

Experimental Analysis of Submerged and Plunging Turbulent Jets with Air Entrainment

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Keywords: PIV, Jets, Entrainment.

ABSTRACT

This paper investigates the flow dynamics of turbulent water jets as they interact with a water free surface. Building on recent experimental work on submerged particle-laden jets, this research expands the analysis to single-phase and bubbly plunging jets. A high-resolution experimental investigation is carried out through Particle Image Velocimetry (PIV) measurements. The central objective is to produce a comprehensive, high-fidelity dataset that elucidates the coupled effects of the Reynolds and Froude numbers on single-phase and two-phase flow regimes ensuing from jet-surface interaction.

1. Introduction

The interaction between liquid jets and free surfaces is a fundamental phenomenon encountered in numerous natural and industrial contexts, including breaking ocean waves, waterfalls, wastewater treatment, chemical reactors, and nuclear reactor safety systems (Biń, 1993; Chanson et al., 2004; Hammad, 2010; Kendil et al., 2012; Hassan et al., 2019; Kandukuri et al., 2025). While submerged jets discharge directly into a liquid medium, plunging jets travel through a gaseous phase—typically air—before impacting the receiving pool (Kendil et al., 2012; Hassan et al., 2019). This impact can result in the entrainment of air, which significantly modifies the downstream flow through air-water mixing and bubble-turbulence interplay (Bertola et al., 2018). Understanding the dynamics of these jets is critical for optimizing mass transfer, heat exchange, and momentum diffusion in engineering applications (Biń, 1993; Miwa et al., 2018; Hassan et al., 2019).

Early experimental investigations often relied on global measurements or intrusive techniques like Pitot tubes and hot-film probes, which provided limited insight into the global flow field evolution (Bonetto & Lahey, 1993). Recent advancements have shifted the focus toward high-resolution, non-intrusive imaging techniques such as Particle Image Velocimetry (PIV), Phase Doppler Anemometry (PDA), and ultrafast X-ray computed tomography (Bonetto & Lahey, 1993; Hammad, 2010;

Qu et al., 2013; Melzer, 2018; Kim et al., 2022). These methods have enabled more detailed quantification of the two-phase velocity fields and the identification of distinct entrainment regimes, ranging from incipient to continuous entrainment (Qu et al., 2013; Melzer, 2018). Furthermore, there is a growing need for detailed experimental databases to validate and refine computational fluid dynamics (CFD) codes, particularly regarding closure laws for interfacial forces and turbulence modeling in mixed-phase flows (Kendil et al., 2012; Melzer, 2018; Yin et al., 2018; Li et al., 2024).

Previous studies have clarified the main differences between submerged and plunging jets. Hassan et al. (2019) focused on a fixed plunging height, showing that the interaction with the free surface promotes the early development of vortical structures and accelerates the erosion of the potential core. Similarly, Qu et al. (2013) compared submerged and impinging configurations in the no-entrainment regime, showing that the plunging jet exhibits stronger fluctuations and a shorter potential core. Limited attention has been directed to studying with PIV techniques a continuous set of configurations, from the submerged jet to increasingly larger plunging heights.

The primary objective of this study is to perform a comprehensive experimental analysis of both submerged and plunging turbulent jets to characterize the flow field below the surface. We utilize PIV techniques to quantify the liquid phase dynamics, focusing on the transition from single-phase to multiphase flow. A test matrix is established by varying three key parameters:

- Jet Reynolds number: from ≈ 5000 to $\approx 20,000$
- Jet height Ratio: from $h/D_N = 1$ to $h/D_N = 5$
- Single-phase or multiphase phase jet depending on the presence of entrained bubbles

2. Experimental methodology

The experiments were performed in a water-jet facility designed to investigate the near-field dynamics of submerged and plunging round jets. The jet was generated by a vertical circular pipe with internal diameter $D_N = 21.4$ mm. In the submerged configuration, the pipe outlet was located below the free surface, with an immersion depth equal to D_N . In the plunging configuration, the pipe outlet was placed above the receiving pool, so that the jet impacted the air–water interface after a prescribed free-fall distance h , defined as the vertical distance between the pipe outlet and the undisturbed free surface. The total pipe length-to-diameter ratio was $L/D_N \simeq 125$, which is sufficiently large for the flow at the pipe outlet to be considered fully developed at the nozzle exit. The jet discharged into a large glass-walled rectangular tank of dimensions $66D_N \times 45D_N \times 50D_N$, providing optical access from all directions and reducing wall-confinement effects. The hydraulic circuit consisted of a pump feeding an elevated header tank equipped with an overflow system, which damped pump-induced flow-rate fluctuations and ensured a constant jet exit velocity. A schematic of the experimental apparatus, including the hydraulic loop, the receiving tank, the

optical arrangement, and the reference coordinate system, is shown in Fig. 1.

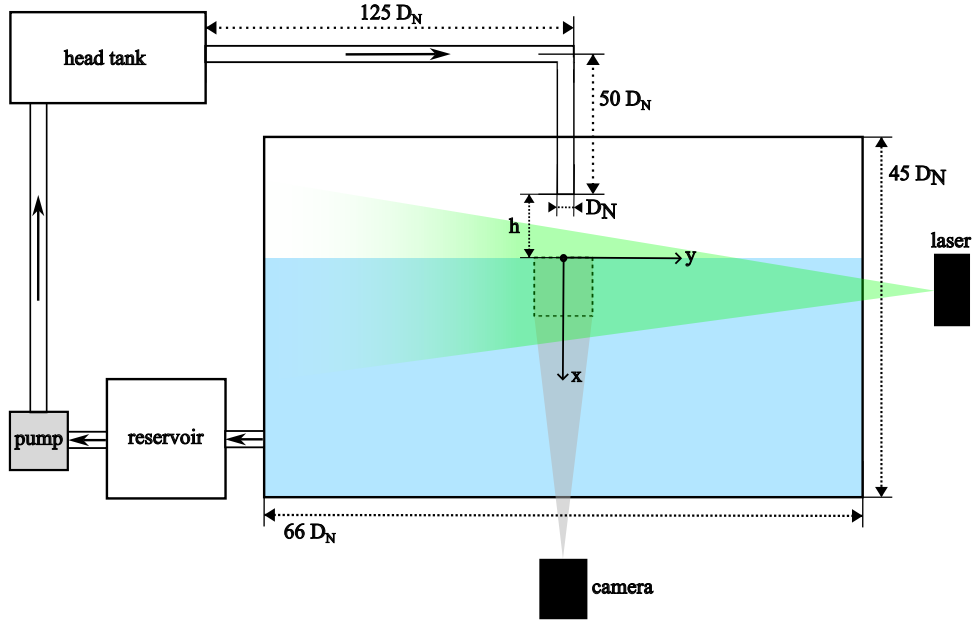


Figure 1. Schematic of the experimental setup.

The matrix of the operating conditions of the present study is reported in Table 1. The operating conditions were defined in terms of the mass flow rate $\dot{m}$, which was measured experimentally. For this purpose, the hydraulic circuit was temporarily closed by shutting the valve connecting the receiving pool to the reservoir; the mass flow rate was then obtained from the time variation of the water level in the tank. The nozzle bulk velocity was computed as

$$U_b = \frac{\dot{m}}{\rho A_N}, \quad (1)$$

and the nozzle Reynolds number as

$$Re_N = \frac{U_b D_N}{\nu}, \quad (2)$$

where $A_N = \pi D_N^2 / 4$ is the pipe cross-sectional area, while ρ and ν are the density and kinematic viscosity of water at 15°C , respectively. For the plunging configurations, the falling height h was defined as the vertical distance between the pipe outlet and the undisturbed free surface. The corresponding height-based Froude number was computed as

$$Fr = \frac{U_b}{\sqrt{gh}}, \quad (3)$$

where g is the gravitational acceleration. The jet impact velocity was estimated, as a first approximation, by assuming free fall of the liquid column between the pipe outlet and the free surface:

$$U_j = \sqrt{U_b^2 + 2gh}. \quad (4)$$

Table 1. Operating conditions considered in the present study.

Case ID	Flow condition	h/D_N	$\dot{m}$ [kg s ⁻¹]	U_b [m s ⁻¹]	Re_N [-]	U_j [m s ⁻¹]	Fr [-]
<i>S-Re21100</i>	Submerged	—	0.405	1.13	21100	—	—
<i>1D-Re6700</i>	Bubble-free plunging	1	0.129	0.36	6700	0.74	0.78
<i>1D-Re10700</i>	Bubble-free plunging	1	0.206	0.57	10700	0.86	1.25
<i>2D-Re5800</i>	Bubble-free plunging	2	0.112	0.31	5800	0.97	0.48
<i>2D-Re12500</i>	Bubble-free plunging	2	0.239	0.66	12500	1.13	1.03
<i>2D-Re16600</i>	Bubble-free plunging	2	0.317	0.88	16600	1.27	1.36
<i>2D-Re18400</i>	Bubbly plunging	2	0.352	0.98	18400	1.34	1.51
<i>3D-Re12500</i>	Bubble-free plunging	3	0.239	0.66	12500	1.30	0.84
<i>4D-Re12500</i>	Bubble-free plunging	4	0.239	0.66	12500	1.46	0.72
<i>5D-Re6700</i>	Bubble-free plunging	5	0.129	0.36	6700	1.49	0.35
<i>5D-Re10700</i>	Bubble-free plunging	5	0.206	0.57	10700	1.56	0.56

$nD-ReR$ denotes a plunging case with falling height $h = nD_N$ and Reynolds number $Re_N \simeq R$.

Planar velocity measurements were performed using a two-dimensional Particle Image Velocimetry (PIV) system. A Nd:YAG laser was used to illuminate the vertical symmetry plane of the jet, while a high-resolution camera was placed orthogonally to the laser sheet. The field of view of each acquisition was 1024×1024 pixels, corresponding to approximately $8.5D_N \times 8.5D_N$. The water was seeded with neutrally buoyant hollow glass spheres with a characteristic diameter of approximately $10 \mu\text{m}$, used as flow tracers. For each acquisition region, $N = 10000$ image pairs at 1000 fps were collected to ensure statistical convergence of the mean and fluctuating velocity fields. The raw images were first pre-processed by subtracting a background image obtained from the pixel-wise mean intensity over the acquisition sequence. This operation reduced the effect of stationary reflections and non-uniform illumination, particularly near the free surface. The velocity fields were computed using the PIVlab package, which implements a multi-pass FFT cross-correlation algorithm with window deformation. The interrogation window size was set to 64×64 pixels for the first two passes, then reduced to 32×32 pixels and finally to 16×16 pixels for the last pass. A 50% overlap was used, resulting in a final vector spacing of eight pixels, corresponding to $0.054D_N$. For bubble-laden plunging-jet cases, the choice of the interrogation window and the robustness of the correlation procedure require additional discussion, since bubbles locally alter the image intensity distribution, reduce tracer visibility, and may introduce spurious correlations. The instantaneous velocity fields were validated by removing spurious vectors through a global standard-deviation filter with a threshold of five standard deviations and a local median filter based on a 3×3 vector kernel with a threshold of three standard deviations. The rejected

vectors were subsequently replaced by interpolation from neighbouring valid vectors. For all the cases considered here, the fraction of rejected vectors remained below 5%, indicating a satisfactory quality of the PIV measurements.

3. Results and discussion

3.1. Free jet

The submerged water jet ($S-Re21100$ in Table 1) is employed to establish the validation of the experimental method for the subsequent investigation. Figure 2 reports the two-dimensional fields of the normalized mean axial velocity and of the axial and radial rms velocity fluctuations. The mean velocity field shows the expected near-field evolution of a turbulent round jet. A high-speed core is observed downstream of the nozzle, extending for approximately $5D_N$ before the onset of a more evident decay region. This value is consistent with the typical potential-core length reported for submerged turbulent jets, although the exact extension depends on the nozzle geometry, inflow profile, Reynolds number and confinement conditions. The rms fields exhibit the classical two-lobed structure associated with the shear layers developing on both sides of the jet core. Downstream, the two high-rms regions progressively broaden and move toward the jet centerline, reflecting the growth of the shear layers and the erosion of the potential core.

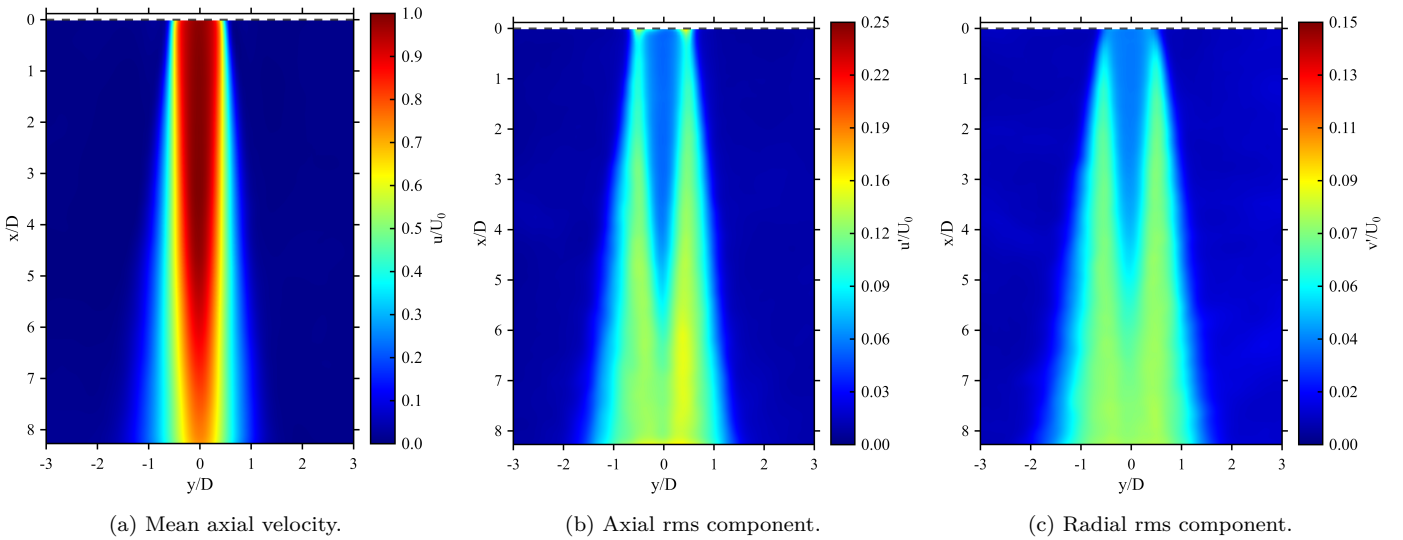


Figure 2. Two-dimensional velocity statistics for the submerged jet.

A quantitative comparison with previous submerged-jet measurements is first performed by considering the near-nozzle mean axial velocity profile, shown in Fig. 3. The profile is compared with the data reported in Vouros & Panidis (2013); Capone et al. (2015), and with a classical power-law distribution representative of a fully developed pipe flow condition. In the comparison, the

present measurements are reported separately on the left and right sides of the jet. The left side corresponds to the profile extracted for $y < 0$ and reflected onto a positive radial coordinate, while the right side corresponds to the profile for $y > 0$. Showing both sides provides an additional check of the symmetry of the measured field and allows a direct comparison with the one-sided reference profiles. The present profiles follow the expected shape in the central region of the jet, while some differences are visible near the edge, where the velocity gradient is steep and the comparison is more sensitive to spatial resolution and inflow conditions.

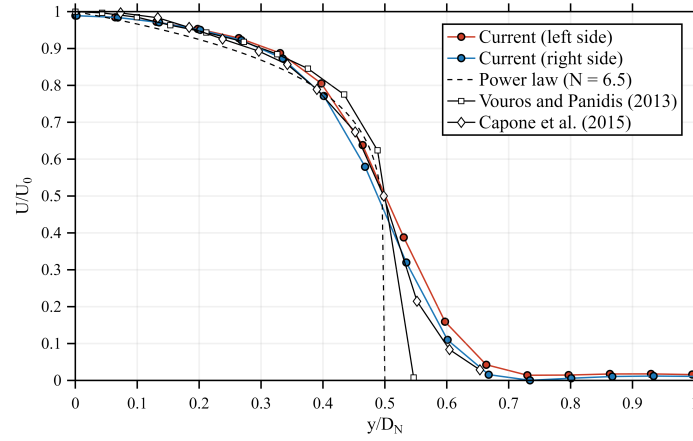


Figure 3. Near-nozzle normalized mean axial velocity profiles for the submerged jet.

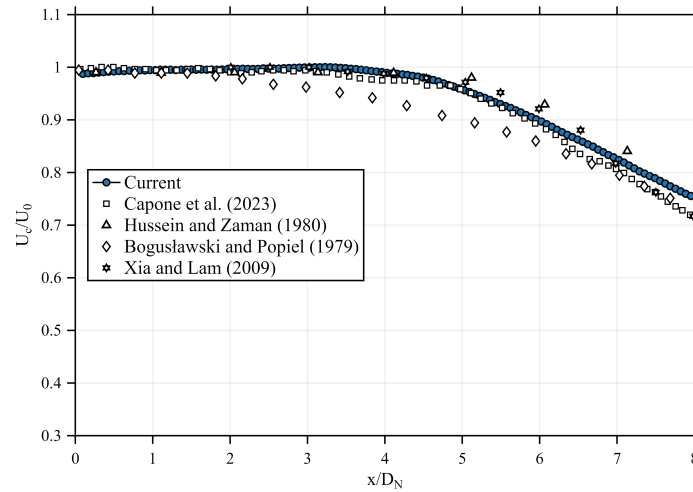


Figure 4. Streamwise evolution of the normalized centerline mean axial velocity for the submerged jet.

The streamwise evolution of the normalized centerline velocity is reported in Fig. 4. The present measurements show an approximately constant value of U_c/U_0 in the near field, confirming the presence of a potential core extending up to about $5D_N$, consistently with the two-dimensional mean velocity field discussed above. Downstream of this region, the centerline velocity progressively decreases as the shear layers merge toward the jet axis and the jet enters the decay region.

The comparison with Capone et al. (2023) shows a satisfactory agreement in both the potential-core region and the subsequent decay trend.

The radial profiles of the rms velocity fluctuations are shown in Fig. 5. The axial rms profiles display the expected near-field structure. Close to the nozzle, the fluctuations are concentrated in the shear layer, where the mean velocity gradients are largest. Farther downstream, the profiles broaden and the region of high rms values moves progressively toward the centerline, reflecting the growth of the shear layers and the erosion of the potential core. A similar behavior is observed for the radial rms component. The values of v'/U_0 are generally lower than those of u'/U_0 , consistent with the anisotropic character of the jet near field.

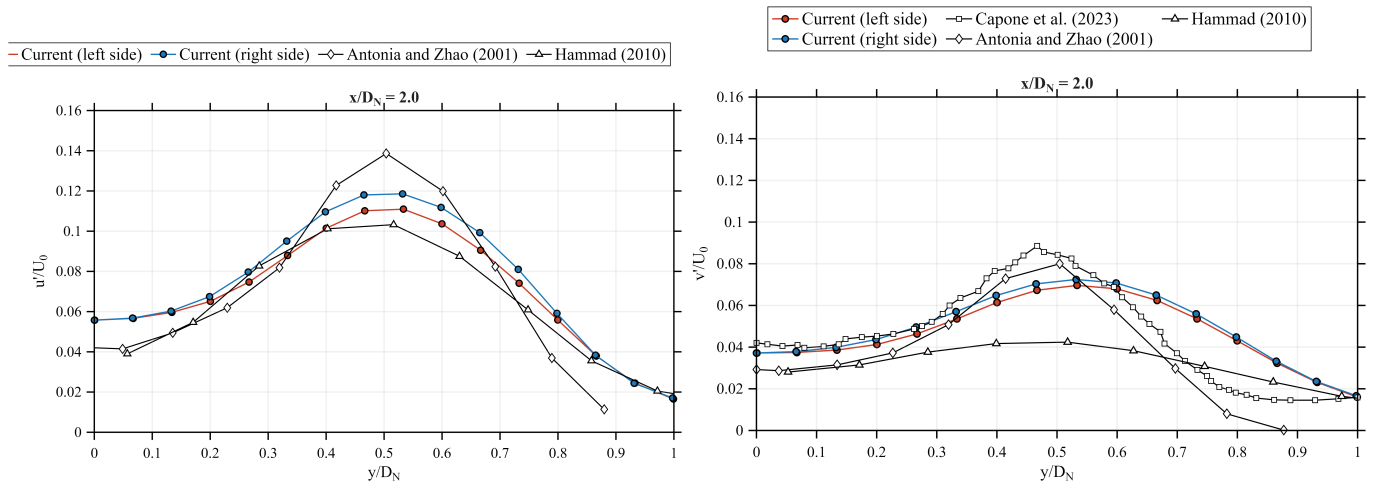


Figure 5. Radial profiles of velocity fluctuations for the submerged jet.

3.2. Regime map

Before analysing the velocity statistics, the operating conditions are first classified according to the occurrence of air entrainment. This provides the experimental framework for distinguishing submerged, bubble-free plunging, and bubbly plunging configurations, and for interpreting the results discussed in the following sections.

Figure 6 reports the regime map obtained in the present experiments in the plane (h, U_j) . The classification of the entrainment regimes adopted in the present work follows the definitions reported by Schmidtke et al. (2009). In the no-entrainment regime, no air bubbles are transported below the free surface. In the incipient entrainment regime, only isolated bubbles are occasionally entrained over a time interval of a few seconds. In the intermittent entrainment regime, packets of bubbles are entrained irregularly, with periods of bubble production separated by intervals where no gas is carried below the interface. Finally, in the continuous entrainment regime, bubbles are generated and transported below the surface continuously, leading to the formation of a persistent bubbly plume. The colored regions are based on the thresholds reported by Qu et al. (2013). In particular,

the no-entrainment region corresponds to nozzle velocities below approximately $U_b = 0.6$ m/s, the incipient/intermittent entrainment region to $0.6 < U_b < 1.2$ m/s, and the continuous entrainment region to $U_b > 1.2$ m/s. The present measurements reproduce well the entrainment behavior reported by Qu et al. (2013), with the observed regimes falling consistently within the corresponding regions of the flow map. Conversely, a more pronounced deviation is observed with respect to the data of Schmidtke et al. (2009). This discrepancy may be related to differences in the experimental setup, inlet conditions, nozzle geometry, and external disturbances.

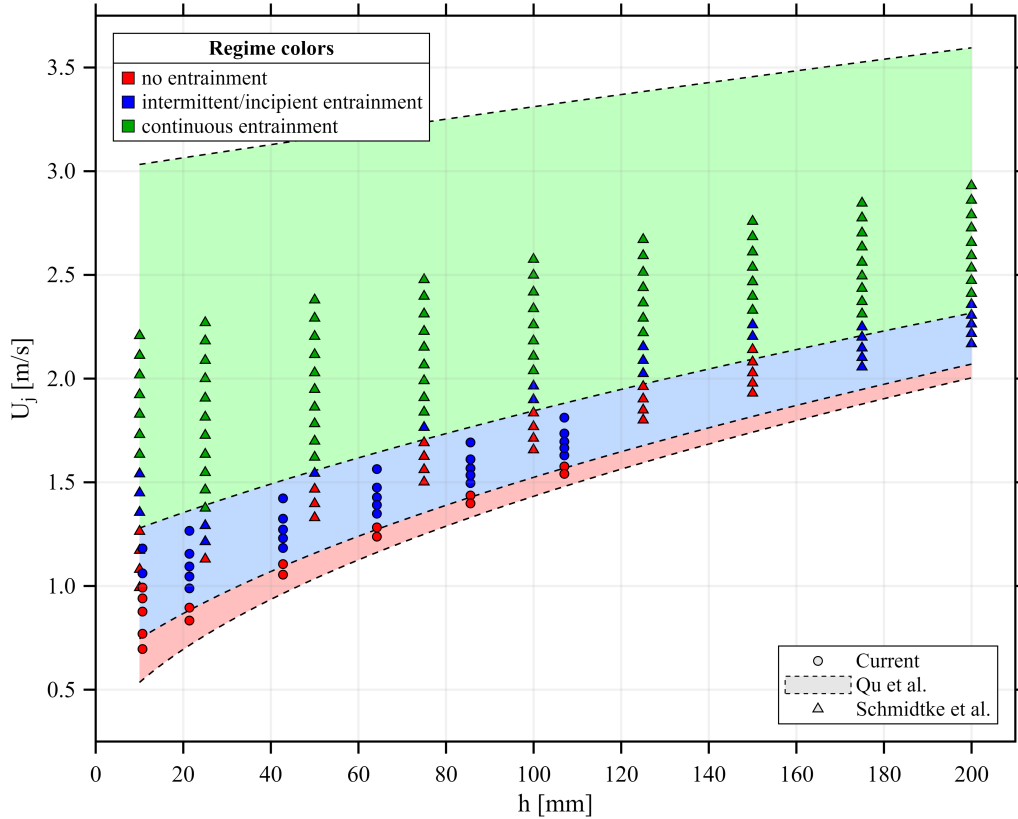


Figure 6. Flow-regime map in the (h, U_j) plane..

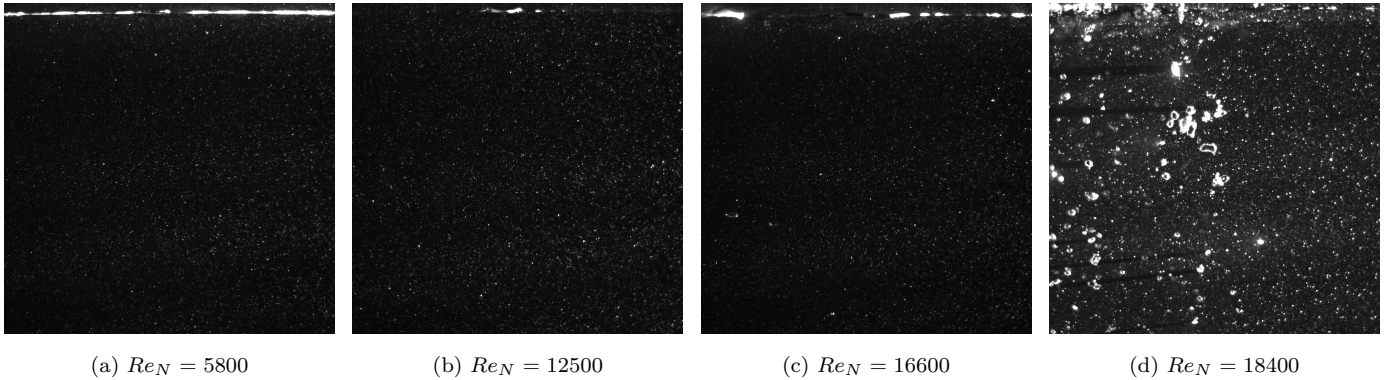


Figure 7. Instantaneous images of the $h/D_N = 2$ plunging configuration for increasing nozzle Reynolds number.

Instantaneous images obtained for plunging height $h/D_N = 2$ at varying Reynolds numbers are shown in Fig. 7. The cases at $Re_N = 5800$ and $Re_N = 12500$ are bubble-free. The case at $Re_N = 16600$ lies in the incipient-entrainment regime: isolated bubbles may occasionally be entrained, but their presence is sufficiently sparse to have a negligible effect on the statistical liquid-phase quantities. Conversely, for $Re_N = 18400$, the impact of the jet on the air–water interface leads to a clearly bubbly plunging jet, with air bubbles transported inside the submerged jet region.

3.3. Bubble-free plunging jet

In the present analysis, the origin of the coordinate system is placed at the free surface, with $x = 0$ corresponding to the air–water interface and positive x directed downstream along the jet axis. The radial coordinate is denoted by y . Therefore, the region $x > 0$ represents the submerged development of the plunging jet after impact, rather than the free-fall region above the pool. Figure 8 shows a representative bubble-free plunging case. The mean axial velocity field highlights the presence of a high-speed core immediately below the free surface, followed by a gradual axial decay and radial spreading of the jet. As the jet moves downstream, the shear layers thicken and progressively interact with the core, leading to the decay of the centerline velocity.

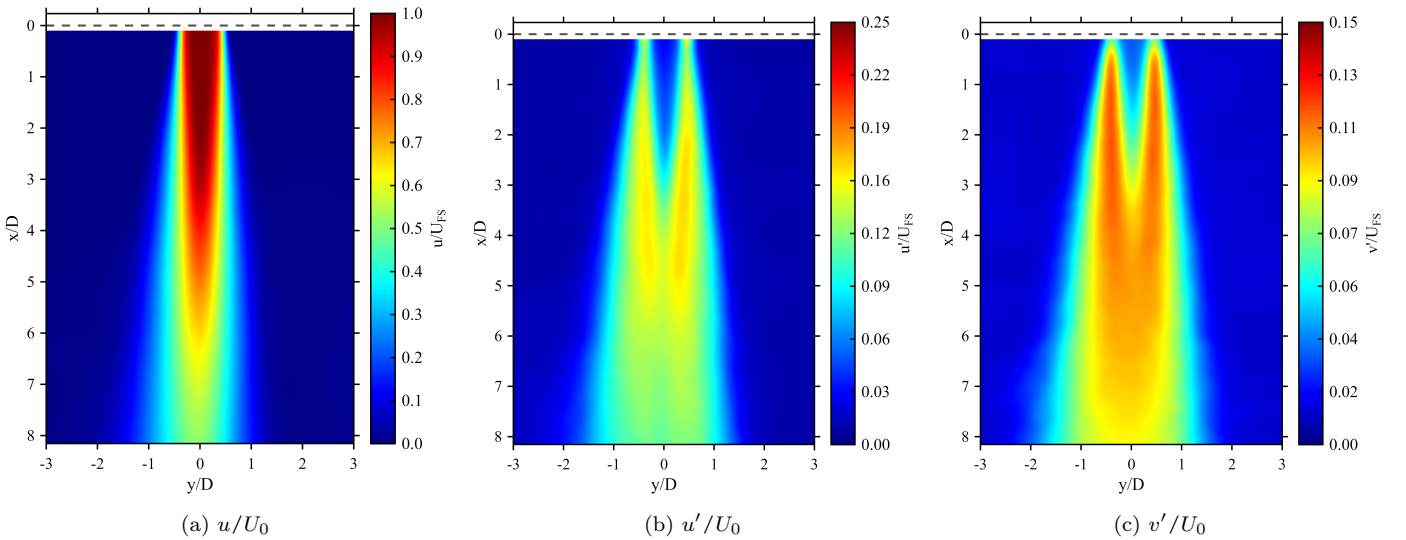


Figure 8. Representative bubble-free plunging jet flow field. The origin of the axial coordinate is located at the free surface, indicated by the dashed line.

As discussed by Hassan et al. (2019), the post-impact diameter D_{FS} is extracted directly from the PIV mean axial velocity profile immediately below the free surface. The jet boundary is identified by imposing a velocity threshold, $u/U_0 = 0.01$, and D_{FS} is computed as the distance between the two radial positions satisfying this condition. An example of this procedure is shown in Fig. 9 for the $h/D_N = 2$ plunging configuration. The effective jet diameter at the free surface increases with the Reynolds number, passing from approximately $D_{FS}/D_N = 0.85$ at $Re_N = 5800$ to $D_{FS}/D_N =$

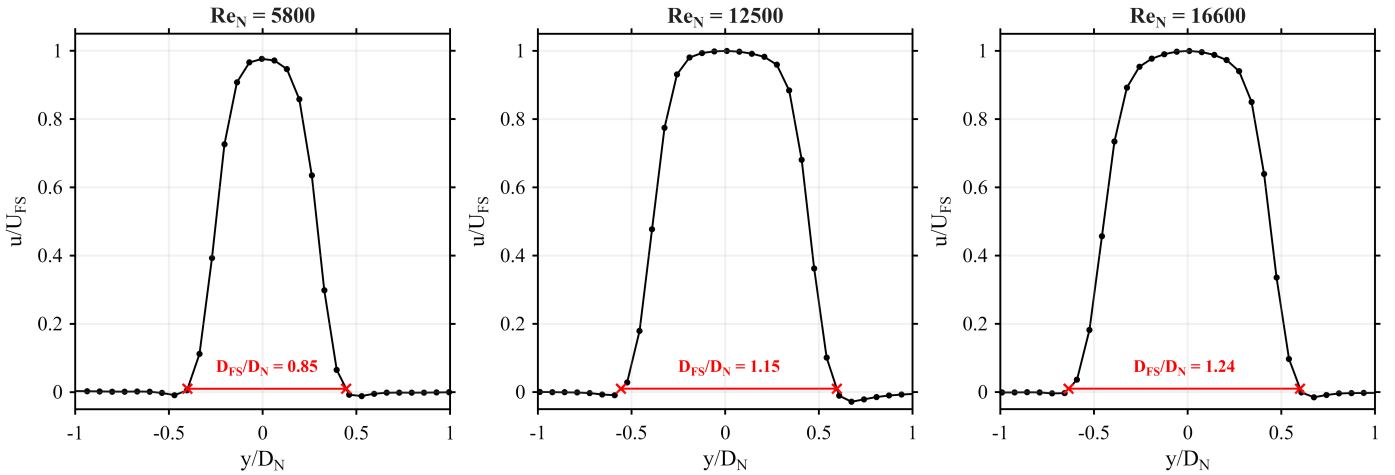


Figure 9. Definition of the free-surface diameter D_{FS} from the mean axial velocity profile immediately below the free surface for the $h/D_N = 2$ plunging configuration. The jet boundary is identified using the threshold $u/U_0 = 0.01$.

1.24 at $Re_N = 16600$. Together with D_{FS} , a local velocity scale U_{FS} is defined as the maximum streamwise velocity measured immediately below the free surface. This velocity corresponds to the axial velocity of the jet core at the beginning of the submerged region. The corresponding free-surface Reynolds number is then defined as

$$Re_{FS} = \frac{\rho U_{FS} D_{FS}}{\mu}, \quad (5)$$

where ρ and μ are the density and dynamic viscosity of water, respectively. This scaling allows the plunging jet to be interpreted as an equivalent free jet starting from the free surface, with characteristic diameter D_{FS} and velocity U_{FS} .

The relevance of the free-surface scaling is assessed in Figs. 10–11, where radial profiles of the mean axial velocity and of the rms velocity fluctuations are reported for the $h/D_N = 2$ plunging configuration. The comparison is performed by considering both the nozzle-based normalization and the free-surface normalization. Figure 10 shows the mean axial velocity profiles. When the profiles are plotted as a function of y/D_N at fixed values of x/D_N , the three Reynolds-number cases do not collapse. In particular, the apparent jet width increases with Re_N , consistently with the increase of D_{FS}/D_N discussed above. Therefore, part of the observed Reynolds-number dependence is not associated with a different intrinsic development of the jet, but with the different effective diameter with which the plunging jet enters the receiving pool. When the same data are instead represented in terms of x/D_{FS} and y/D_{FS} , the profiles collapse remarkably well at all the considered axial stations. This confirms that D_{FS} is the appropriate length scale for the submerged development of the plunging jet. Once the actual jet diameter at the free surface is used, the mean velocity field becomes nearly independent of the nozzle Reynolds number in the investigated range. The spreading of the shear layers and the progressive reduction of the centerline velocity are therefore governed by the local jet scale at the interface rather than by the nominal

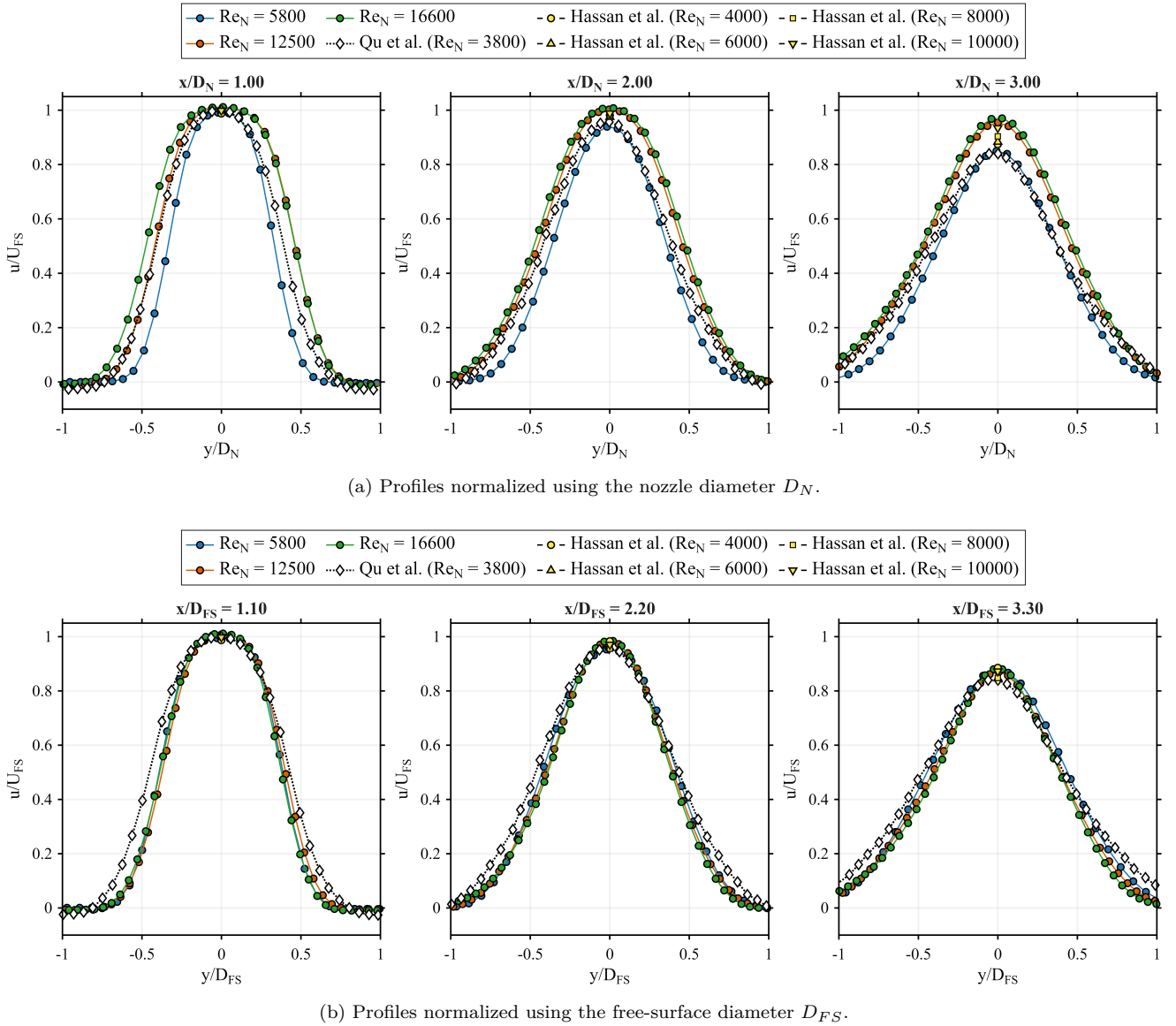


Figure 10. Radial profiles of the normalized mean axial velocity for the $h/D_N = 2$ plunging jet.

nozzle diameter alone.

The same behaviour is observed for the turbulent fluctuations. Figure 11 show the radial profiles of the radial rms components. With the nozzle-based normalization, the two peaks associated with the shear layers appear at different radial positions depending on Re_N . Moreover, their relative distance and the width of the fluctuation region change from one Reynolds number to another. This again reflects the fact that the shear layers originate from an effective impact diameter that varies with the Reynolds number. After rescaling the coordinates with D_{FS} , the rms profiles show a much clearer collapse. The position of the two fluctuation peaks, their amplitude, and their downstream evolution become nearly Reynolds-independent. The free-surface scaling also enables a consistent comparison with previous experimental results (Hassan et al., 2019; Qu et al.,

2013).

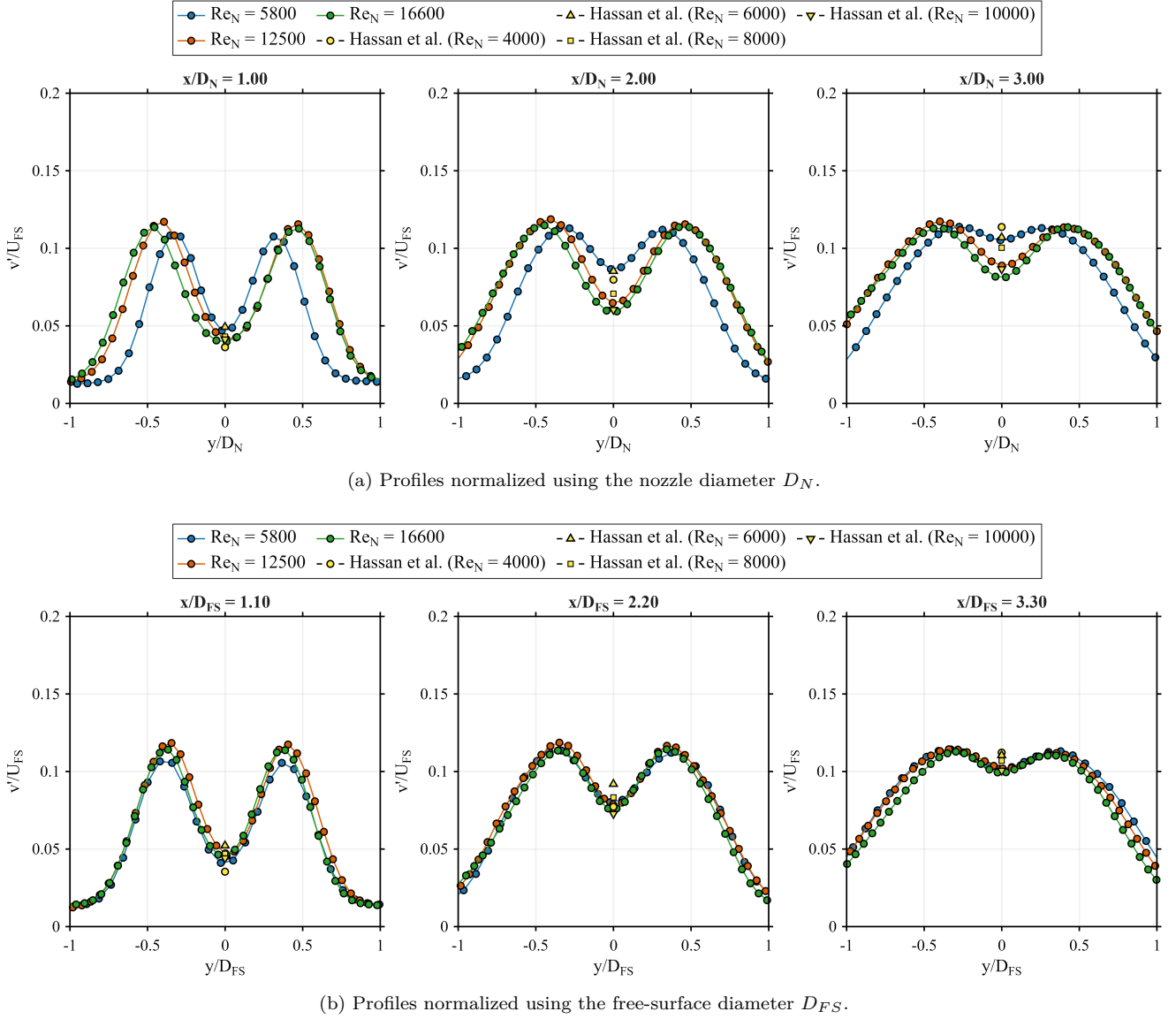


Figure 11. Radial profiles of the normalized radial rms velocity fluctuations for the $h/D_N = 2$ plunging jet.

The collapse observed in the radial profiles is also reflected in the axial evolution of the centerline quantities. Figures 12 and 13 show the centerline mean velocity and the centerline rms velocity fluctuations for the $h/D_N = 2$ plunging configuration, using the free-surface scaling introduced above. The mean centerline velocity, shown in Fig. 12 starts to decay at approximately $x/D_{FS} \simeq 2$ – 2.5 , in agreement with the behaviour reported by Hassan et al. (2019) and Qu et al. (2013). This confirms that the potential core of a bubble-free plunging jet is significantly shorter than that of a classical submerged free jet. Downstream of the potential core, U_c/U_0 decreases monotonically as a consequence of the progressive entrainment of ambient liquid and the radial diffusion of axial momentum. The decay is rapid in the near field and the centerline velocity reaches values close to $U_c/U_0 \simeq 0.5$ at $x/D_{FS} \simeq 7$ – 8 . The centerline rms fluctuations are reported in Fig. 13. The axial

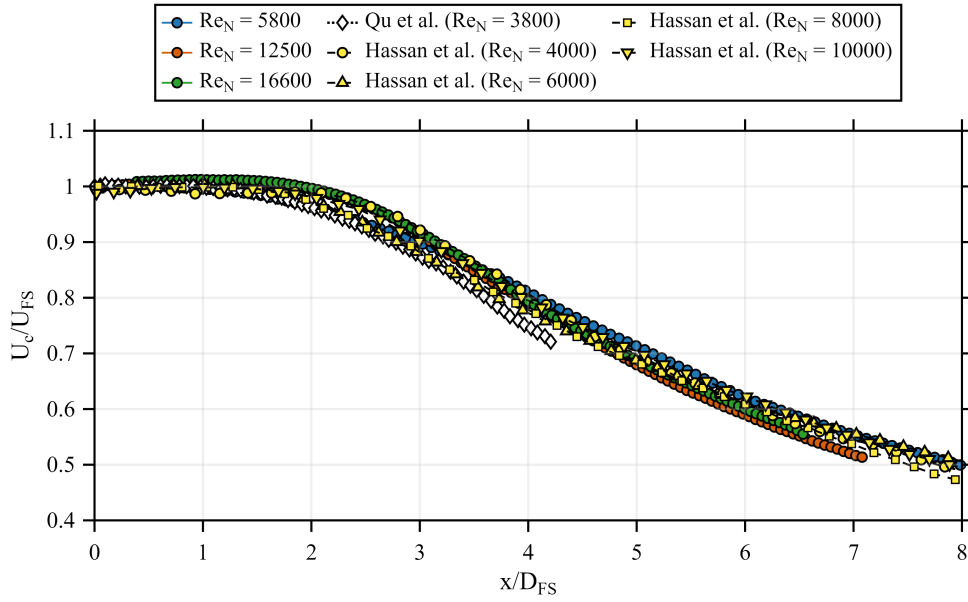


Figure 12. Axial evolution of the normalized centerline mean velocity for the $h/D_N = 2$ plunging jet.

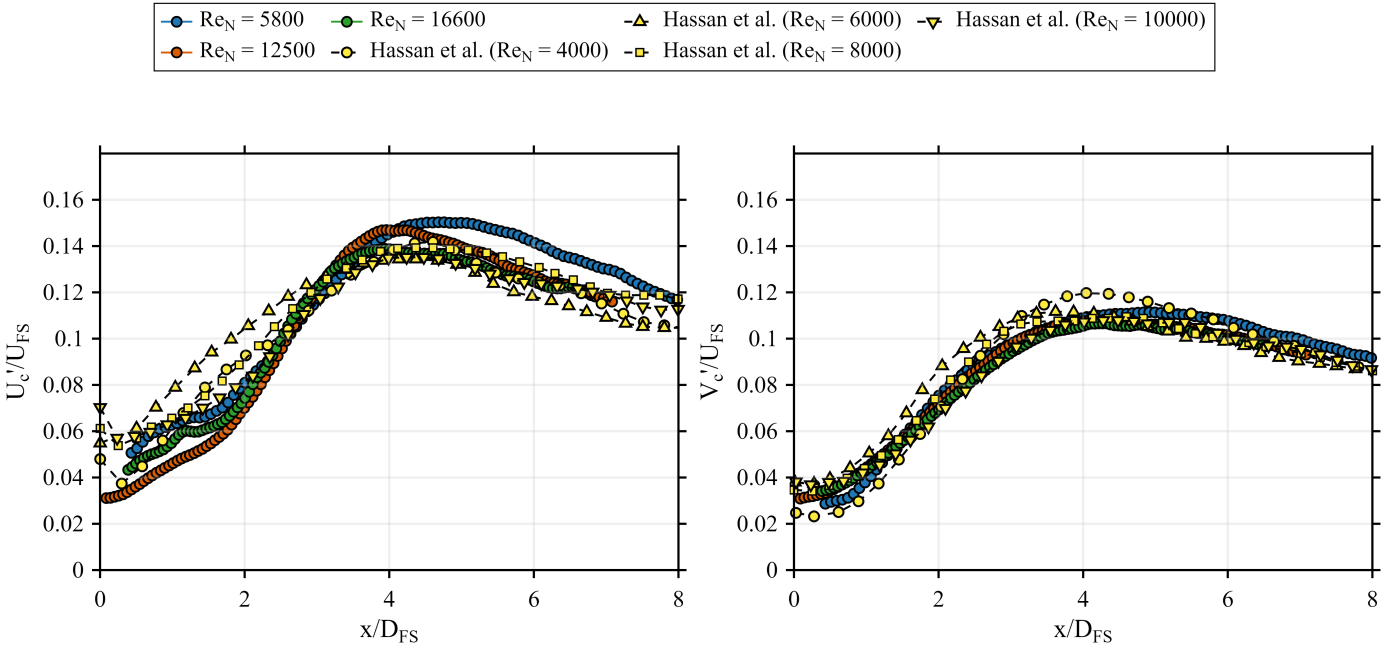


Figure 13. Axial evolution of the normalized centerline rms velocity fluctuations for the $h/D_N = 2$ plunging jet.

component is relatively small close to the free surface, since the centerline is still located inside the potential core. Moving downstream, u'_c/U_0 increases as the two shear layers grow and approach the jet axis. The maximum value is reached at approximately $x/D_{FS} \simeq 4-5$, which corresponds to the region where the shear layers interact with the centerline and the potential core is fully eroded. This position is again consistent with the observations of Hassan et al., who associated the upstream peak of the centerline rms fluctuations with the earlier closure of the shear layers

in plunging jets. A similar evolution is observed for the radial rms component, albeit with lower magnitude. The comparison among the three Reynolds-number cases shows that the centerline quantities are only weakly dependent on Re_N once the axial coordinate is normalized by D_{FS} . Small differences are visible in the early part of the rms profiles, especially close to the free surface, where the flow is more sensitive to the details of the impact and to free-surface disturbances.

3.3.1. Dependence on the plunging height

To investigate the effect of plunging height, a subset of the operating conditions reported in Table 1 was selected. The selected cases are *S-Re21100*, *1D-Re10700*, *2D-Re12500*, *3D-Re12500*, *4D-Re12500*, and *5D-Re10700*.

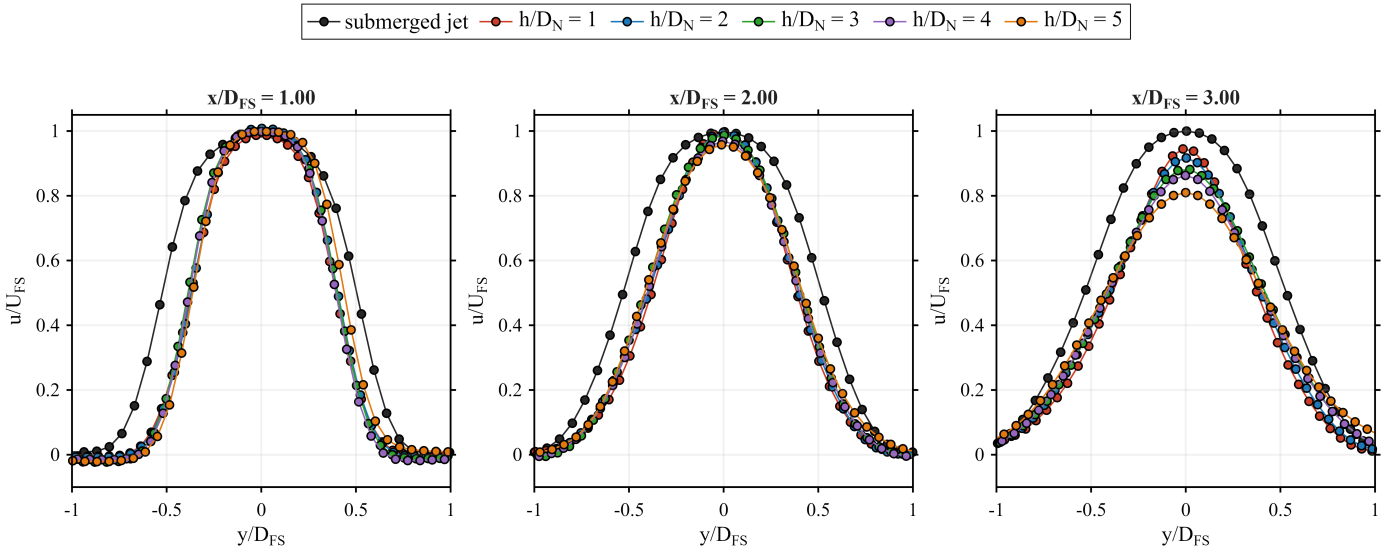


Figure 14. Mean axial velocity for different plunging heights.

Figure 14 reports the radial profiles of the mean axial velocity for the submerged jet and for the plunging configurations from $h/D_N = 1$ to $h/D_N = 5$. All plunging profiles are normalized using the corresponding value of D_{FS} , so that the comparison is performed at equivalent downstream stations measured from the free surface. At $x/D_{FS} = 1 - 2$, all configurations are still dominated by the high-speed core and the differences among the plunging cases are limited. Moving downstream to $x/D_{FS} = 3$, the differences become more evident. The plunging profiles spread wider and show a lower centerline value, while the submerged jet preserves a more compact core.

Figures 15 and 16 show the radial profiles of the axial and radial rms components. For the submerged jet, fluctuations are weaker and more confined. A stronger impact with the free surface progressively increases fluctuations intensity, profile broadening, and peaks merging due to faster and stronger interaction of the shear layers. This accelerates jet development, entrainment, and erosion of the potential core (Fig. 17).

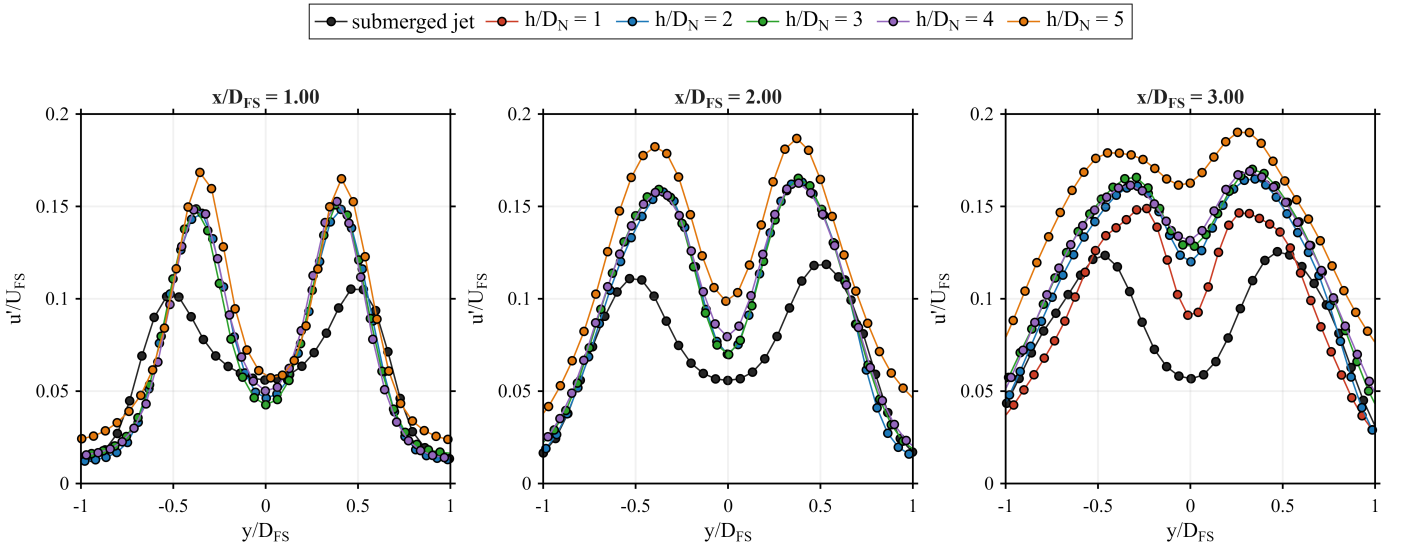


Figure 15. Axial rms velocity fluctuations for different plunging heights.

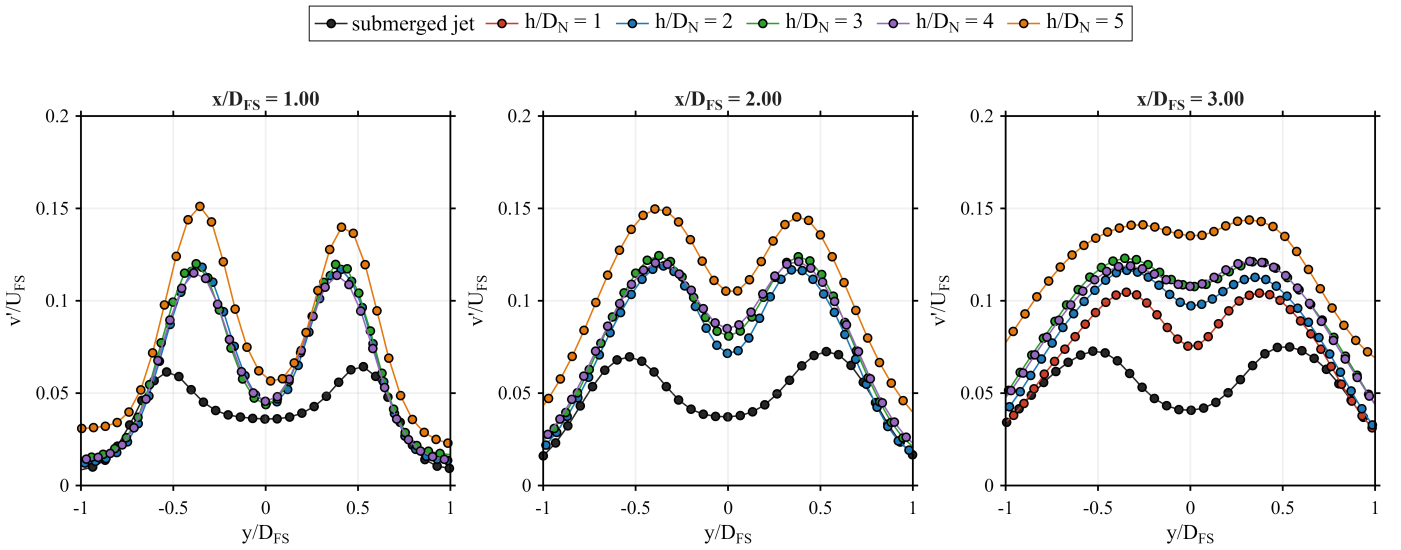


Figure 16. Radial rms velocity fluctuations for different plunging heights.

Therefore, even in the absence of air entrainment, the plunging jet cannot be interpreted simply as a submerged jet with a different inlet velocity. The free-surface interaction introduces additional disturbances that alter the early turbulent development of the flow. The present results therefore extend the conclusions of Hassan et al. (2019) and Qu et al. (2013). While those studies demonstrated that plunging jets decay faster than submerged jets and exhibit stronger near-field fluctuations, the present comparison shows that this effect increases with the plunging height. The transition from submerged jet to increasingly deeper plunging configurations reveals a continuous amplification of shear-layer activity, centerline velocity decay, and transverse turbulent mixing.

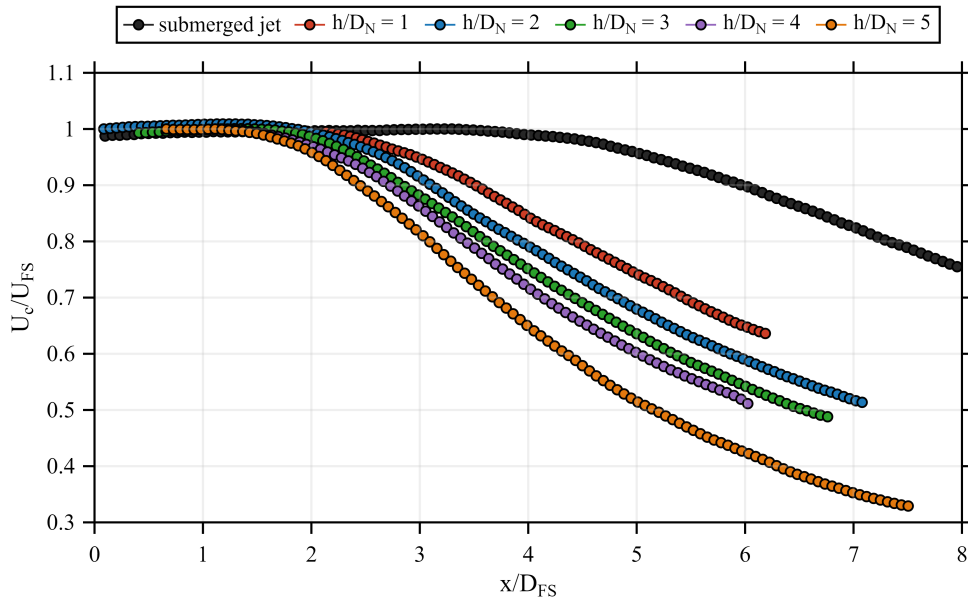


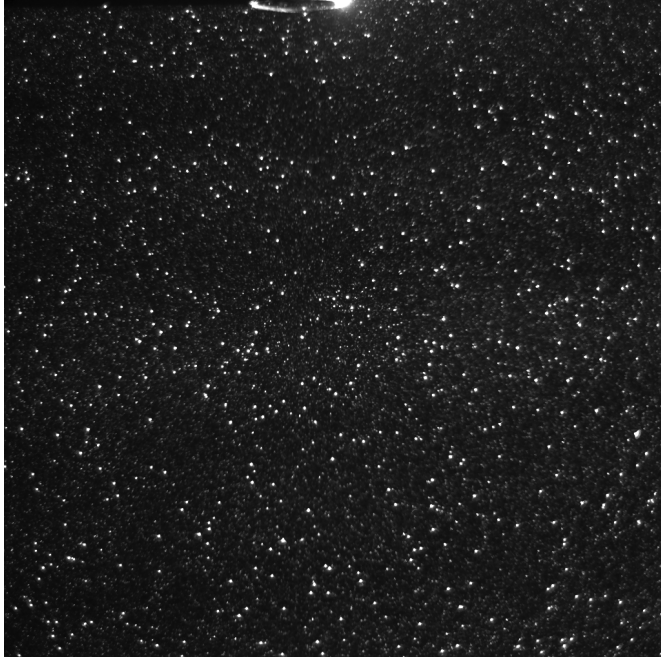
Figure 17. Normalized centerline mean velocity for submerged and plunging jets.

3.4. Bubbly plunging jet

The presence of entrained bubbles introduces significant difficulties for a standard PIV analysis of the liquid phase. In conventional PIV, both tracer particles and bubbles are illuminated by the laser sheet and recorded by the camera. However, bubbles do not behave as passive tracers of the liquid phase. Their optical response is much stronger and less controlled than that of the seeding particles, since it depends on bubble size, shape, deformation, position within the light sheet, and instantaneous orientation with respect to the camera. As a consequence, bubbles introduce intense reflections and local intensity peaks that reduce the signal-to-noise ratio of the particle images. In addition, when bubbles cross the laser sheet, they can locally block or deflect the light, producing shadow regions where the tracers are poorly illuminated. These effects make the illumination field highly non-uniform and can lead to poor or biased cross-correlation, especially in the regions where the bubble concentration is high. Previous PIV studies on bubbly plunging jets addressed this issue by applying image-processing procedures to separate the liquid and gas phases. In Hammad (2010), raw multiphase images were pre-processed using low-pass, high-pass and morphological filters for background subtraction, bubble detection and phase separation. The regions occupied by bubbles were identified and then subtracted from the original images in order to obtain a liquid-phase image suitable for PIV processing. This approach performs an artificial removal of the bubbles at the image-processing level. In the present study, a different strategy is adopted. Instead of removing the bubble footprints a posteriori, the liquid-phase signal is isolated optically by using fluorescent tracer particles. By placing an optical filter on the camera, only the light emitted by the fluorescent tracers is recorded, providing a direct optical separation between the liquid-phase tracer and bubbles.

3.4.1. PIV validation with fluorescent tracers

Figure 18 shows instantaneous pictures of a free jet ($Re_N \simeq 2.1 \times 10^4$) with and without the optical filter. Both standard and fluorescent tracers are present in the fluid, yielding a lower seeding density when the filter is employed.



(a) Standard acquisition without optical filter.



(b) Fluorescent acquisition with optical filter.

Figure 18. Instantaneous PIV images acquired for the submerged jet.

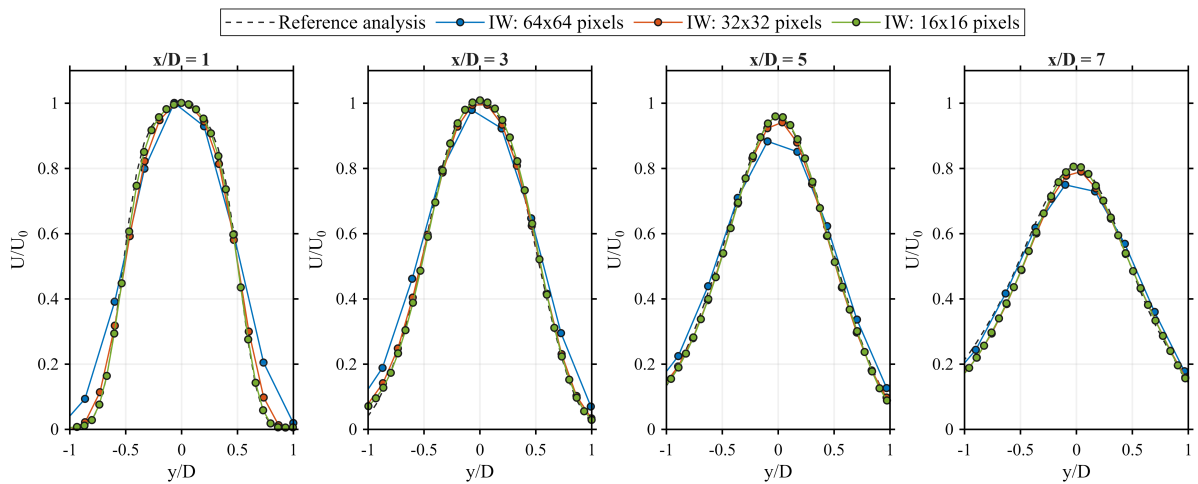


Figure 19. Mean axial velocity profiles obtained from the fluorescent acquisition.

Different final interrogation-window sizes (64×64 , 32×32 and 16×16 pixels) are tested on the fluorescent tracer acquisition. The results in terms of mean axial velocity and fluctuating components

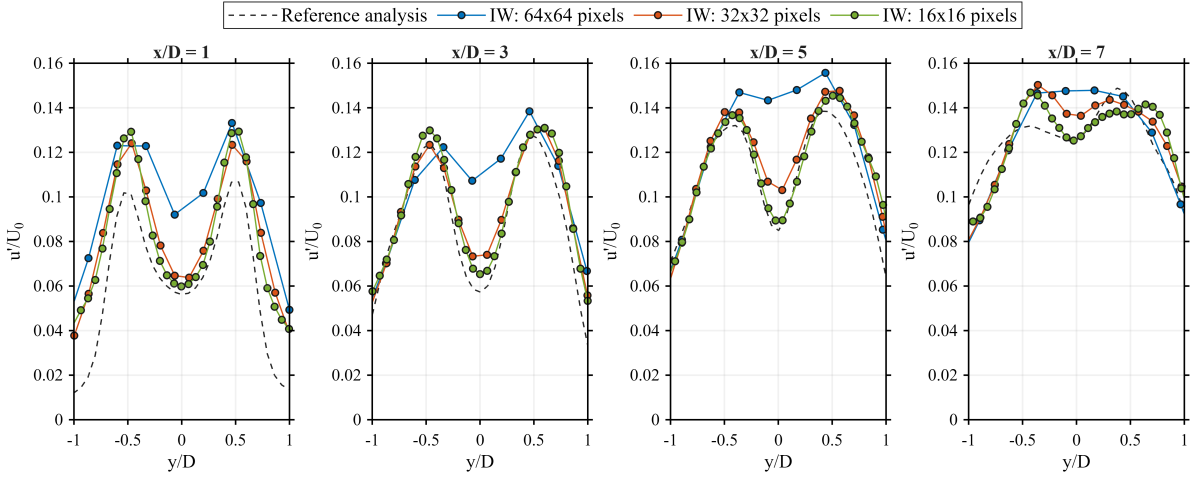


Figure 20. Axial rms velocity profiles obtained from the fluorescent acquisition.

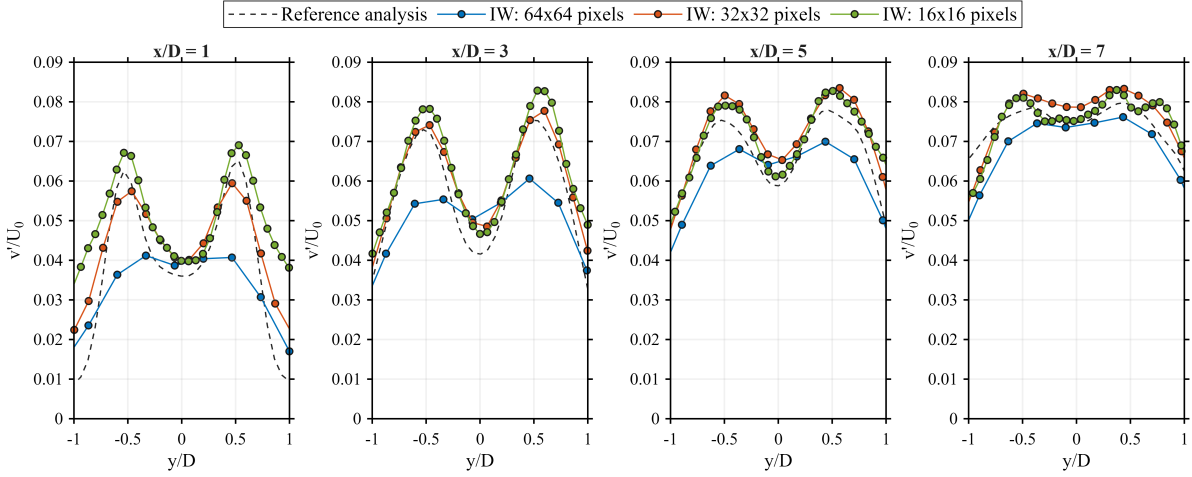


Figure 21. Radial rms velocity profiles obtained from the fluorescent acquisition.

(Figs. 19, 20, 21) are compared with the reference analysis obtained from the standard acquisition. The mean velocity profiles (Fig. 19) show an excellent agreement with the reference analysis for interrogation windows of 32×32 pixels and 16×16 pixels. The jet core, the shear-layer gradients and the downstream decay are well reproduced. The rms velocity fluctuations are more sensitive to the interrogation-window size and to the reduced particle density (Figs. 20 and 21). A larger error level is present outside the jet, especially for low x/D . Based on this comparison, the 16×16 pixels final interrogation window is selected but only in the range of $-D < y < D$.

3.4.2. Effect of air bubbles on velocity statistics

A fixed plunging height equal to $h/D_N = 2$ is considered in this section. Intermittent air entrainment is obtained by increasing the nozzle Reynolds number from $Re_N = 16600$ to $Re_N = 18400$ (see also Fig. 7). By changing the Reynolds number, the overlapped effects of different jet bound-

ary conditions and bubbles turbulence modulation are present.

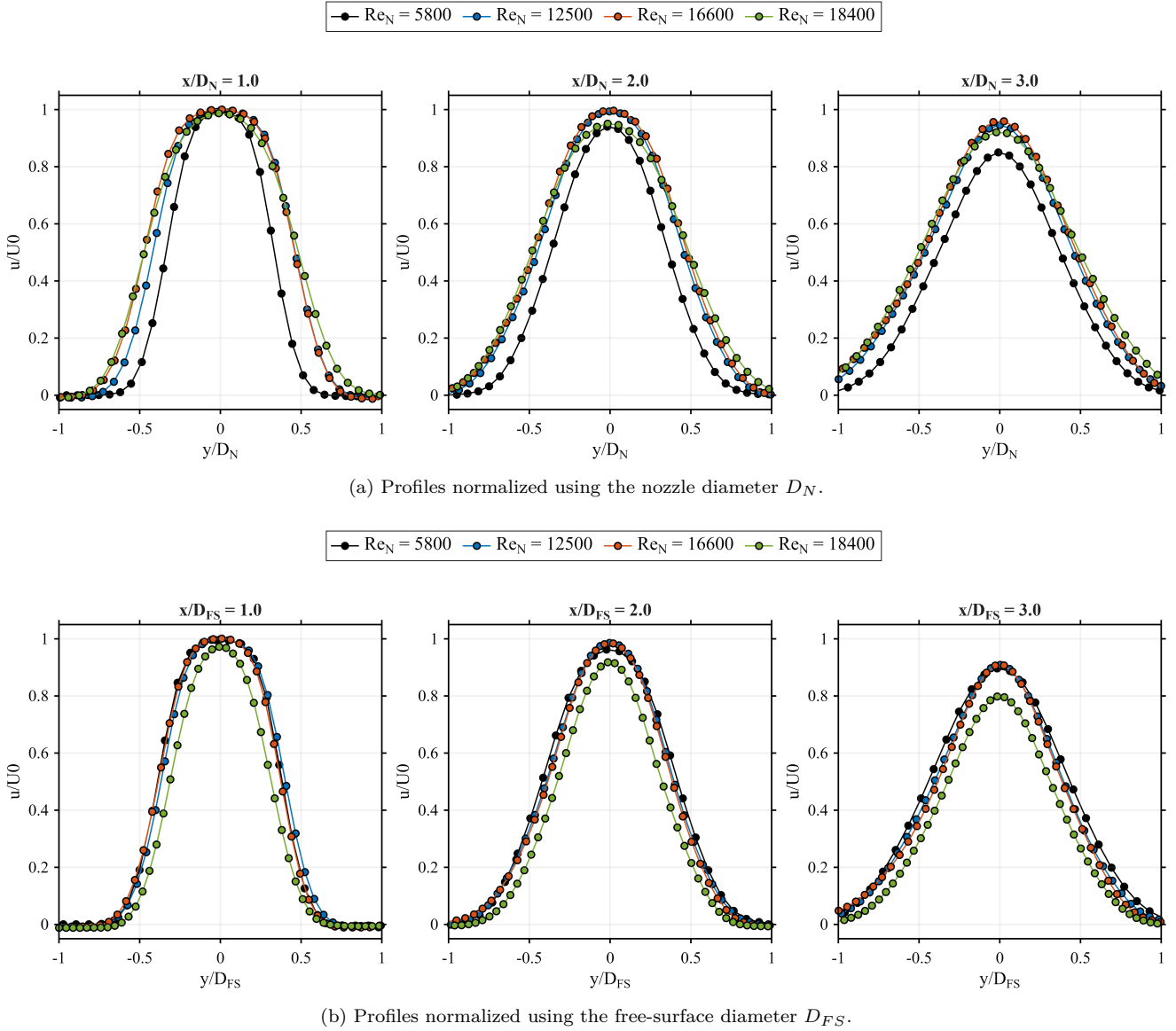


Figure 22. Radial profiles of the normalized mean axial velocity for the $h/D_N = 2$ plunging configuration.

To separate these two contributions, the same free-surface normalization introduced for the bubble-free cases is adopted here. Spatial coordinates are normalized by the local free-surface diameter D_{FS} , while velocities are normalized by the characteristic jet velocity at the free surface (Fig. 22). In the absence of a statistically relevant dispersed gas phase, the use of D_{FS} reduces the apparent Reynolds-number dependence of the velocity statistics. The scaling therefore allows to quantitatively assess the sole effects of the bubbly flow on the liquid phase. The case at $Re_N = 18400$ exhibits a lower centerline velocity and a more advanced decay of the mean profile (Fig. 22b), indicating that the entrained bubbles accelerate the loss of axial momentum from the jet core.

The appearance of the spreading and decay of the jet are strongly influenced by the use of the nom-

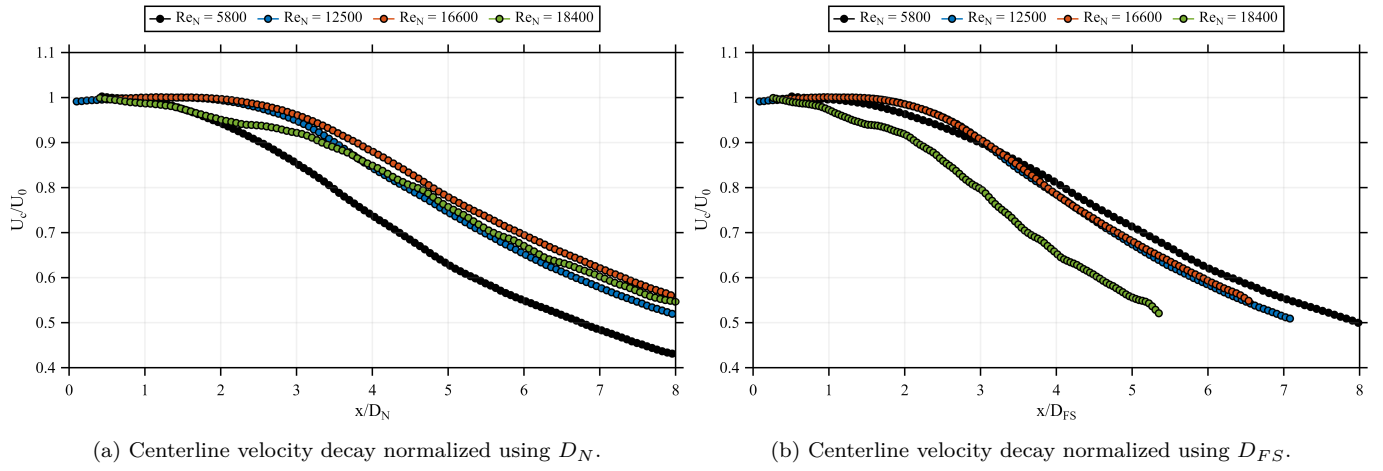


Figure 23. Axial decay of the normalized centerline mean velocity for the $h/D_N = 2$ plunging configuration.

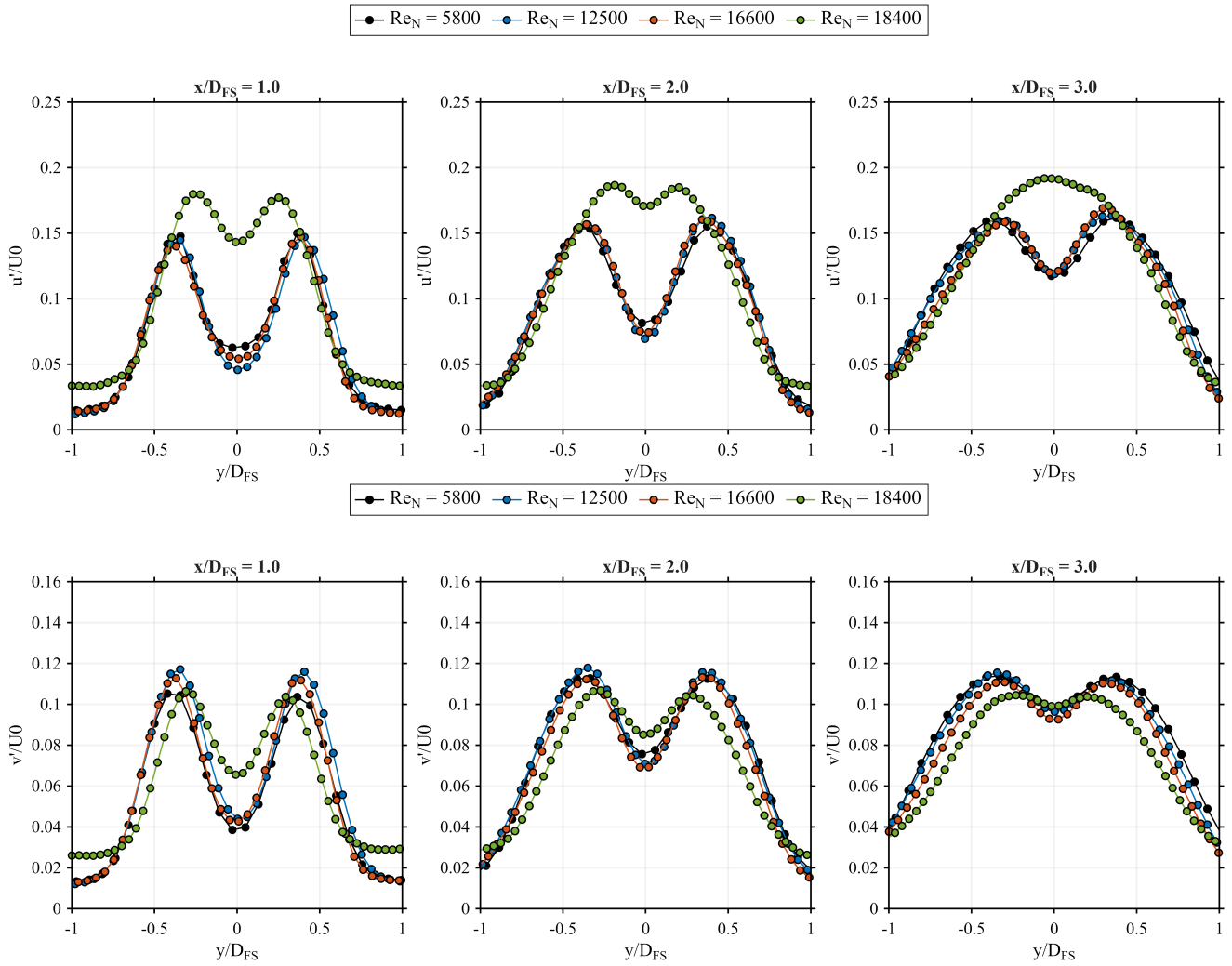


Figure 24. Radial profiles of velocity fluctuations for the $h/D_N = 2$ plunging configuration.

inal nozzle diameter as length scale: the lower-Reynolds-number case appears more advanced in its development when plotted against x/D_N , while the higher-Reynolds-number cases are shifted downstream because of the larger effective jet diameter at the free surface (Fig. 23). By using the correct scaling, the shorter potential core and its faster erosion in the presence of air bubbles can be observed.

The effect of air entrainment on the turbulent velocity fluctuations is shown in Fig. 24. The bubbly case exhibits significantly larger values of u'/U_0 starting from the free surface, even at the jet core, and show accelerated merging of the shear layers. On the other hand, values of the v'/U_0 component are generally smaller than their bubble-free counterparts. These effects are due to the dispersed gas phase and not to the higher Reynolds number of the bubbly case. Results are consistent with the observations of Hammad (2010), who reported that bubble entrainment suppresses the liquid-phase mean velocity while enhancing the streamwise rms fluctuations and reducing the radial rms component.

4. Conclusions

PIV measurements of submerged and plunging jets have been performed in this study. The plunging jets have been analyzed by varying both the Reynolds and the Froude numbers, obtaining a regime map including no air entrainment or intermittent air entrainment.

For the bubble-free plunging jets, a scaling based on the free-surface diameter and velocity has been successfully used to reduce the dependency on the Reynolds number of the profiles of mean velocity and rms fluctuations. By varying the falling height, a progressive growth of fluctuations intensity, profile broadening, and peaks merging due to faster and stronger interaction of the shear layers has been observed. The acceleration of the jet development, entrainment, and erosion of the potential core has been quantitatively reported.

For the bubbly plunging jet, a parametric analysis on the interrogation window size has been performed in order to validate the technique employing fluorescent tracer with the optical filter. With the correct scaling, the bubbly flow shows increased decay of the jet core in terms of mean velocity. Turbulence modulation appears as accentuated axial fluctuations and attenuated radial fluctuations, altering the flow anisotropy.

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