

RESEARCH ARTICLE | MARCH 10 2025

Laboratory study of orifice jets from a pressurized pipe

D. Ferraro ; R. Gaudio ; S. Ferrari 



Physics of Fluids 37, 035139 (2025)

<https://doi.org/10.1063/5.0256087>



Articles You May Be Interested In

Transforming underground to surface mining operation – A geotechnical perspective from case study

AIP Conference Proceedings (November 2021)

Monthly prediction of rainfall in nickel mine area with artificial neural network

AIP Conference Proceedings (November 2021)

Estimation of Karts groundwater based on geophysical methods in the Monggol Village, Saptosari District, Gunungkidul Regency

AIP Conference Proceedings (November 2021)

Laboratory study of orifice jets from a pressurized pipe

Cite as: Phys. Fluids **37**, 035139 (2025); doi: [10.1063/5.0256087](https://doi.org/10.1063/5.0256087)

Submitted: 2 January 2025 · Accepted: 16 February 2025 ·

Published Online: 10 March 2025



View Online



Export Citation



CrossMark

D. Ferraro,^{1,a)} R. Gaudio,¹ and S. Ferrari²

AFFILIATIONS

¹Dipartimento di Ingegneria Civile, Università della Calabria, Via P. Bucci, Cubo 42B, 87036 Rende, Italy

²Dipartimento di Ingegneria Civile, Ambientale e Architettura, Università di Cagliari, Via Marengo 2, 09123 Cagliari, Italy

^{a)}Author to whom correspondence should be addressed: domenico.ferraro@unical.it

ABSTRACT

Orifice jet through a small opening or orifice into a surrounding fluid exhibits intricate fluid dynamics, encompassing the interaction of the jet with the fluid. Although the dynamics of simple jets has been extensively studied, there are still unresolved issues that need to be addressed. In this study, we experimentally investigated the characteristics of non-buoyant jets emerging from a sharp-edged orifice located in the wall of a pipe with a constant flow rate. Specifically, we examined how the ratio between the variable jet flow rate to the constant pipe flow rate upstream of the orifice influences not only the jet trajectory but (for the first time to the authors' knowledge) also the jet velocity-related features. Particle image velocimetry measurements were performed to explore the velocity fields in the near and intermediate regions of the jet and data were analyzed in terms of fields of time-averaged velocity components, turbulent intensities, Reynolds shear stresses, vorticity, and Q-criterion. The transversal velocity profiles were shown and their Gaussianity investigated via skewness and kurtosis. Thus, second-order statistics of turbulence of the velocity fluctuations were carried out. Moreover, a spectral analysis was performed after the Taylor hypothesis verification was proved and a net scale separation was guaranteed to develop the inertial sub-range. The influence of variable jet flow rate and the constant pipe flow rate on the jet behavior is shown and, in particular, how, as this parameter decreases, the jet moves away from the typical axisymmetric features of a round simple jet. In addition, the spectra analysis is used to identify the jet potential core and the large-scale organization zones, highlighting the effect of variable jet flow rate and the constant pipe flow rate on the extension of the potential core region and on the mixing layer.

Published under an exclusive license by AIP Publishing. <https://doi.org/10.1063/5.0256087>

I. INTRODUCTION

Orifice jet is a fascinating hydraulic phenomenon involving fluid flow through a small opening or orifice into a surrounding fluid. This simple configuration exhibits intricate fluid dynamics, encompassing the interaction of the jet with the surrounding fluid, the formation of vortices and secondary flows, and the propagation of the jet into the environment. Owing to the various engineering applications, orifice jets have a crucial importance. A relevant application is the discharge of wastewater into the sea, or other receiving bodies, through submerged jets issuing from ports in the wall of pressurized pipes, where the ports can be made in the form of sharp-edged¹ or thin-walled orifices.² A multi-port diffuser configuration is often employed (see, e.g., French,³ Hosseini *et al.*,⁴ Masria *et al.*⁵) and, in this case, the flow rate upstream of a jet is larger than the one downstream of it. The multi-port jet diffuser configuration is also employed for the disinfection processes, via a chlorine solution, in wastewater treatment plants.⁶ Moreover, high-pressure water jets are also used to circulate water

through the fish tanks to maintain the water quality and keep the fish healthy.⁷ The same technique is employed in seaweed farms to maintain the water quality and optimize the growth of the seaweed.⁸ Additionally, other cases have driven to study the wall pipe jet as the accidental spillage generated from damage in the pipeline wall, that can be assumed as a leak from an orifice.^{9–12} Previous examples are only a few uses of orifice jets into a surrounding fluid in the environmental field. These applications may forecast a simple geometric scheme compound of a pressurized pipe, in which a fluid flows and leaks out of lateral wall openings (circular orifices). However, to the best of the authors' knowledge, the previous research types have not been focused on the characterization of the features of the jet issuing from the orifice, in particular when the jet to pipe flow rate is varied, as in the case of multiport diffusers.

The mixing layer generated by a jet flow is a complex phenomenon due to the involved length scales: namely, the initial shear layer momentum thickness and jet diameter, in which the former is

considerably smaller than the last.¹³ Instabilities are observed at the axisymmetric jet edge, owing to lobes raising as proof of a ring-like vortex. This promotes the mixing of the large-scale coherent structures present at the jet edge, pushing it into the jet core vortex in a breaking-down process up to the appearance of fine-grained turbulent structures. Hussain¹⁴ asserts that a well-organized mixing layer becomes turbulent as the diameter Reynolds Number (Re_D) increases. The jet coherent structures (JCSs) (e.g., vortex ring) are born inside the mixing layer and connect laminar/turbulent fluid mass with phase-correlated vorticity, that are responsible for heat and momentum transport; these JCSs have a size comparable to the transverse dimension of the shear flow. Large-scale organization in the near-orifice region ($y/D < 5$, where y is the distance, along the jet, from the orifice, and D the orifice diameter) was observed at a high Reynolds number by Brown and Roshko¹⁵ and Yule,¹⁶ whereas Cantwell¹⁷ discussed the evidence that turbulent boundary layers at high Reynolds numbers are also organized into large scales. As suggested by Dimotakis *et al.*,¹⁸ the large-scale organization may suggest revising models for turbulent transport mechanisms based on turbulent fluxes proportional to local gradients of mean quantities. Corrsin and Kistler¹⁹ pointed out that such models assume that local fluctuations are much smaller than the transverse extent of the region of turbulent jet flow. Thus, the interest in turbulent scales analysis is still actual, especially in real-world conditions as this work would treat. According to Limbourg and Nedić,²⁰ jets produce an intricate train of vortices as well as vortex rings as a function of the nozzle geometry case. The evolution of the jet coherent structure (JCS) due to the interaction with the surrounding fluid and sustainability in the downstream direction depends on orifice shape, fluid nature, Reynolds number, and Strouhal number.²¹ Thus, the near field is primarily governed by the ratio of the nozzle diameter D to the initial momentum thickness, by the Reynolds number, and, then, by the incoming level of turbulence.²² Close to the jet limb, the axisymmetric vortical structures (vortex ring) developed as a result of Kelvin-Helmholtz instability due to the inflectional instability of the shear layer.^{23–25} A further crucial parameter is the Strouhal number (St_D) based on diameter (D) and jet bulk (or efflux) velocity (U_b). Low-frequency instability was first observed by Crow and Champagne²⁴ in the near-orifice region ($y/D = 4$) for $St_D \approx 0.3$, whereas Gutmark and Ho²⁶ observed instabilities into a range of $St_D \approx 0.3 - 0.6$ for different initial conditions. Mullyadzhazhanov *et al.*²² found that, for a high Reynolds number, no characteristics of high-frequency were observed in the near field of a jet coming out from a fully developed pipe flow. On the contrary, inside the shear layers, wide peaks in the power spectrum low-frequency range ($St_D \approx 0.14$) were observed, which could correspond to large coherent structures (helical waves) entering with the pipe flow and not connected to the Kelvin-Helmholtz instability.

Owing to the complexity of the coherent structures' motion and their scale interactions,¹⁶ a statistical approach is suggested. Namely, spectral analysis of velocities correlation functions could show characteristic frequencies or wavenumber and wavelength of the most energetic structures. The structures in a round jet can be explored by techniques such as two-point correlation to support the content that characteristic structures are present in the turbulent orifice jet flow field.²⁷ Being sure to respect all the prescriptions needed to perform the spectral analysis in the frequency domain for time-depending signals, the energy cascade suggested before by the breaking-down process may show some characteristics forecasted by the well-known

turbulent laws.²⁸ In cases of net scale separations, ensured by high enough Reynolds number and a certain distance from the orifice to allow the development of turbulence inside the jet flow, a $-5/3$ -like law could be shown.

Although a sort of convergence about the large-scale presence in the nozzle jet as well as the orifice jet in the boundary layer is achieved, there are still doubts about the nature of these coherent structures and their interaction with the smaller scales induced by velocity fluctuations. Many studies are focused on close-to-laminar inflow, consisting of a uniform flow in the pipe center and a thin boundary layer near the pipe wall. Generally, the pipe ends with an orifice plate or even a nozzle from which the jet developed,²⁹ whereas less attention was paid to the orifice jet coming out from the lateral pipe wall. As pointed out at the beginning of the introduction, many applications involve an orifice made (or generated by a fracture) in a pipe wall, in which a fluid is flowing. To investigate such a real-world situation, an experimental campaign in the laboratory was performed, where different ratios between the variable jet flow rate and the constant pipe flow rate (r_Q) were set and maintained constant during each test. As a consequence, the main targets of the present work are to investigate the influence of r_Q on the jet behavior, in terms of spatial fields of time-averaged velocity components, turbulent intensities and Reynolds shear stresses, as well as on the jet symmetry and trajectory, and on the jet potential core and large-scale organization zones. Particle image velocimetry (PIV) measurements were performed to explore the velocity fields in the near and intermediate regions of the jet and data were analyzed in terms of fields of time-averaged velocity components, turbulent intensities, Reynolds shear stresses, vorticity, and Q-criterion. The transversal velocity profiles were shown and their Gaussianity investigated via skewness and kurtosis. To the best of the authors' knowledge, the influence of r_Q on the turbulent features of the jets has not been investigated yet.

The paper is organized as follows. In Sec. II, the experimental setup, measurements, and procedure are presented. Section II A shows the experimental campaign, where, for four tests, a simple jet coming out from a circular sharp-edged orifice made in the wall of a circular pipe was considered. Into the pipe, a constant discharge was flowing, whereas the orifice jet was released into a still fluid with the same density. In Sec. III, a two-dimensional (2D) time-resolving PIV data set was used to capture the flow field in the axisymmetric section. Velocity fields were used to perform low-order moments analysis obtaining mean velocity maps and turbulent stresses maps (Sec. III A). In Sec. III B, the so-called frozen-in Taylor hypothesis verification was carried out to identify the zones where the Fourier transform can be performed. In addition, in Sec. III C, the Kolmogorov-like law was verified in a certain range of frequencies, in order to observe a cascade of energy at different points in the sampled domain. The spectral analysis was used to identify the characteristics of length scales in the core of the orifice jet as well as at the jet edge. Finally, in Sec. IV, conclusions and remarks are presented.

II. EXPERIMENTAL SETUP

In this work, an experimental campaign was carried out at the Department of Civil-Environmental Engineering and Architecture (DICAAR) of the University of Cagliari, Italy. The main target of the designed laboratory setup was to generate a circular sharp-edged orifice jet, issuing from the lateral wall of a pipe where a fluid is flowing. The fluid flowing inside the pipe is water, as well as the fluid the jet is

released into, so the conditions were the ones of a simple jet, as defined, among the others, by Fisher *et al.*³⁰ The test facility, shown in Fig. 1, consisted of a closed continuous hydrodynamic circuit with a first tank to guarantee constant upstream head, discharging through a sharp-edged orifice into a second constant downstream head tank. This tank is made with transparent Perspex walls and is 2.0 m long, 1.0 m wide, and 1.0 m high, with a volume of 2.0 m³. The fluid is then recirculated to the first tank through a pump. The tank walls were made with transparent Perspex to have optical access to the flow and to perform non-intrusive image-analysis velocity measurements.

The orifice is placed on a Perspex pipe of constant inside diameter $D_p = 64.0$ mm with divergent and convergent sections at its

upstream and downstream ends, respectively, to connect to a flexible pipe with an inside diameter $D_t = 25.4$ mm. The Perspex pipe contains the sharp-edged orifice of diameter $D = 8.0$ mm, positioned between these two sections. The sharp-edged orifice has been achieved by filing the pipe wall until a thickness of 1.0 mm was reached: by this way, the ratio of the orifice port thickness to its diameter is lower than 0.5 and can be defined, according to Nemlioglu and Yilmaz,² as a thin-walled sharp-edged port.

As shown in Fig. 1(c), the orifice is located at a distance $L_1 = 9.4D_p$ from the upstream section, where the divergent section increases the pipe diameter from D_t to D_p , and $L_2 = 1.6D_p$ from the downstream section of the pipe, where the convergent section returns

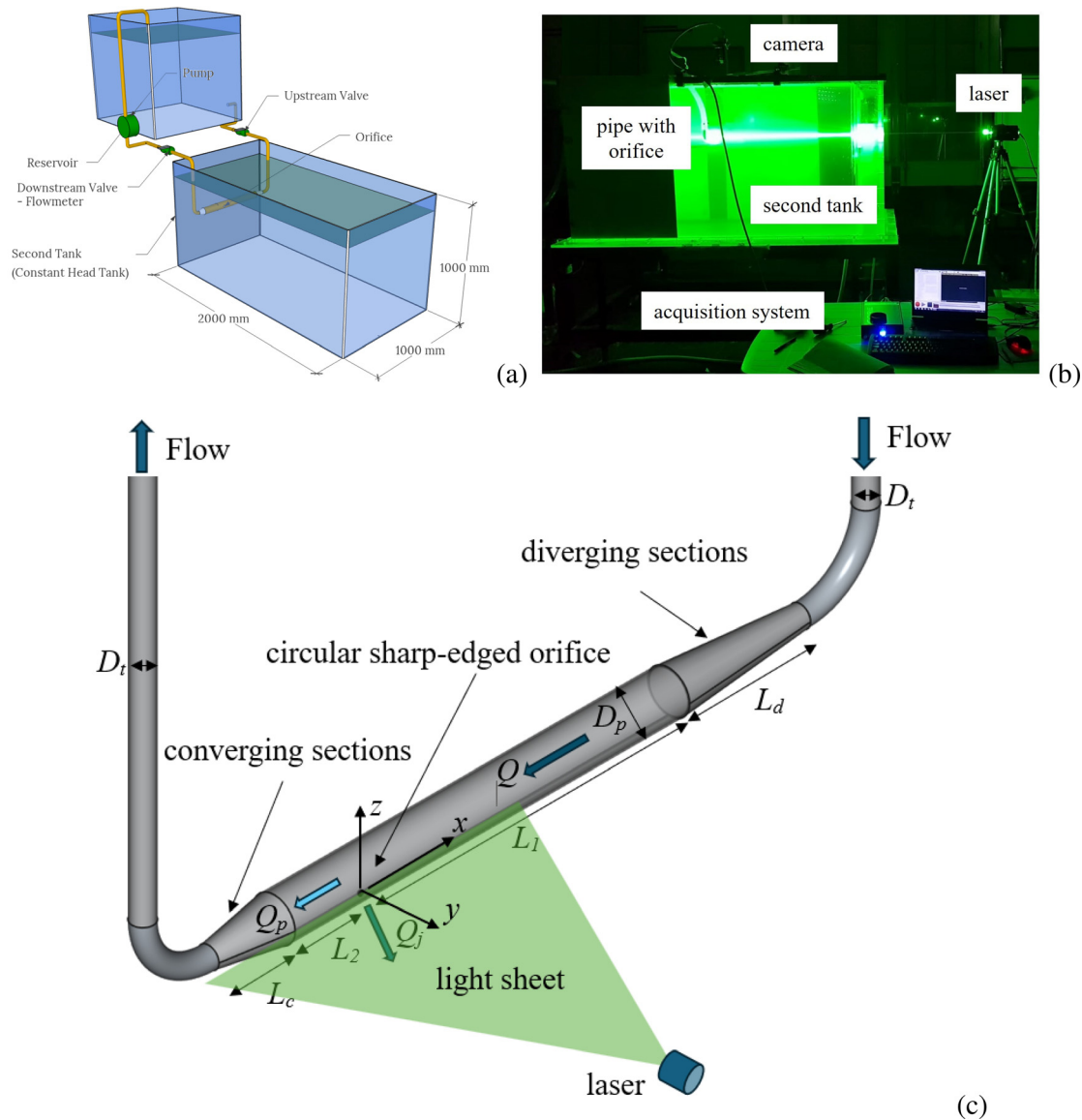


FIG. 1. (a), sketch of the experimental facility; (b), schematic of the experimental measurement setup, with the camera, laser, and the acquisition system; (c) zoom of the pipe with the divergent part, the orifice and the convergent part, light sheet, and reference frame.

the pipe diameter to D_t (with an angle less than 17°). The lengths L_1 and L_2 refer to the axial distances from the orifice to the respective ends of the Perspex tube. So, a constant flow rate Q reaches the divergent section, where the upstream pipe ends and expands toward the Plexiglas pipe. Then, a part of the flow Q_j passes from the orifice and causes the jet, while the remaining flow Q_p pursues in the pipe toward the convergent section. In accordance with Eaton *et al.*,³¹ to minimize the flow separation at the tested backward step Reynolds number, the divergent length was $L_t = 2.9D$ with a wall slope of $\approx 6^\circ$. For the same reasons, the convergent part of the pipe was $L_c = 0.78D$ long and with a wall inclination of $\approx 20^\circ$. In addition, the distance L_1 from the divergent to the orifice is large enough to ensure the flow reattachment in the case of a sudden expansion (see, e.g., Eaton *et al.*³¹) and, consequently, even more so in the present case of a gradual expansion through a divergent reach.

The two upstream and downstream bends have a curvature (the ratio of the curvature radius R_c to the diameter D_t) of around 0.66, and the distance from the end of the upstream bend to the orifice is around $31D_t$. This distance is the maximum we can set to place the pipe along the short side, avoiding eventual impinging phenomena (risk of interactions with the frontal wall). In curved pipes, the flow differs from that in straight pipes owing to the presence of a secondary motion characterized by a pair of symmetric, counter-rotating vortices. The intensity of this secondary flow can be quantified using the Dean number (De), which is defined as³²

$$De = Re \sqrt{\frac{D_t}{2R_c}}. \quad (1)$$

De in the present work is ≈ 1570 .

Smyk *et al.*,³² in agreement with Nippert,³³ observed in their numerical simulations that a complete stabilization of the flow can appear (for similar Re and De in the present work) at a distance greater than $40D_t$. Even so, some observations must be taken into considerations. Nevertheless, Ferreira *et al.*,³⁴ studying this phenomenon in similar condition, found that swirls and velocity oscillations are largely reduced already at $16D_t$.

A sharp-edged orifice was selected for two key reasons. First, previous studies^{35,36} on simple jets have demonstrated that jets released from a sharp-edged orifice exhibit higher mixing efficiency than those emitted from other configurations, such as long pipes, sudden expansions, or smooth contraction nozzles. Second, sharp-edged orifice jets are widely used across various practical applications (see, e.g., Mi *et al.*³⁷). To balance the system, two valves were placed upstream and downstream of the Perspex pipe with the orifice and maneuvered to set the discharge inside the pipe and consequently regulate the flow rate of the jet: the upstream valve was used only before the experimental campaign, to obtain the desired constant flow rate Q , while the downstream valve was adjusted before each run to obtain the desired jet flow rate Q_j .

A. Experimental campaign and conditions

The experimental campaign includes four laboratory tests, all using the same pipe configuration. In each test, all the features such as the pipe diameter, converging and diverging sections, pipe position within the tank, and orifice diameter remain equal. The four tests differ from each other for the different jet flow rates, while the pipe flow

before the orifice was kept constant. Tests conditions are reported in Table I, where D_p and D are the pipe and orifice diameter, respectively; Q represents the flow rate in the pipe upstream of the orifice; Q_p is the passing discharge; and $Q_j = Q - Q_p$ is the jet discharge [see Fig. 1(c)], from which we can define the jet flow ratio $r_Q = Q_j/Q$. U and U_j are the velocities in the pipe and flowing out from the jet, respectively; finally, the pipe Reynolds number $Re = UD_p/\nu$ and jet Reynolds number $Re_j = U_j D/\nu$ are calculated by considering the kinematic viscosity $\nu = 1.0 \cdot 10^{-6}$ for water at 20°C .

Test00 can be considered as the reference test, where the downstream valve is completely closed and all the flow running into the pipe is ejected from the orifice, i.e., $r_Q = 1$. In the remaining tests, the downstream valve was progressively opened to obtain the r_Q value in Table I. Furthermore, details about the test condition will be given in the following Sec. II A 1.

1. Measurement instruments and procedure

A Transonic 400-series flowmeter coupled with a TS410 tubing module was employed to measure the discharge in the final portion of the facility, after the convergent part of the pipe. At the beginning of each test, Q was measured in the absence of any jet by closing the orifice, while Q_p was measured once the orifice was opened, and finally, Q_j was derived.

The velocity flow field of the free jet was investigated using the PIV, a non-intrusive optical technique widely employed for fluid flow analysis. A comprehensive overview is provided in Raffel *et al.*³⁸ The PIV setup used in this work is shown on Fig. 1(b). The PIV frame, in Fig. 1(c), was oriented to have the pipe axis coincident with the x axis and the related velocity component was named u , whereas the perpendicular y axis is in the direction of the v spanwise velocity component.

The imaging system used for PIV analysis consisted of a laser to illuminate the investigation area and a high-frequency camera, integrated with an inline acquisition system. The horizontal laser sheet was generated by a diode-pumped solid-state (DPSS) continuous green laser, that emits a beam with a wavelength of 532 nm, with a cylindrical lens placed in front of it. The system consisted of an MGL-W532A-10W laser head, coupled with a PSU-W-LED power supply, by CNI (Changchun New Industries optoelectronics technology Co., Ltd.), able to produce an adjustable laser beam up to 10 000 mW. As the camera acquisition frequency increased (see below), the exposure time

TABLE I. Test conditions.

	Test00	Test01	Test02	Test03
D_p (m)	0.064	0.064	0.064	0.064
D (m)	0.008	0.008	0.008	0.008
Q (m ³ /s)	$9.07 \cdot 10^{-5}$	$9.07 \cdot 10^{-5}$	$9.07 \cdot 10^{-5}$	$9.07 \cdot 10^{-5}$
Q_p (m ³ /s)	$0.00 \cdot 10^{-4}$	$3.52 \cdot 10^{-5}$	$4.70 \cdot 10^{-5}$	$8.59 \cdot 10^{-5}$
Q_j (m ³ /s)	$9.07 \cdot 10^{-5}$	$5.55 \cdot 10^{-5}$	$4.37 \cdot 10^{-5}$	$4.81 \cdot 10^{-6}$
r_Q	1.000	0.612	0.482	0.053
U (m/s)	$2.82 \cdot 10^{-2}$	$2.82 \cdot 10^{-2}$	$2.82 \cdot 10^{-2}$	$2.82 \cdot 10^{-2}$
U_j (m/s)	$1.80 \cdot 10^0$	$1.10 \cdot 10^0$	$8.69 \cdot 10^{-1}$	$9.56 \cdot 10^{-2}$
Re	$1.80 \cdot 10^3$	$1.80 \cdot 10^3$	$1.80 \cdot 10^3$	$1.80 \cdot 10^3$
Re_j	$1.44 \cdot 10^4$	$8.83 \cdot 10^3$	$6.95 \cdot 10^3$	$7.65 \cdot 10^2$

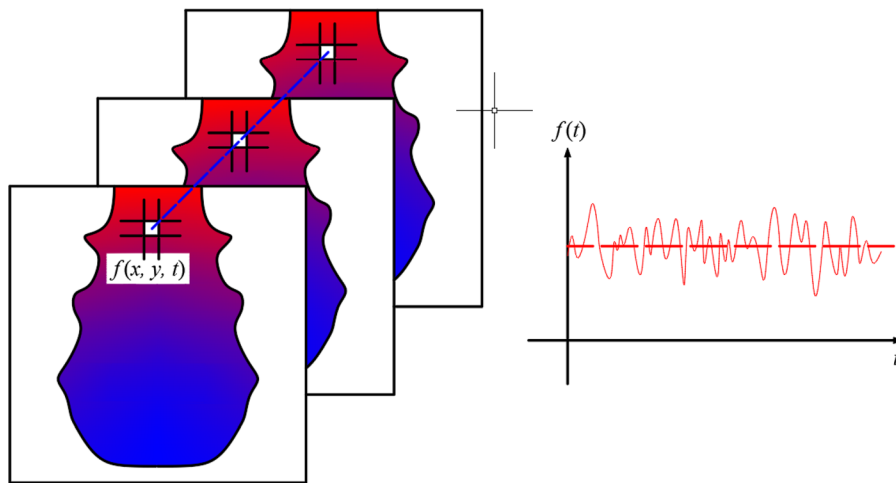


FIG. 2. Time-averaging process of a generic sampled variable $f(x, y, t)$, where for each interrogation window (fixed x and y), the averaging process was carried out in the time (t) ranging into the sampling time.

was consequently reduced and the laser power was increased to ensure the recording of particles bright enough to allow the PIV measurements. The laser sheet illuminates pine pollen non-buoyant particles (with mean diameter of 20 μm), uniformly dispersed into both the tanks before the experiments, as in Badas *et al.*³⁹ In addition, particles motion in turbulent flow confirms a high-frequency response and sufficient capacity to trace the flow up to the desired sampling frequencies. A CMOS (Complementary Metal-Oxide-Semiconductor) Mikrottron EoSens 4CXP CoaXPress camera, with a spatial resolution of $2336 \times 1728 \text{ pixel}^2$ and a Mono8 bit resolution (i.e., 256 grayscale levels), was used to capture the scattered light from the particles. The camera can record images with the full resolution at a maximum acquisition frequency of 563 Hz, while reducing the image size the acquisition frequency can be higher than 1 kHz. In the present tests, the acquisition frequency was increased from 400 Hz for Test03 to 560 Hz for Test02, 650 Hz for Test01 and 800 Hz for Test00, while the image size was reduced from $2336 \times 1728 \text{ pixel}^2$ for Test03 and Test02 down to $2336 \times 1478 \text{ pixel}^2$ for Test01 and to $2336 \times 1228 \text{ pixel}^2$ for Test00. In the latter, the camera was also rotated horizontally of 90° with respect to the other three tests, in order to have the longest image side in the jet direction, as the jet is almost perpendicular to the pipe axis. Moreover, the camera position started from a first attempt position and was adjusted for each test, after some preliminary recordings, to optimize it with respect to the jet behavior and the acquisition parameters. As a portion of the pipe had to be included in the recorded images to have a physical reference to measure the pixel/mm ratio on each test, this portion of the pipe was then deleted, as no velocity data could be found there. For these reasons, the regions of interest are different for the four tests. The acquired images were stored inline during the experiments on a storage system. Both the camera parameters and the storage system were controlled by an acquisition system. For each test, the measurement plane is placed in the middle of the pipe and so, of the orifice, which is placed along the jet central axis.

Although Uzol and Camci⁴⁰ deemed reliable turbulence statistics by using 1000 samples, the used datasets for each test encompass 20 000 image samples. The data were processed using the DynamicStudio software provided by DANTEC. The particle images were divided into an equally spaced grid of $16 \times 16 \text{ pixel}^2$, with an adaptive interrogation window with a minimum size of $16 \times 16 \text{ pixel}^2$,

an a maximum one of $128 \times 128 \text{ pixel}^2$, with a minimum of 50% overlap, to calculate spatial correlation and generate velocity vectors.

In this work, according to Fig. 2, the time-averaging process was used to decompose the time-dependent generic function (or signal) $f(x, y, t) = \bar{f} + f'$, where $\bar{f}$ represents the time-averaged value of the global function f , whereas f' is its time-depending fluctuation component.

According to the technical literature,^{41,42} the experimental uncertainties of velocity components ($\varepsilon_{u'}$ and $\varepsilon_{v'}$), RMS fluctuations ($\varepsilon_{u'}(RMS)$ and $\varepsilon_{v'}(RMS)$) and Reynolds shear stress ($\varepsilon_{u'v'}$) have been evaluated and are presented in Table II. Note that all the uncertainties are normalized by using U_j . σ'_u and σ'_v represent the normalized levels of velocity fluctuations for u' and v' , respectively, whereas R^2_{uv} denotes the cross correlation coefficient between u' and v' . Finally, N refers to the number of samples.

Finally, the spatial resolution of the PIV measurements was compared with the Kolmogorov length scale, $\eta = (\nu^3/\varepsilon)^{1/4}$, where ε is the viscous dissipation, defined as $\varepsilon = 15\nu(\partial v/\partial y)^2$, $\partial v/\partial y$ representing the gradient of the velocity fluctuation. In all tests, the Kolmogorov length scale was smaller than the spatial resolution, implying that the dissipation range was not fully resolved. Nevertheless, the present resolution was sufficient to capture a significant portion of the inertial sub-range, as illustrated in Secs. III B and III C.

III. RESULTS AND DISCUSSION

The subsequent paragraphs present the time-averaged measurements of velocity and stresses. These measurements are crucial for understanding the dynamics of the jets. These results are useful to identify regions of turbulence and assess the efficiency of fluid transport mechanisms. Similarly, time-averaged stress measurements provide valuable information on the distribution of forces. Furthermore, in this paragraph, we perform the Taylor hypothesis validation, which is preliminary to the spectral analysis used for computing the characteristics scales dominating these types of jets.

A. Time-averaged low-order moments

We explore the characteristics of the jet, throughout both time-averaged velocity components, $\bar{u}$ parallel to the pipe axis and $\bar{v}$

TABLE II. Uncertainty analysis.

	Test00	Test01	Test02	Test03
$\varepsilon_{u'} = \sigma'_{u'}/(U_j/\sqrt{N})$	$1.34 \cdot 10^{-3}$	$8.62 \cdot 10^{-4}$	$9.25 \cdot 10^{-4}$	$1.33 \cdot 10^{-3}$
$\varepsilon_{u''} = \sigma'_{v'}/(U_j/\sqrt{N})$	$1.65 \cdot 10^{-3}$	$1.18 \cdot 10^{-3}$	$1.21 \cdot 10^{-3}$	$1.55 \cdot 10^{-3}$
$\varepsilon_{u'}(RMS) = \sigma'_{u'}/(U_j/\sqrt{2(N-1)})$	$9.47 \cdot 10^{-4}$	$4.17 \cdot 10^{-4}$	$6.54 \cdot 10^{-4}$	$9.41 \cdot 10^{-4}$
$\varepsilon_{v'}(RMS) = \sigma'_{v'}/(U_j/\sqrt{2(N-1)})$	$1.16 \cdot 10^{-3}$	$8.37 \cdot 10^{-4}$	$8.61 \cdot 10^{-4}$	$1.10 \cdot 10^{-3}$
$\varepsilon_{u'v'} = \sigma'_{u'}\sigma'_{v'}/(U_j^2/\sqrt{(1+R_{uv}^2)/(N-1)})$	$4.76 \cdot 10^{-4}$	$3.56 \cdot 10^{-4}$	$3.25 \cdot 10^{-4}$	$4.37 \cdot 10^{-4}$

perpendicular to it. Note that in the following figures the x and y coordinates were made dimensionless by the orifice diameter.

In Fig. 3, $\bar{v}/U_j$ (left column) and the $\bar{u}/U_j$ (right column) velocity maps are shown for the four tests. Note that for $\bar{v}/U_j$ we consider positive the velocity going up to down, whereas for $\bar{u}/U_j$ we take positive the velocity moving according to the pipe flow direction (right to left).

Figure 3(a) shows that, in Test00 and Test01, positive $\bar{u}$ velocities (toward the orifice center) are visible for $y/D < 1.5$, whereas a velocity inversion can be seen for $y/D > 1.5$. This behavior is in accordance with the straight behavior observed in Gori *et al.*⁴³ for comparable Re_j numbers, even if in Test01 the jet is not perfectly straight. Nevertheless, the $\bar{u}$ map shows a slight asymmetry, in the near region, with respect to the jet centerline, probably since the flow does not approach the orifice perpendicularly. So, the jet with $r_Q = 1$ (Test00), as expected in the case of a round simple jet, follows a straight trajectory perpendicular to the orifice plate and a symmetric behavior, both for $\bar{v}/U_j$ and $\bar{u}/U_j$. However, when r_Q decreases, from 0.612, in Fig. 3(c) (Test01), to 0.053, in Fig. 3(g) (Test03), a different behavior arises: the more r_Q decreases, the more the jet trajectory tends to form an angle with the direction perpendicular to the orifice plate and to lose its symmetry. In addition, the decrease in r_Q also biases the distribution of the $\bar{u}/U_j$, with the positive components (the ones with the same direction of the flow inside the pipe) tending to prevail over the negative ones, which explain the inclined direction of the jet. In Test02 and Test03, the $\bar{u}$ component of velocity becomes greater as r_Q decreases. Finally, small negative values of $\bar{u}$ in Test02 are visible in the jet portion where enlargement is recognizable (at the left side of the orifice for smaller y/D), whereas in Test03 a weak negative $\bar{u}$ area is located adjacent to the downstream limb of the orifice and a second negative $\bar{u}$ area is evident between $10 > y/D > 5$ and $-10 < x/D < -7$ (not visible, owing to the color scale limit). The almost complete absence of the negative $\bar{u}$ zone in the right side maps (i.e., where $x/D > 0$) suggests that it is responsible for the one-side jet divergence and the inclination of the jet with respect to the orifice perpendicular direction.

In addition, as expected, in all the tests, $\bar{v}$ is approximately equal to the efflux velocity near the orifice, with a subsequent decay as moving away. Test00 and Test01 results are consistent with the Gori *et al.*⁴³ findings, that show an almost constant velocity profile up to $y/D = 7$ for similar Re_j . The constant velocity profile is reduced at about $y/D = 2$ in Test02 and $y/D = 1$ in Test03, which are considered the lengths of the potential core.⁴³

In summary, in Test00 and Test01, the ones with the highest r_Q , an almost canonical straight and axisymmetric jet behavior occurs, with the jet diverging almost specularly with respect to the orifice center

($x/D = 0$). A slightly inclined jet was observed in Test02 for a reduced distance $y/D < 0.5$, whereas the jet deviated from the orifice perpendicular direction for $y/D > 0.5$. Finally, in Test03, the jet at the orifice limb and no straight neither axisymmetric jet behavior was observed. Hence, we can speculate that the jet is laterally spread, owing to jet-edge instabilities induced by the velocity gradient between the jet and the surrounding fluid, as r_Q decreases. This can be due to the velocity inside the pipe that interacts asymmetrically with the orifice limb as r_Q diminishes. To corroborate this speculation more investigations are required, involving also the velocity inside the pipe.

Following Gori *et al.*,⁴³ the zone of flow establishment, in which the velocity on the centerline is comparable to the efflux velocity, can be observed in Test00 for $y/D < 4.2$ and in Test01 for $y/D < 2.0$, where the jet is laterally confined (constant width). The zone of established flow takes place in the range $y/D > 4$ in Test00 and $y/D > 2$ in Test01, where the jets spread out and the regions of mixing fluid develop up to reach the core of the jets. In Test02 and Test03, the establishment zone is not visible, as it can be influenced by the asymmetrical interaction of the jet flow with the orifice limb, promoting different mixing processes with respect to the case in which the efflux is almost perpendicular to the orifice.

Figure 4 shows the normalized velocity magnitude ($\mathbf{u}^+ = \mathbf{u}/U_j$) superimposed with time-averaged streamlines. The velocity magnitude is defined as $\mathbf{u} = \sqrt{\bar{u}^2 + \bar{v}^2}$.

The streamline topology revealed a straight behavior in the core of the jet for all the tests, suggesting that the fluid velocity direction is uniform throughout the field. This implies that the fluid particles move along straight and parallel trajectories, without any change in direction, before they expand radially. In particular, in Test00 and Test01, the streamlines remain parallel to the jet direction for $y/D < 7$, whereas in Test02 and Test03 they are parallel for $y/D < 2$ and then, according with r_Q , decreases. Although the velocity magnitude varies with the distance from the orifice, the direction remains preserved within the aforementioned ranges. In addition, the streamline topology at the jet edge, confirms the suction of surrounding still water due to flow acceleration in the near-field region, as discussed above. Finally, the streamline parallelism does not necessarily imply the absence of vorticity that is expected where velocity gradient is observed and then the streamline thickening.

Additional insights on the mean flow are obtained with profiles of the time-averaged resultant velocity ($\bar{u}_r$) normalized with U_j , taken along an inclined coordinate (ξ) following the jet centerline at distances $\xi/D = 1, 3, 5, 7$, and 9, as shown in Fig. 5. Note that the coordinate ξ represents the distance from the orifice along the resultant velocity

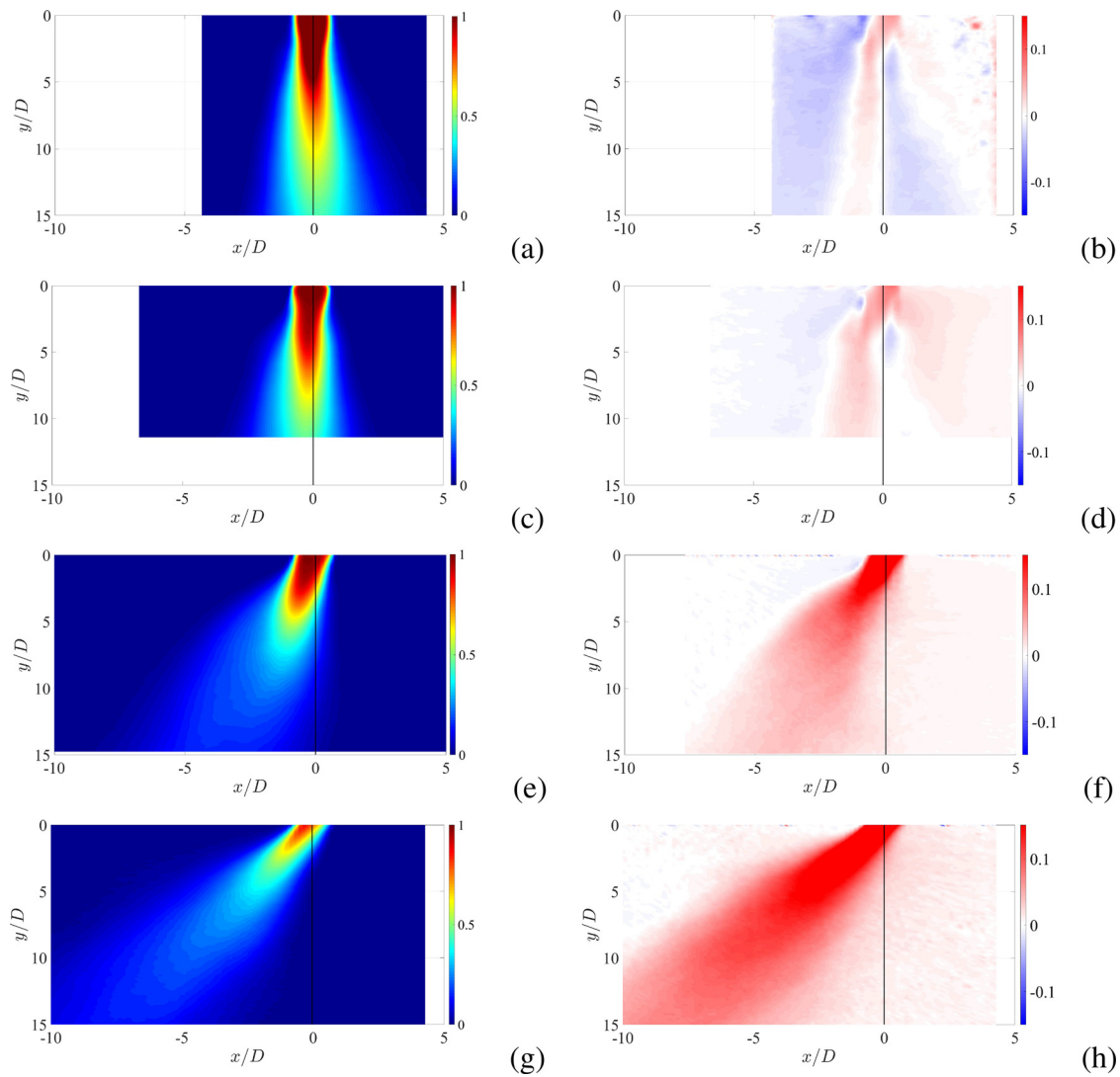


FIG. 3. Time-averaged velocity maps. In the left column, $\bar{v}/U_j$ are shown; (a) Test00 ($r_Q = 1.000$), (c) Test01 ($r_Q = 0.612$), (e) Test02 ($r_Q = 0.482$), and (g) Test03 ($r_Q = 0.053$). In the right column, $\bar{u}/U_j$ maps are shown; (b) Test00, (d) Test01, (f) Test02, and (h) Test03. Black vertical lines represent the orifice central axis.

direction in the near region of the orifice efflux and at the center of the orifice itself.

The $\bar{u}_r$ profiles exhibit distinct features modulated by the r_Q ratio. The condition $r_Q = 1.000$ shows canonical axisymmetrical profiles from the vicinity of the orifice up to the explored distance.^{44–46} As the ratio $r_Q = 0.612$, $r_Q = 0.482$ decreases a non-symmetrical saddle-backed profile is shown for the closer profile position $\xi/D = 1$. In contrast, in Test03 ($r_Q = 0.053$), the closer profile is characterized by a thin single-peak compared to the other tests. This behavior can be ascribed to the development of a non-symmetrical shear layer due to the wall shear inside the pipe. A further interesting point is the displacement of the velocity distributions peak for the furthest distances from the orifice in tests with the lowest r_Q ratios, consistently with the findings of Ferrari *et al.*⁴⁷

According to Ghaem-Maghani and Johari,⁴⁵ $\bar{u}_r$ profiles can be fitted by a Gaussian distribution. Here, Skewness (Sk) was used to measure the lack of symmetry and Kurtosis (Ku) to analyze heavy or light-tailed relative to a normal distribution. In Fig. 6(a), for all the tests, closer to the orifice Sk approach the value of 1 suggests that the velocity profiles are skewed to the downstream side of the orifice. Moving away, to the orifice position Sk decays according to the r_Q ratio. Test00 and Test01, which are the most similar to the canonical jet behavior, tend to approach the neutral value of skewness suggesting a normal organization of the velocity profile ($Sk < 0.5$) further away from the orifice ($\xi/D \geq 7$).

Test02 and Test03 show positive values of Sk closer to the orifice and negative values for further away positions, suggesting a displacement of the velocity profile from the downstream side to the upstream side (according to the pipe flow direction). This behavior is traduced

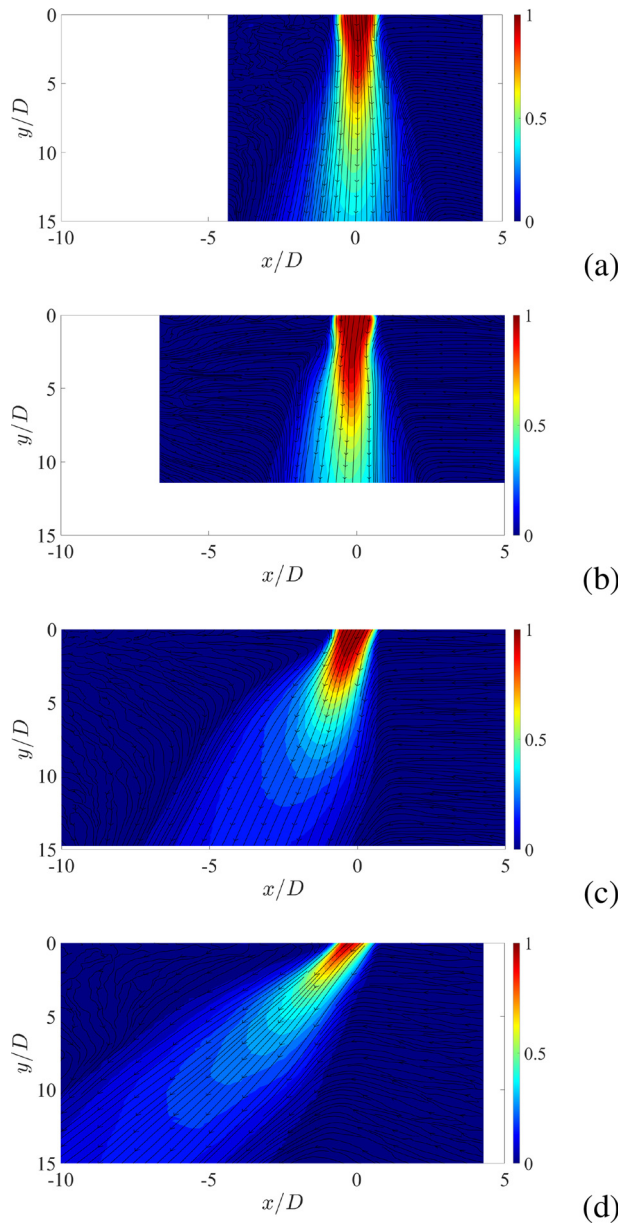


FIG. 4. Normalized velocity magnitude superimposed to time-averaged streamlines represented by the black lines. (a) Test00, (b) Test01, (c) Test02, and (d) Test03.

in a double curvature of the jet along the jet direction for the jet having the lowest r_Q ratios. Finally, Fig. 6(b) shows Ku distribution providing insight into how edge velocities of the jet behave relative to the mean velocity. For all the tests, Ku is slightly smaller than 3 along the explored ξ/D range, which means that there is a tendency to platykurtic distributions instead of a normal distribution used to predict the velocity issuing from an orifice made in the lateral wall of a pressurized pipe. In particular, tests with a high ratio of r_Q (Test00 and Test01) show a Ku distribution with a downward concavity and a decrease in Ku as ξ/D increases. In contrast, an opposite behavior was observed in

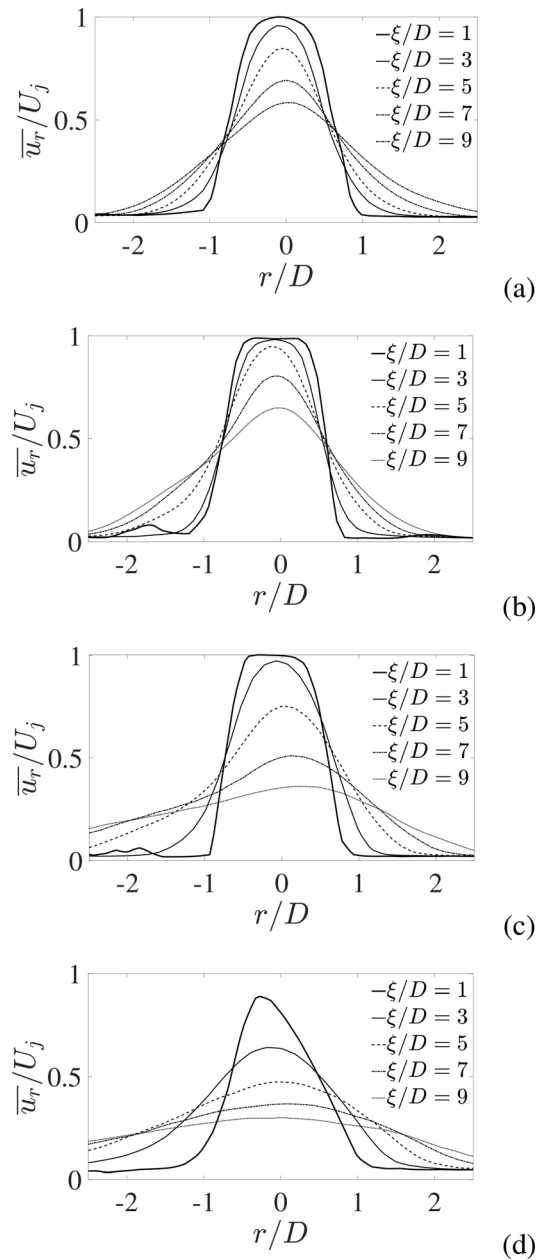


FIG. 5. Time-averaged resultant velocity profiles at different positions from the orifice along the jet direction. (a) Test00, (b) Test01, (c) Test02, and (d) Test03.

tests with lower r_Q (Test02 and Test03). This fact suggests that, in Tests02 and Test03, the interaction of the jet with the downstream lip of the orifice promotes a non-axisymmetric mixing with the surrounding still water decreasing the similitude with a normal distribution of the jet down to $\xi/D \approx 4-5$, and then, an increase in Ku is observed for further away distance, probably ascribed to the momentum redistribution along r/D . We underline that more investigations are needed to shed light on this fact, suggesting future lines of research (both experimental and numerical).

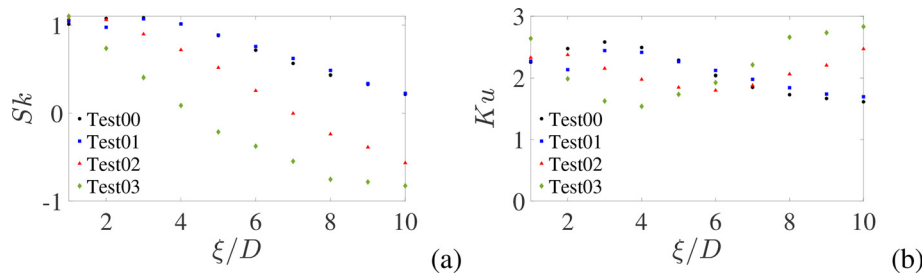


FIG. 6. Skewness (panel a) and Kurtosis (panel b) tests for the time-averaged resultant velocity profiles along the dimensionless coordinate ξ/D .

In Fig. 7, the normalized turbulence intensity perpendicular to the orifice ($\overline{v'^2}/U_j^2$, left column) and parallel to it ($\overline{u'^2}/U_j^2$, right column) are shown for all the tests. Note that the prime symbol refers to fluctuation and the overbar to the time-averaged quantities.

The $\overline{v'^2}/U_j^2$ maps reveal a turbulent zone in the proximity of the orifice limb for Test00 and Test01. These high-turbulent zones are large according to the Re_j magnitude. The low turbulent intensity visible in the core of the jets, inside the near-field region, is due to the

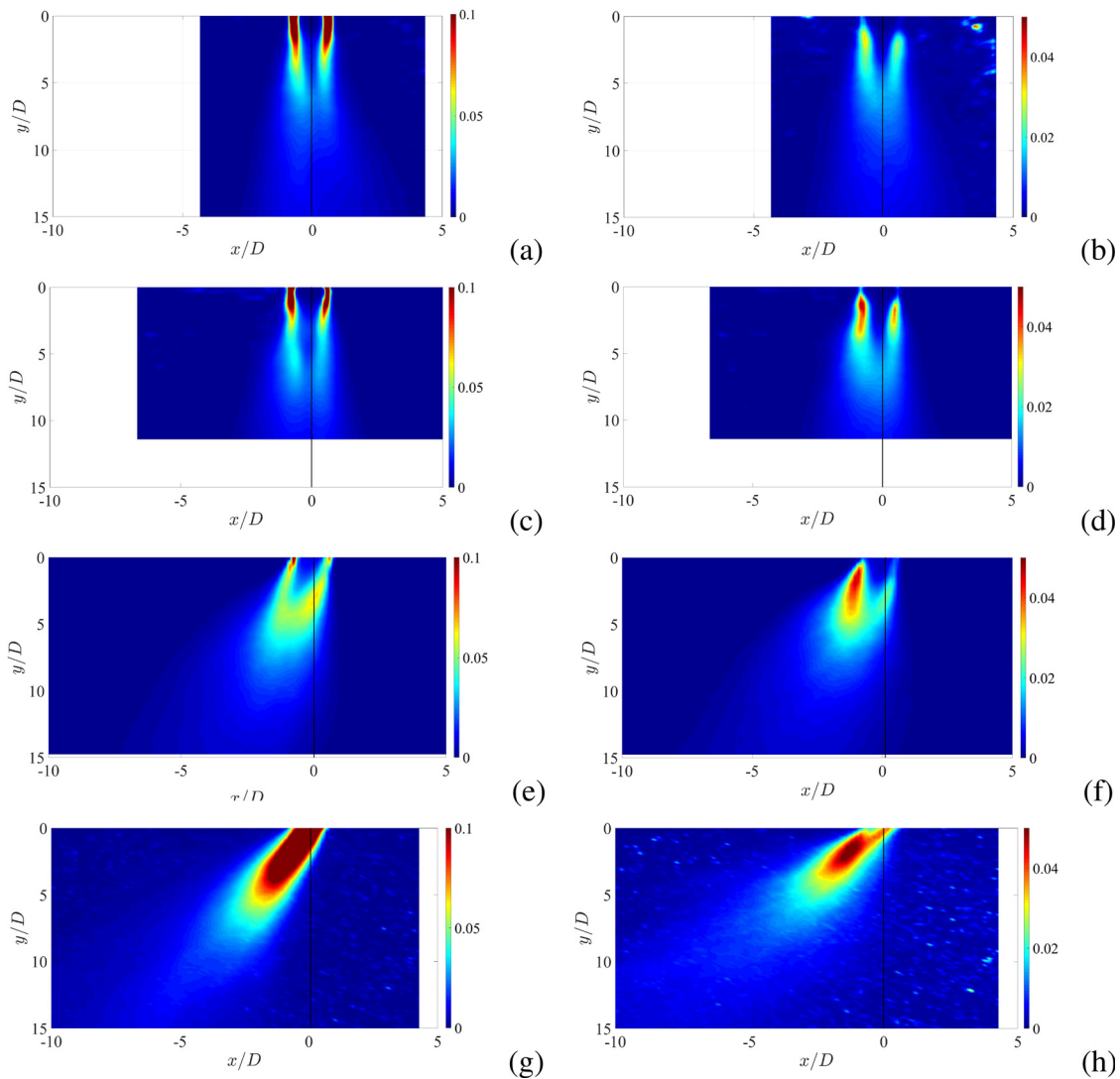


FIG. 7. Normalized turbulence intensities maps $\overline{v'^2}/U_j^2$ are shown in the left column; (a) Test00 ($r_Q = 1.000$), (c) Test01 ($r_Q = 0.612$), (e) Test02 ($r_Q = 0.482$), and (g) Test03 ($r_Q = 0.053$). Normalized turbulence intensities map $\overline{u'^2}/U_j^2$ are shown in the right column; (b) Test00, (d) Test01, (f) Test02, and (h) Test03. Black vertical lines represent the orifice central axis.

large-scale formation, as also suggested by Ball *et al.*²⁹ In Test02, similarly to Test00 and Test01, a large-scale formation zone is observable for a reduced distance ($y/D < 2.5$); after that, an annular mixing region can be observed for $y/D > 6$. Finally, in Test03, no jet core region associated with low $\overline{v'^2}$ value is visible, as the asymmetrical interaction of jet flow with respect to the orifice limb promotes an increase in $\overline{v'^2}$ closer to the orifice, that survives down to $y/D \approx 5$, and a subsequent decay of the turbulent intensity can be observed for $y/D > 5$. In the near region of Test00 and Test01, the high intensity of $\overline{u'^2}$ suggests, also, a suction effect, namely, the annular mixing region

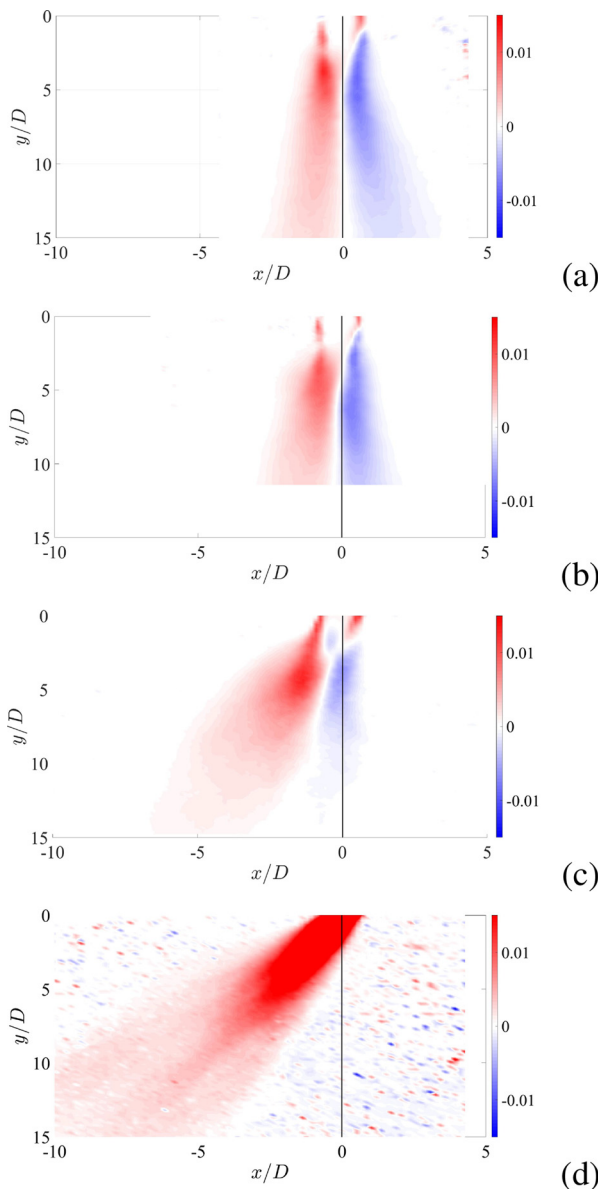


FIG. 8. Normalized shear stress maps $\overline{u'v'}/U_j^2$. (a) Test00 ($r_Q = 1.000$), (b) Test01 ($r_Q = 0.612$), (c) Test02 ($r_Q = 0.482$), and (d) Test03 ($r_Q = 0.053$). Black vertical lines represent the orifice central axis.

surrounding the core of the jet promotes the vortex roll-up, that penetrates the core of the jet; consequently, $\overline{u'^2}$ and $\overline{v'^2}$ show comparable intensity level. This process is consistent with the model proposed in the literature.²⁹ Finally, $\overline{u'^2}$ decreases as the potential core end and the mixing layer develop. It is worthwhile to note that, even in Test00, the $\overline{u'^2}$ distribution is never perfectly symmetric, with higher values on the left orifice limb (opposite to the flow motion inside the pipe), which highlights that, even in the case of Test00 with $r_Q=1$, the jet cannot be considered perfectly symmetric. In Test02 the vortex roll-up effect, described above, is reduced since $\overline{u'^2}$ and $\overline{v'^2}$ show different intensities, suggesting elongated coherent structures inside the jet radial edge. In Test03 the annular mixing layer completely disappears and no annular turbulent intensity can be observed.

In Fig. 8, the normalized shear stress maps are shown for all the tests.

The $\overline{u'v'}/U_j^2$ results in Test00 and Test01 are similar, once again, to a perpendicular jet issuing from the orifice plane. As expected, elongated tails of antisymmetric shear stress are shown with respect to the centerline.⁴⁵ Following the observation of Xu *et al.*,⁴⁶ the highest values are located along the half-radius of the orifice, reaching their maximum (absolute) values at $y/D > 8$ in Test00 and $y/D > 4$ in Test01, according to the Re_j decrease, whereas the shear stress is almost zero along the centerline. In Test02, the shear stress is thrown in the pipe flow direction observing asymmetric positive and negative shear stress tails. This trend is magnified in Test03, where no negative shear stress was observed.

Similar to Ali and Tariq,⁴⁸ vorticity and Q -criterion distributions are shown for all the tests. In particular, Fig. 9 shows the normalized vorticity ($\omega^+ = \omega D/U_j$) superimposed to velocity direction represented by arrows, and the normalized $Q^+ = QD^2/U_j^2$ superimposed to time-averaged streamlines. The out-of-plane vorticity is defined as $\omega = \partial v/\partial x - \partial u/\partial y$, and the normalized Q -criterion is defined as $Q = 0.5(|\Omega|^2 - |S|^2) = -0.5[\frac{\partial u}{\partial y} \frac{\partial v}{\partial x}]$.

Figures 9(a), 9(c), 9(e), and 9(g) show the out-of-plane ω^+ distribution that, as anticipated, identifies the vorticity where a velocity gradient is present, namely, at the jet edge with the highest value located at the orifice proximity. Blue and red areas identify the presence of anticlockwise and clockwise vortices, respectively, which are the track of annular instabilities (vortex roll-up) observed on the literature.^{29,49} As expected, owing to the direct proportionality between shear stress and vorticity, high vorticity regions correspond to regions of significant shear stress by Batchelor.⁵⁰ Hence, the observed symmetry in shear stress of Test00 and Test01 is also observed here. Moreover, the losses of symmetry in the shear stress distribution as r_Q decrease were observed also in the vorticity distribution. Figures 9(b), 9(d), 9(f), and 9(h) show the normalized Q^+ . Positive value of Q^+ is associated with regions of strong rotation, whereas negative Q^+ denotes region of dominant shear strain as observed in all the tests. In fact, $Q^+ < 0$ is located in annular regions in the orifice proximity where velocity gradient as well as vorticity are dominant. The overlap between ω^+ and Q^+ distributions, due to the roll-up entrainment of fluid from the surrounding flow, propagates downstream, as demonstrated by Anghan *et al.*⁴⁹ Their findings suggest that the vortex ring originates at the orifice lip, as also discussed above. This view aligns with the observations from Test00 and Test01, where the jet direction remains nearly perpendicular to the

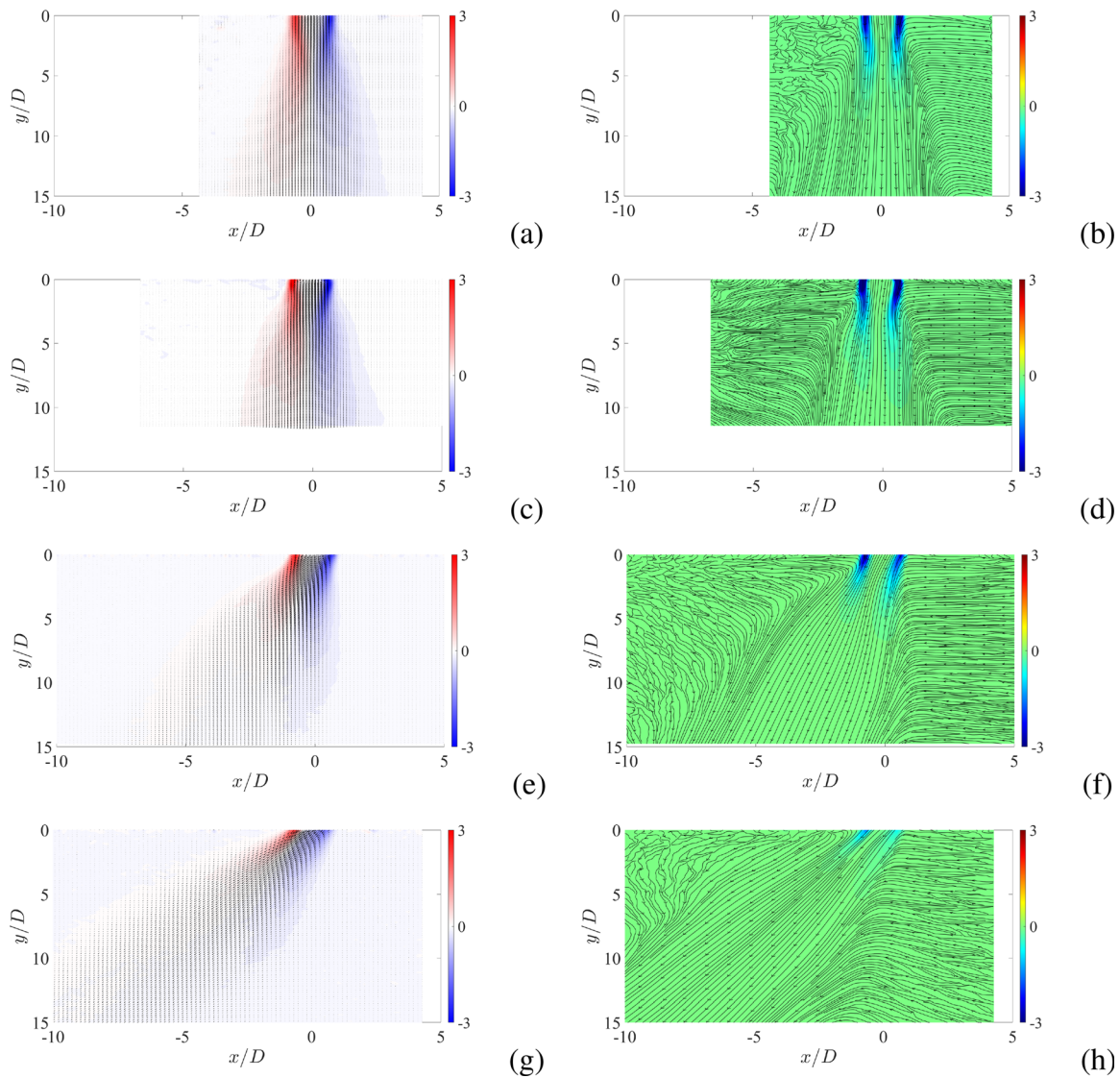


FIG. 9. Normalized vorticity superimposed to velocity direction represented by arrows. (a) Test00, (c) Test01, (e) Test02, and (g) Test03. Normalized Q-criterion superimposed to time-averaged streamlines. (b) Test00, (d) to Test01, (f) to Test02, and (h) Test03.

orifice plane. However, in Test02 and Test03, the progressive deviation from perpendicularity between the efflux jet direction and the orifice plane, along with the interaction between the jet and the downstream lip of the orifice, promotes non-axisymmetric mixing. This process disrupts vortex roll-up formation and leads to the Q^+ value approaching zero.

TABLE III. Taylor hypothesis verification.

	Test00	Test01	Test02	Test03
λ_T (m)	$3.53 \cdot 10^{-5}$	$4.52 \cdot 10^{-5}$	$5.09 \cdot 10^{-5}$	$1.54 \cdot 10^{-4}$
λ_K (m)	$4.20 \cdot 10^{-9}$	$8.09 \cdot 10^{-9}$	$1.11 \cdot 10^{-8}$	$2.11 \cdot 10^{-7}$

B. Taylor hypothesis verification

The second-order statistics of turbulence are analyzed by the correlation function and the power spectra of the velocity fluctuations, by considering the validity of the Taylor hypothesis, that can be defined as $\bar{v}(x, y) \gg \sigma_{v(x, y)}$ with $\sigma_{v(x, y)} = \sqrt{v'^2(x, y)}$. Namely, local streamwise velocity should be much larger than the variance of the velocity fluctuations. Thus, the following analyses are confined to the areas in which the Taylor hypothesis is respected in the tests: namely, inside the jet and close to the jet edges. In addition, to determine whether a net scale separation between the larger (energy-containing) scales and the smaller dissipative scales exists, we calculated the Taylor microscale as $\lambda_T \approx Re_j^{-1/2} D$, which is related to the inertial subrange, and the

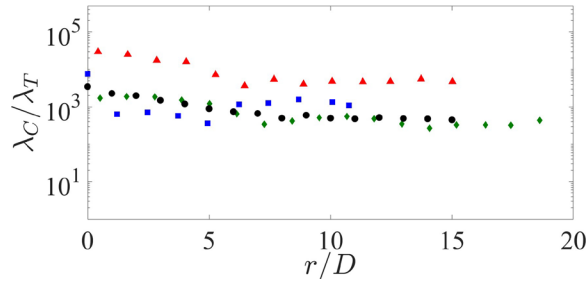


FIG. 10. Integral length scale and Taylor microscale comparison along the jet centerline. Black bullets refer to Test00, blue squares to Test01, red triangles to Test02, and green diamonds to Test03.

Kolmogorov dissipation scale $\lambda_K \approx Re_j^{-3/2} D$, that approximates the size of the smallest eddies⁵¹ (see Table III).

In turbulent flows, when considering a time-averaged velocity for a specific point, the flow autocorrelation function can be defined as $C(x, y, \tau) = \overline{v'(x, y, t)v'(x, y, t + \tau)}$. Using the Taylor hypothesis, the lag time can be converted into space increments as $C(x, y, \tau) \rightarrow C(x, y, r)$, where $r = |\bar{v}|\tau$. Hence, the correlation length, which approximates the size of the biggest eddies, can be defined as follows:

$$\lambda_C = \frac{1}{C(x, y, 0)} \int_0^{r_{max}} C(x, y, r) dr, \quad (2)$$

where r_{max} represents the maximum space increment corresponding to a value of the autocorrelation function equal to the noise level.

Finally, we can compare the Taylor microscale with the energy-containing scale λ_C . Note that, in the present study, the diameter of the orifice provides the characteristic size. In Fig. 10, the quantity λ_C/λ_T is shown along the centerline of the jets. In all the tests, a net scale separation is present, with more than one order of magnitude.

Although this analysis is a rough test of the scale separation, it is preparatory to the spectral analysis and to the expectation of the inertial subrange observation.

C. Spectral analysis

Analyzing turbulence through second-order statistics involves studying the correlation function and spectral density of velocity fluctuations. Through the spectral analysis, we gathered significant insights into turbulence dynamics and calculated these statistics throughout the jet centerline. As introduced in the previous sections, the interaction between the orifice limb and the jet flow leads to the birth of the mixing layer and to an increase in turbulence moving away from the orifice itself, reaching a maximum value and a subsequent decrease as the jet loses energy. This process induces large-scale motion organization, and thus, energy-containing scales are born into the jet core in the near region. Afterward, these vortices break down in smaller scales down to eddies dimensions that drop in the dissipation range where energy is converted into heat. This aspect is marginally studied in simple jet cases and little is known about the cascade of energy in the configuration presented in this study. To prove the existence of the inertial subrange and a sign of the Richardson cascade⁵² existence, we performed the spectral analysis of the autocorrelation functions of the velocity fluctuations. The spectral densities were computed as follows.

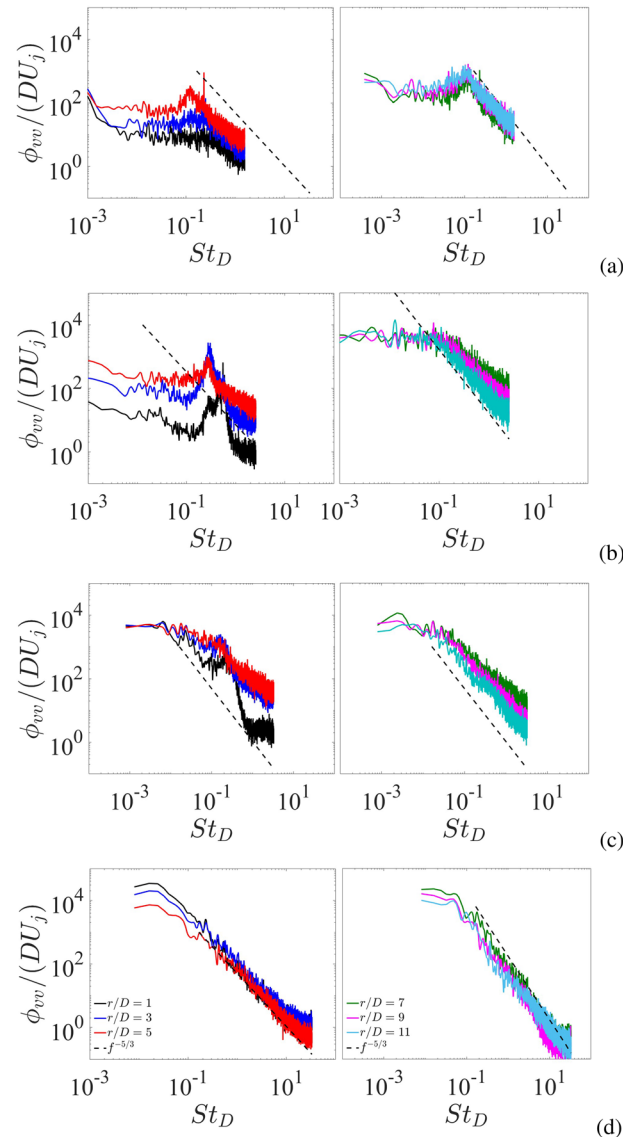


FIG. 11. Spectral density of $C(x, \tau)$. (a) Test00 ($r_Q = 1.000$), (c) Test01 ($r_Q = 0.612$), (e) Test02 ($r_Q = 0.482$), and (g) Test03 ($r_Q = 0.053$). Dashed lines represent the Kolmogorov scaling law.

The autocorrelation functions $C(x, y, \tau)$ were calculated and the Fourier transform was applied to it and tapered with a Hann window, leading to the spectral density in the frequency domain. Finally, this procedure was used to compute the spectra at different streamwise locations along the jet centerline. Fellouah *et al.*⁴⁴ demonstrated a dependence of $v - velocity$ spectra on Re_j to develop the Kolmogorov inertial subrange. These authors fixed a limit of $Re_j > 3 \cdot 10^4$ to observe the inertial subrange. In Test00 and Test01, Re_j is closer than the limit suggest by Fellouah *et al.*;⁴⁴ nevertheless, in Test02, which shows a Re_j lower than the above limit, the inertial subrange is visible in certain positions. The spectral density is depicted in Fig. 11 for different locations (multiples of the orifice diameter) along the jet

centerline. Note that the frequency domain was converted in the non-dimensional Strouhal frequency, defined as $St_D = fD/U_j$.

As a first observation, in Figs. 11(a)–11(c) left panels (near position to the orifice in Test00, Test01, and Test02, respectively), for $r/D = 1, 3$, and 5 , no clear Kolmogorov scaling law can be observed. This is consistent with Figs. 7(a), 7(c), and 7(e), where the presence of large-scale organization area in positions closer to the orifice was hypothesized. A net energy injection is recognizable at $St_D = 0.2$ – 0.5 , which corresponds to a dimension approximately equal to 5 times the orifice diameter, as also observed by Burattini *et al.*⁵³ The energy injection in the near region is in accordance with the finding of Fellouah *et al.*,⁴⁴ who observed the same peaks in tests with comparable Re_j and in the same r/D positions, where the increased energy content suggested the formation of coherent structures. In addition, the presence of an energy peak in the spectra at $St_D \approx 0.5$, observed near the orifice, which tends to diminish as Re_j increases, is consistent with the observations of Anghan *et al.*⁴⁹ They attributed this spectral peak to the roll-up frequency. Moving away from the potential core region and once the mixing layer is completely developed, spectra show a Kolmogorov-like scaling law. As shown by Ferraro *et al.*,⁵⁴ a slight flat slope on the spectra can be attributed to the presence of large energy-containing structures, that can be anisotropic. This is not surprising, given the shear nature of such jets. In Test03, the absence of the potential core and then the large-scale organization region in the near-field region [see Figs. 7(g) and 7(h)] is also reflected at the position closest to the orifice [Fig. 11(d)]. Namely, the absence of a jet potential core region, probably destroyed by the jet interaction with the limbs orifice, does not allow large-scale organization. Thus, in Test03, the mixing layer is expected owing to the closest positions to the orifice. This speculation is supported by the Kolmogorov-like scaling law of the spectra at $r/D < 5$.

IV. CONCLUSIONS

Although the dynamics of circular simple jets has been extensively studied, there are still unresolved issues that need to be addressed with the support of theory and tests. Even if the studied configuration has practical implications in many engineering fields such as the dispersion of pollutants in marine environments, aquaculture feeding strategy, and so on, it was marginally studied.

In particular, most of the investigations on this topic assume the jet to be axisymmetric and perpendicular to the pipe axis, very few focus on the inclination of the trajectory and no one, to the best of the authors' knowledge, investigated the influence of r_Q on the velocity-related features of the jets. As a consequence, in the present work, we have investigated experimentally, in a laboratory of Hydraulics, the effect of r_Q on the features of four jets issuing from a sharp-edged orifice, made in the wall of the pipe, with four different r_Q (i.e., jet velocities). Hence, a reference test (Test00), where $r_Q = 1$ (i.e., the entire flow discharges in the pipe exits from the orifice) was performed. Then, Test00 was compared with the remaining three tests where a certain flow passed over the orifice section (that is, where r_Q decreased).

PIV measurements have allowed exploring the velocity fields in the near and intermediate regions of the jet, contributing to update the literature state of the art related to submerged turbulent free jets. Data have been presented in terms of temporally averaged velocity fields turbulent intensities, Reynolds shear stresses, vorticity, and Q-criterion. The transversal velocity profiles were shown and their

Gaussianity investigated via skewness and kurtosis. Furthermore, a spectral analysis was performed.

The macroscopic analysis of the experimental results reveals features that are in agreement with previous studies for the reference test (Test00) and the ones with the highest tested r_Q (Test01) where a close behavior similar to the canonical simple jet was observed, whereas the remaining tests (with the lowest tested r_Q) progressively forsake such characteristics. The effect of the r_Q parameter was demonstrated not only along the direction perpendicular to the jet, but also along the jet direction which is more inclined as r_Q decreases. In addition, as r_Q decreases, the velocity-related features move over from the canonical velocity fields and profiles, as well as the turbulence intensities and the Reynolds shear stress distributions. In particular, the extension of the potential core region decreases as r_Q diminishes until no core region was observed in Test03. On the contrary, the mixing layer develops as close to the orifice as the r_Q becomes greater. Taylor hypothesis verification was preparatory to the second-order statistics of turbulence, analyzed by the correlation function and the power spectra of the velocity fluctuations. The Taylor hypothesis was verified only along the central axis inside the jet. Spectral analysis revealed that, inside the potential core, no inertial subrange was observed, probably owing to the large-scale organization suggested in the cited literature. Finally, the behavior of the spectra in Test03 showed an inertial subrange also for $r/D < 5$, in agreement with the turbulent intensities maps, where no potential core region was detected. Finally, we highlight the limitations to this study. To avoid interaction of the jet with the frontal wall, the distance after the upstream bend was large enough to significantly reduce the secondary flow but not to completely remove it, even if, at the tested Re and De , the secondary flow is stable and the statistically irrelevant. As a consequence, the flow conditions inside the pipe can be considered as constant upstream the jet. Moreover, only one pipe flow rate has been investigated in the present work. We have planned future investigations with different flow rates and measuring the flow features also in vertical planes.

ACKNOWLEDGMENTS

The authors thank Dr. Luca Salvadori, who took part in the experimental activity during his Ph.D. thesis, Mr. Alberto Secci, who took part in the experimental activity during his MSc thesis, and Mr. Antonio Mascia, for his help in building up the experimental setup. The authors acknowledge the financial support provided by the University of Calabria and by the University of Cagliari.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Domenico Ferraro: Conceptualization (supporting); Data curation (supporting); Formal analysis (lead); Funding acquisition (supporting); Investigation (supporting); Methodology (lead); Project administration (equal); Resources (equal); Software (supporting); Supervision (supporting); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (supporting). **Roberto**

Gaudio: Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Funding acquisition (lead); Investigation (supporting); Methodology (supporting); Project administration (equal); Resources (equal); Software (lead); Supervision (supporting); Validation (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Simone Ferrari:** Conceptualization (lead); Data curation (lead); Formal analysis (supporting); Funding acquisition (supporting); Investigation (lead); Methodology (supporting); Project administration (equal); Resources (equal); Software (supporting); Supervision (lead); Validation (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- ¹T. B. Bleninger, F. Opila, R. L. Doneker, and A. S. Ramachandran, "Comparison of calculation methods for head losses in multiport diffuser outfall design," in *38th IAHR World Congress - "Water: Connecting the World"* (2019).
- ²S. Nemlioglu and S. Yilmaz, "Initial dilution comparison of wastewater marine outfall diffusers with sharp-edged ports in thick diffuser pipe wall and duckbill check valves," *Desalin. Water Treat.* **65**, 136 (2017).
- ³J. A. French, "Internal hydraulics of multiport diffusers," *J. (Water Pollut. Control Fed.)* **44**, 782–795 (1972), available at <http://www.jstor.org/stable/25037453>.
- ⁴S. S. Hosseini, M. Taherian, A. Mohammadian, S. Ferrari, and P. J. Roberts, "Mixing behavior of multiport diffusers with non-uniform port orientation," *Desalination* **567**, 116962 (2023).
- ⁵A. Masria, K. Elejla, M. Abualtayef, K. Qahman, A. K. Seif, and T. O. Alshammari, "Modeling the dispersion of wastewater pollutants in Gaza's coastal waters," *Mar. Pollut. Bull.* **208**, 117071 (2024).
- ⁶J. H. Lee, Q. Qiao, S. Chan, K. Choi, and H. K. Chau, "Reduction of Chlorine Disinfection Dosage through Optimal Jet Design in the Hong Kong Harbor Area Treatment Scheme," *J. Environ. Eng.* **149**, 05022009 (2023).
- ⁷R. A. Labatut, J. M. Ebeling, R. Bhaskaran, and M. B. Timmons, "Hydrodynamics of a Large-scale Mixed-Cell Raceway (MCR): Experimental studies," *Aquacult. Eng.* **37**, 132 (2007).
- ⁸A. Neori, "Essential role of seaweed cultivation in integrated multi-trophic aquaculture farms for global expansion of mariculture: An analysis," in *19th International Seaweed Symposium: Proceedings of the 19th International Seaweed Symposium, Held in Kobe, Japan, 26–31 March, 2007* (Springer, 2009), pp. 117–120.
- ⁹J. E. van Zyl, "Theoretical modeling of pressure and leakage in water distribution systems," *Proc. Eng.* **89**, 273 (2014).
- ¹⁰S. H. Han, D. Chang, and J. S. Kim, "Experimental investigation of highly pressurized hydrogen release through a small hole," *Int. J. Hydrogen Energy* **39**, 9552 (2014).
- ¹¹J. Van Zyl, A. Lambert, and R. Collins, "Realistic Modeling of Leakage and Intrusion Flows through Leak Openings in Pipes," *J. Hydraul. Eng.* **143**, 04017030 (2017).
- ¹²Y. Shao, T. Yao, J. Gong, J. Liu, T. Zhang, and T. Yu, "Impact of main pipe flow velocity on leakage and intrusion flow: An experimental study," *Water* **11**, 118 (2019).
- ¹³K. Zaman and A. Hussain, *Turbulent Shear Flows* (Pennsylvania State University, 1977), p. 11.
- ¹⁴A. F. Hussain, "Coherent structures—Reality and myth," *Phys. Fluids* **26**, 2816 (1983).
- ¹⁵G. L. Brown and A. Roshko, "On density effects and large structure in turbulent mixing layers," *J. Fluid Mech.* **64**, 775 (1974).
- ¹⁶A. Yule, "Large-scale structure in the mixing layer of a round jet," *J. Fluid Mech.* **89**, 413 (1978).
- ¹⁷B. J. Cantwell, "Organized motion in turbulent flow," *Annu. Rev. Fluid Mech.* **13**, 457 (1981).
- ¹⁸P. E. Dimotakis, R. C. Miake-Lye, and D. A. Papantoniou, "Structure and dynamics of round turbulent jets," *Phys. Fluids* **26**, 3185 (1983).
- ¹⁹S. Corrsin and A. L. Kistler, "Free-stream boundaries of turbulent flows," Technical Report (NTRS - NASA Technical Reports Server, 1955).
- ²⁰R. Limbourg and J. Nedić, "An extended model for orifice starting jets," *Phys. Fluids* **33**, 067109 (2021).
- ²¹A. Kumar, A. K. Saha, and P. Panigrahi, "Time-frequency analysis of submerged synthetic jet," *Fluid Dyn. Res.* **49**, 065510 (2017).
- ²²R. Mullyadzhannov, S. Abdurakipov, and K. Hanjalić, "Helical structures in the near field of a turbulent pipe jet," *Flow. Turbul. Combust.* **98**, 367 (2017).
- ²³H. A. Becker and T. Massaro, "Vortex evolution in a round jet," *J. Fluid Mech.* **31**, 435 (1968).
- ²⁴S. C. Crow and F. Champagne, "Orderly structure in jet turbulence," *J. Fluid Mech.* **48**, 547 (1971).
- ²⁵A. Michalke, "Survey on jet instability theory," *Prog. Aerosp. Sci.* **21**, 159 (1984).
- ²⁶E. Gutmark and C.-M. Ho, "Preferred modes and the spreading rates of jets," *Phys. Fluids* **26**, 2932 (1983).
- ²⁷M. Takahashi, R. Fukui, K. Tsujimoto, T. Ando, and T. Shakouchi, "Helical structures in a temporally developing round jet in the developed state," *Flow. Turbul. Combust.* **111**, 59–79 (2023).
- ²⁸A. N. Kolmogorov, "Dissipation of energy in the locally isotropic turbulence," *Proc. R. Soc. London Ser. A: Math. Phys. Sci.* **434**, 15 (1991).
- ²⁹C. Ball, H. Fellouah, and A. Pollard, "The flow field in turbulent round free jets," *Prog. Aerosp. Sci.* **50**, 1 (2012).
- ³⁰H. Fisher, E. List, R. Koh, J. Imberger, and N. Brooks, *Mixing in Inland and Coastal Waters* (Academic Press, 1979), pp. 315–389.
- ³¹J. Eaton, J. Johnston, and R. Westphal, "Experimental study of flow reattachment in a single-sided sudden expansion," Contractor report 3765 (NASA, 1986).
- ³²E. Smyk, M. Stopel, and M. Szyca, "Simulation of flow and pressure loss in the example of the elbow," *Water* **16**, 1875 (2024).
- ³³H. Nippert, "Über Den Stromungswiderstand in Gekrummten Kanälen," *Forsch. Arb. Ing.-Wes. N.* **320** (1929).
- ³⁴R. N. Ferreira, L. M. da Rosa, and J. G. Janzen, "Effect of 90° elbows on pump inlet flow conditions," *Appl. Water Sci.* **10**, 1 (2020).
- ³⁵J. Mi, G. Nathan, and D. Nobes, "Mixing Characteristics of Axisymmetric Free Jets From a Contoured Nozzle, an Orifice Plate and a Pipe," *J. Fluids Eng.* **123**, 878 (2001).
- ³⁶A. Hashiehbafe and G. P. Romano, "Particle image velocimetry investigation on mixing enhancement of non-circular sharp edge nozzles," *Int. J. Heat Fluid Flow* **44**, 208 (2013).
- ³⁷J. Mi, P. Kalt, G. Nathan, and C. Wong, "PIV measurements of a turbulent jet issuing from round sharp-edged plate," *Exp. Fluids* **42**, 625 (2007).
- ³⁸M. Raffel, C. E. Willert, F. Scarano, C. J. Kähler, S. T. Wereley, and J. Kompenhans, *Particle Image Velocimetry: A Practical Guide* (Springer, 2018).
- ³⁹M. G. Badas, S. Ferrari, M. Garau, A. Seoni, and G. Querzoli, "On the flow past an array of two-dimensional street canyons between slender buildings," *Boundary. Layer Meteorol.* **174**, 251 (2020).
- ⁴⁰O. Uzol and C. Camci, "The effect of sample size, turbulence intensity and the velocity field on the experimental accuracy of ensemble averaged PIV measurements," in *4th International Symposium on Particle Image Velocimetry* (2001), Vol. 69, ISSN 14348462.
- ⁴¹N. Ali and A. Tariq, "Aerothermal characteristics past a matrix structure inside a rectangular serpentine passage," *Appl. Therm. Eng.* **237**, 121796 (2024).
- ⁴²N. Ali, A. Chand, V. Sharma, and A. Tariq, "Flow mechanism across 180° sharp bend of matrix-cooled serpentine channel," *Int. J. Heat Fluid Flow* **112**, 109683 (2025).
- ⁴³F. Gori, I. Petracchi, and M. Angelino, "Flow evolution of a turbulent submerged two-dimensional rectangular free jet of air. Average Particle Image Velocimetry (PIV) visualizations and measurements," *Int. J. Heat Fluid Flow* **44**, 764 (2013).
- ⁴⁴H. Fellouah, C. G. Ball, and A. Pollard, "Reynolds number effects within the development region of a turbulent round free jet," *Int. J. Heat Mass Transfer* **52**, 3943 (2009).
- ⁴⁵E. Ghaem-Maghami and H. Johari, "Velocity field of isolated turbulent puffs," *Phys. Fluids* **22**, 115105 (2010).

- ⁴⁶M. Xu, J. Zhang, J. Mi, G. Nathan, and P. Kalt, "PIV measurements of turbulent jets issuing from triangular and circular orifice plates," *Sci. China Phys. Mech. Astron.* **56**, 1176 (2013).
- ⁴⁷S. Ferrari, L. Salvadori, M. Garau, and G. Querzoli, in *EPJournal Web of Conferences* (EDP Sciences, 2022), Vol. 269, p. 01013.
- ⁴⁸N. Ali and A. Tariq, "Vortex evolution and merging mechanism across 180° sharp bend for laminar inflow," *Phys. Fluids* **35**, 075143 (2023).
- ⁴⁹C. Anghan, S. Dave, S. Saincher, and J. Banerjee, "Direct numerical simulation of transitional and turbulent round jets: Evolution of vortical structures and turbulence budget," *Phys. Fluids* **31**, 065105 (2019).
- ⁵⁰G. K. Batchelor, *An Introduction to Fluid Dynamics* (Cambridge University Press, 2000).
- ⁵¹P. A. Davidson, *Turbulence: An Introduction for Scientists and Engineers* (Oxford university Press, 2015).
- ⁵²L. F. Richardson, *Weather Prediction by Numerical Process* (University Press, 1922).
- ⁵³P. Burattini, R. Antonia, S. Rajagopalan, and M. Stephens, "Effect of initial conditions on the near-field development of a round jet," *Exp. Fluids* **37**, 56 (2004).
- ⁵⁴D. Ferraro, S. Servidio, V. Carbone, S. Dey, and R. Gaudio, "Turbulence laws in natural bed flows," *J. Fluid Mech.* **798**, 540 (2016).