unmixed fluid within the turbulent region and this is attributed to engulfed fluid and also the three-dimensional structure of the scalar field. These pockets of unmixed fluid are removed from the analysis because the primary aim of this study is to examine the outer interface. Similarly, the detached fluid elements that exist in the non-turbulent region are removed because they do not retain their vorticity, Westerweel et al (2009). Finally, the outermost interface points are selected to make the interface monotonic in the streamwise direction, $z$. 

Figure 12: Overlap of the multi-scale PIV data. The left image shows the collapse of the self-similar axial velocity profiles between $50 < z/D < 54$; solid lines represent the LFOV and the x’s represent the SFOV. The right image shows an instantaneous velocity magnitude distribution of axial velocity; the SFOV is located with the black box.

Figure 13: Process to identify scalar interface (left-to-right, top-to-bottom): 1- Raw PLIF image. 2- PLIF image normalised for laser sheet intensity distribution and shadows in image. 3- Image binarised based on threshold. 4- Holes within turbulent jet region are removed. 5- Detached fluid elements are removed. 6- Outermost points along binary
image are selected as interface (shown as white line superimposed on scalar concentration field).

As discussed in §1, the averaged instantaneous and mean interfacial surface areas and velocities must scale equally to ensure a constant entrainment flux into the jet. To evaluate this scaling, the instantaneous and mean scalar interfaces were revolved 360° to estimate the three-dimensional surface areas within the PLIF FOV, as given by the equation:

$$S = \int_{a}^{b} 2\pi r(z) \sqrt{1 + \left(\frac{dr}{dz}\right)^2} \, dz$$

where $r$ is the local interface radial location, and $a$ and $b$ are the FOV bounds. The ratio between the instantaneous and mean interfacial surface areas is plotted in Figure 14. This ratio remains relatively constant ($S/A \approx 2$) for the range of thresholds considered; the range of thresholds may be interpreted as proxy for distance from the jet core. Although, as shown by van Reeuwijk & Holzner (2014), there is a non-linear relationship between threshold (enstrophy, in their case) and distance from the jet core. The constant surface area ratio implies a constant ratio between $u_r$ and $v_r$ and is independent of distance from the jet core. The confirmation of a constant $u_r/v_r$ ratio for a turbulent jet forms one of the aims of this investigation.

![Figure 14: Ratio of the average surface area of the instantaneous interface against the averaged interface surface area](image)

5. Conclusions

The aim of this study is to investigate the entrainment processes in a turbulent jet. This will be achieved by analysing time-resolve, simultaneous multi-scale-PIV/PLIF data that were measured in the far-field of a turbulent jet. The far-field characteristics of the jet were validated with the examination of the self-similar velocity profiles, the centreline velocity decay, and jet half-width growth rates, which are all in agreement with the classical scaling laws for jets. The simultaneous multi-scale-PIV/PLIF technique successfully captures the velocity and scalar fields of the turbulent jet. A constant surface area scaling between the instantaneous and mean interfaces indicates a constant scaling between the global and local entrainment velocities. This is made possible by time-resolved measurements which captured the interface velocity which is necessary to determine the local entrainment velocity. This will be investigated in future analysis of this turbulent jet flow.

6. References


