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Move with the flow to track the evolving turbulent/non-turbulent interface

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This study investigates the turbulent/non-turbulent interface (TNTI) in self-similar turbulent axisymmetric jet flows, focusing on a novel approach named 'move with the flow' where the image acquisition is space-based rather than time-based. Experiments were conducted at three different Reynolds numbers (9×10^3, 12×10^3, and 31×10^3), utilising particle image velocimetry (PIV) and laser-induced fluorescence (LIF) techniques. The core of this research was developing a traverse system specifically designed to follow the evolving flow structures at the TNTI synchronously. We succeeded in tracking large-scale events in TNTI from creation to dissolution.

1. Introduction

The turbulent/non-turbulent interface (TNTI) is a layer that separates rotational and irrotational regions in fluid flows, characterised by a sharp change in turbulence properties (Westerweel *et al.*, 2005). The TNTI plays a significant role in the entrainment process, a mechanism where non-turbulent fluid is incorporated into the turbulent flow region, thereby influencing the growth and spread of turbulence. At the TNTI, two key phenomena occur: large-scale engulfment and small-scale nibbling structures (Da Silva *et al.*, 2014).

Recent advancements have been made in the experimental study of TNTI. Techniques like simultaneous particle image velocimetry (PIV) and laser-induced fluorescence (LIF) allow for detailed observation of both velocity vectors and scalar concentration fields in fluid flows. These methods have enabled researchers to obtain conditionally averaged statistics at the TNTI (Bisset *et al.*, 2002). However, there are notable limitations in current approaches. High Reynolds number flows pose a challenge for achieving high spatial resolution, restricting the detail and accuracy of observations. Furthermore, most experiments are stationary, which limits the ability to fully capture the large-scale engulfment processes (Da Silva *et al.*, 2014; Mistry *et al.*, 2019; Kankanwadi & Buxton, 2023). The scale of these processes often extends beyond the typical field-of-view, hindering comprehensive analysis. There is a lack of understanding of the Lagrangian evolution of structures within these flows, an aspect crucial for a complete picture of TNTI dynamics.

To address these gaps, our study sets two primary objectives. First, we aim to follow the motion of structures within the TNTI, focusing on their dynamic behaviour and interactions. Second, we seek to enhance spatial resolution in high Reynolds number experiments, extending observations up to $40D$ to $100D$ downstream from the jet nozzle, where D is the jet diameter.

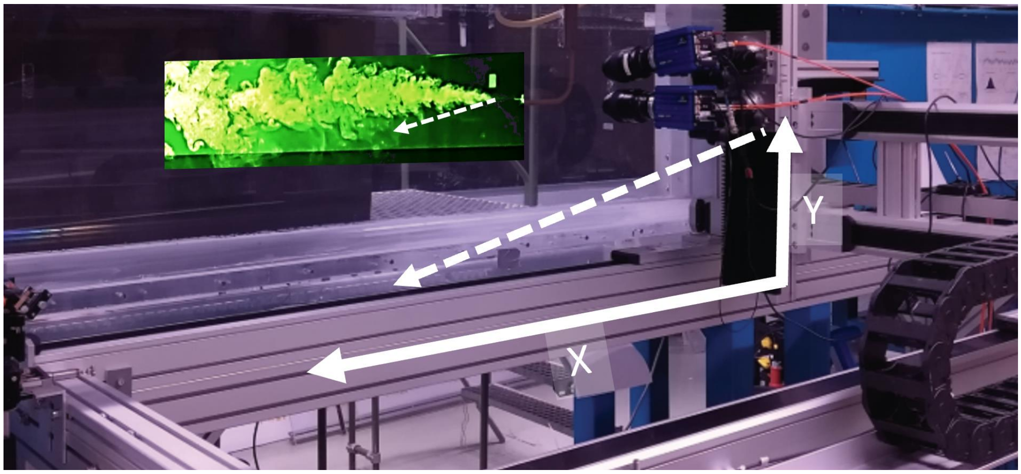

Figure 1. Move with the flow experiment setup. A traversing system moves with an angle to follow the turbulent/non-turbulent interface (TNTI).

2. Experiment Setup

The experiment is set up to quantify the TNTI in a self-similar turbulent axisymmetric jet, using a combination of PIV and LIF techniques for three Reynolds numbers of 9×10^3, 12×10^3, and 31×10^3. Employing two high-resolution sCMOS cameras operating at 15Hz, we achieve a field-of-view of 120×100 mm^2 with an image magnification of 20 px/mm. The first camera exclusively records the light emitted from Rhodamine-B dye using a low-pass filter, while the other camera records the light scattered from spherical hollow glass sphere particles, allowing for simultaneous PIV and LIF measurements (see figure 1) at an f-stop of 5.6. This setup reaches a PIV spatial resolution of 10η and a LIF spatial resolution of 0.5η, where η is the local Kolmogorov scale.

2.1. Move with the Flow

Our experimental setup features a traverse system designed to move synchronously with the TNTI. This system is driven by three stepper motors (MDrive 23 Hybrid, Schneider Electric, USA), with a 2-meter span along the x-axis parallel to the jet and a 1-meter span in the vertical y-axis. Two cameras are mounted on the system; the PIV camera aligns with the y-axis, and the LIF camera, positioned 10 cm above the PIV camera, is tilted downwards by approximately 3 degrees to match with the PIV field-of-view. The motors are programmed to trigger the laser and cameras at predetermined positions, moving at constant velocities between 1.5 and 5.2 cm/s, and at an 11-degree angle with respect to the jet axis. Since the velocity in the jet drops considerably with increasing distance from the jet nozzle, this approach enables us to use a variable laser exposure time; this is more favourable than the commonly used fixed laser emission frequency and laser exposure time delay.

As the camera system moves with the flow, it is necessary to convert all snapshots to a global coordinate system. We determine the relative motion of the traverse system and transform each snapshot into a global coordinate system. Assuming that the camera starts at the zero origin of the global coordinate system and moves at a constant velocity at an angle of 11 degrees with respect to the x-axis, we define a transformation function that maps the local x and y coordinates to the

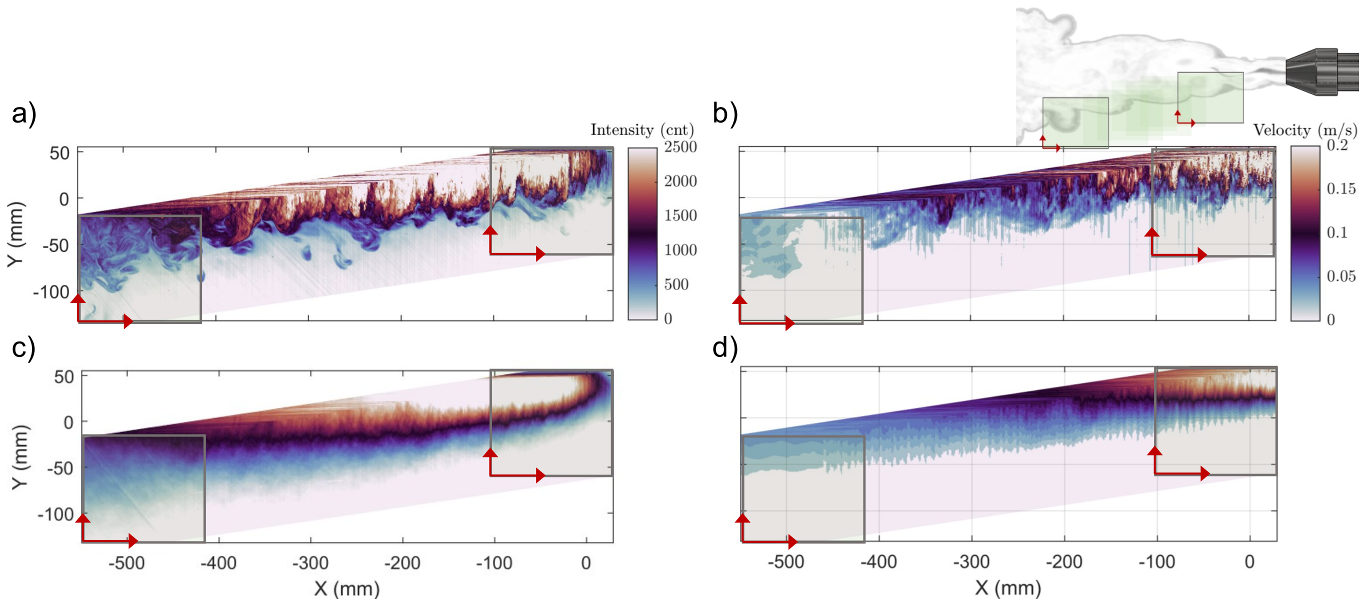

Figure 2. Results for the velocity and concentration fields in global coordinates. Superimposed instantaneous LIF concentration (a) and velocity (b) fields. Time-averaged of the concentration (c) and velocity (d) fields.

global X and Y coordinates (see figure 2).

2.2. Detection of the interface

In an ideal scenario, the interface between the turbulent (rotational) and non-turbulent (irrotational) flow regions would be determined directly using vorticity (Bisset *et al.*, 2002). However, in our experimental studies, we utilised the fluorescent dye as the passive scalar (Prasad & Sreenivasan, 1989; Westerweel *et al.*, 2005), characterised by low diffusivity, corresponding to a Schmidt number (Sc) of $2{\times}10^3$.

Our initial attempts to identify the interface using the threshold-based method proposed by Prasad & Sreenivasan (1989) were unsuccessful. This method proved inadequate as it failed to consistently identify the interface, especially given the changing interface characteristics downstream of the jet, which required continuous threshold adjustments. We adopted the K-means clustering approach (Pedregosa *et al.*, 2011) for more reliable interface detection, as shown in figure 3. The clustering approach showed better performance at lower Reynolds numbers; however, it failed at higher Reynolds numbers. Eventually, we trained an Artificial Intelligence (AI)-based segmentation model called Flow Segmentation, as explained in Khojasteh *et al.* (2024) and available in the (github.com/AliRKhojasteh/Flow_segmentation) repository. The Flow Segmentation model demonstrated reliable interface detection across various Reynolds numbers and throughout the entire flow.

3. Conclusions and Outlook

This research marks an advancement in the study of the TNTI. The 'move with the flow' setup has proven effective in providing quasi-Lagrangian information about the evolution of flow structures

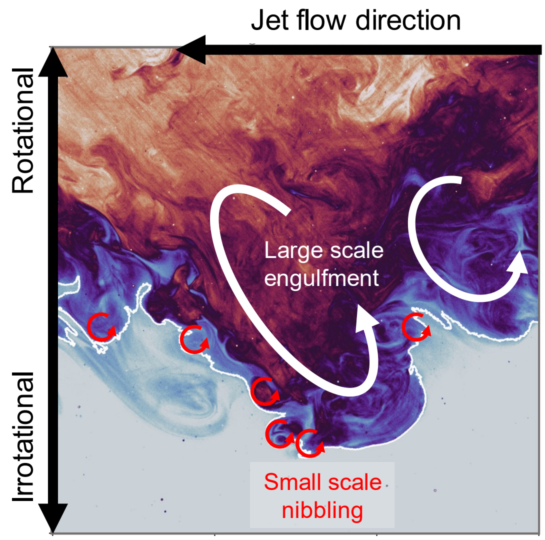

Figure 3. One snapshot of the LIF concentration field. The white line shows the interface between rotational and irrotational flow obtained from the clustering method.

at the turbulent/non-turbulent interface. In order to accommodate the variation of the jet velocity with downstream distance, we use an exposure sequence based on position, rather than a fixed laser-exposure timing and exposure time delay. We find the limitations of recent threshold-based interface detection methods when applied to non-stationary scenarios like those in our study. These methods often require constant adjustment of thresholds to maintain reliability and robustness, making them unsuitable for situations where the interface properties change continuously. To overcome this challenge, we implement an AI-based flow segmentation approach, which provides a more consistent and reliable identification of the TNTI.

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