

Swirl switching in spatially developing bent pipesValerio Lupi ^{1,2,*}, Daniele Massaro ^{1,3}, Adam Peplinski ¹ and Philipp Schlatter ^{1,4}¹*SimEx/FLOW, Engineering Mechanics, KTH Royal Institute of Technology, 10044 Stockholm, Sweden*²*Gran Sasso Science Institute, 67100 L'Aquila, Italy*³*Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*⁴*Institute of Fluid Mechanics, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany*

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Swirl switching refers to the temporal rotation of the plane of symmetry of the cross-sectional vortices about the equatorial plane of the curved pipe and may induce significant vibrations in piping systems. The origin of this phenomenon is not yet understood, and its relationship with turbulent fluctuations in the upstream straight section is still debated in the literature. To assess the effect of upstream turbulence, direct numerical simulations are performed for spatially developing bent pipe flows under both laminar and turbulent inflow conditions. Additionally, the influence of the bending angle on swirl switching and time-averaged flow characteristics is investigated. Proper orthogonal decomposition (POD) is applied to three-dimensional velocity fields to extract spatially coherent structures responsible for swirl switching. The phenomenon is observed for both inlet velocity profiles and bending angles, although it does not correspond to the dominant mode in the case of laminar inflow conditions. A reduced-order reconstruction using the most energetically relevant antisymmetric POD modes indicates a link between swirl switching and the shear layer within the bend. We therefore infer that swirl switching could arise because of a symmetry-breaking shear layer instability, representing a stage in the bifurcation cascade that leads to turbulence.

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Curved pipes are constitutive elements of various biological systems, such as the respiratory and cardiovascular ones. They are also employed in several industrial applications, including gas transport pipelines and cooling systems for nuclear reactors [1]. Curved pipes can be distinguished between continuously bent pipes, which have a continuous curve throughout their length, and spatially developing bent pipes, where the fluid travels through two straight sections joined by a bend. Continuously bent pipes exhibit homogeneous flow in the streamwise direction and serve as idealized cases to focus solely on the effect of geometrical parameters such as curvature and torsion. In contrast, spatially developing bent pipes are more representative of real-world scenarios and display more intricate flow characteristics. The main feature of flows in curved pipes is the

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occurrence of a secondary motion of Prandtl's first kind, which arises in both laminar and turbulent regimes [2] and was first observed experimentally by Eustice [3]. For toroidal pipes with infinitely low curvature δ , defined as the ratio between the radius of the cross section of the pipe, R_p , and the radius of curvature of the torus centerline, R_c , Dean [4] analytically demonstrated that the secondary flow consists of two symmetric, counter-rotating vortices, named after him. They increase heat transfer and cross-plane mixing and affect the friction factor [5,6]. Hence, they are extremely relevant to engineering applications.

For laminar flows through spatially developing bends, the secondary motion is symmetric about the equatorial plane [7,8]. In contrast, for turbulent bent pipe flows, this symmetry is retained only in the time-averaged field, whereas the secondary motion is instantaneously asymmetric. Tunstall and Harvey [9] were the first to observe this feature and to describe it as the abrupt switching of the rotational direction of the dominant vortex in the cross section. They attributed the phenomenon to upstream turbulence and the nonsymmetric separation region at the inner corner of the bend. However, the term "swirl switching" was coined only later by Brücker [10] to define the alternating rotation (or rocking) of the plane of symmetry of the vortices about the geometric plane of symmetry of the bend. He observed a flow pattern considerably different from that reported by Tunstall and Harvey [9], and suggested that swirl switching was due to an instability increasing the strength of one of the two vortices and eventually leading to a self-sustained feedback loop.

Rütten *et al.* [11,12] conducted the first numerical investigations on swirl switching by performing large eddy simulations (LES) of the flow through a 90° -bend pipe with $\delta = 0.167, 0.5$ (defined as the ratio of the pipe cross-sectional radius, R_p , to the radius of curvature of the bend centerline, R_c) at $Re_b = 5000, 10\,000, 27\,000$, with the bulk Reynolds number Re_b based on the bulk velocity U_b , the diameter of the pipe cross section D , and the kinematic viscosity ν . For all values of Re_b , the spectra of the force integrals on the pipe walls exhibit peaks at Strouhal numbers $St = fD/U_b \approx 0.2\text{--}0.3$, with f being the frequency. Additionally, they reported large amplitudes of the spectra at $St \approx 0.01$ for $Re_b = 27\,000$. The authors attributed the high-frequency peaks to the instability of the shear layer arising between the flow at the inner and outer walls, and the low-frequency ones to the oscillation of the Dean vortices, i.e., swirl switching. In contrast with Tunstall and Harvey [9], Rütten *et al.* [12] described the phenomenon as a smooth motion. Furthermore, their study ruled out flow separation as the primary cause of swirl switching since the phenomenon was also observed for $\delta = 0.167$, where reversed flow does not occur. Later, Sakakibara and Machida [13] applied particle image velocimetry (PIV) to study the turbulent flow through a 90° -bend pipe with $\delta = 0.5$ at $Re_b = 27\,000$ and found that the displacement of the stagnation point at the inner side of the downstream straight section, and hence swirl switching, is linked to streaks originating upstream of the bend and extending in a quasistreamwise direction. These streaks were thought to be related to very large-scale motions (VLSM) identified by Kim and Adrian [14].

Several subsequent experimental and numerical studies exploited proper orthogonal decomposition (POD) to investigate swirl switching. Kalpakli and Örlü [15] applied snapshot POD to the time-resolved, two-dimensional, three-component PIV measurements of the turbulent flow $0.67D$ downstream of a 90° bend with $\delta = 0.31$ at $Re_b = 34\,000$. By reconstructing the flow fields using the six most energetic POD modes, they showed that Dean vortices oscillate, with one of them alternately dominating but without suppressing the other vortical structure. The frequency of the switching was found to correspond to $St \approx 0.04$. Hellström *et al.* [16] also employed POD to extract the most energetic structures from PIV data of the turbulent flow downstream of a 90° bend with curvature $\delta = 0.5$ at $Re_b = 25\,000$. Their analysis focused on the in-plane velocity components sampled at three different cross sections downstream of the bend exit. The most energetic POD mode appears as a single-cell structure at all investigated streamwise locations and was referred to as the swirl switching mode. The spectrum of the associated temporal coefficient has a dominant peak at $St \approx 0.33$ and a smaller one at $St \approx 0.16$. Instead, the second most energetic POD mode represents tilted Dean vortices, and its corresponding temporal coefficient has considerable energy content

at $St \approx 0.16$. By analyzing the flow fields reconstructed using the most energetic POD modes, Hellström *et al.* [16] concluded that one of the Dean vortices is suppressed during the transition between the two rotational directions of the swirl switching mode, and the shear flow region at the inner wall, which in turn is affected by upstream perturbations, was deemed responsible for this suppression. A similar spatial structure of the POD modes was detected by Kalpakli Vester *et al.* [17] for the flow downstream a 90° bend with $\delta = 0.14, 0.39$ at $Re_b = 23\,000$. For both curvatures, they observed that the most energetic mode $1D$ downstream of the bend exit corresponds to a single swirl spanning the entire cross section, whereas the second and third most energetic modes at the same location represent tilted Dean vortices. They also showed that mounting a honeycomb upstream of the sharpest bend substantially alters the secondary flow pattern and the POD modes. Therefore, they concluded that the device might delay swirl switching, causing it to occur further downstream than in the case without a honeycomb. Based on these findings, Kalpakli Vester *et al.* [17] suggested that swirl switching was related to large-scale structures arising in the upstream straight section, as proposed by Sakakibara and Machida [13]. However, they also argued that these structures were unlikely to be the sole cause of the phenomenon.

To investigate the impact of curvature, Carlsson *et al.* [18] carried out LES of the flow in a 90° -bend pipe with $\delta = 0.32, 0.5, 0.7, 1$ at $Re_b = 34\,000$ and performed POD on the in-plane velocity fields sampled at a cross section located $0.67D$ downstream of the bend outlet. Furthermore, they applied POD to three-dimensional velocity fields for the smallest and largest curvatures ($\delta = 0.32$ and $\delta = 1$). Based on their results, the authors distinguished between low- and high-frequency switching. The former is associated with VLSM generated in the upstream straight section, whereas the latter, predominant at $\delta = 1$, corresponds to structures generated within the bend and is thus related to curvature.

The challenges in understanding swirl switching were highlighted by Hufnagel *et al.* [19], who carried out direct numerical simulations (DNS) of the turbulent flow through a 90° -bend pipe with curvature $\delta = 0.3$ at $Re_b = 11\,700$. By applying POD to three-dimensional velocity fields, they uncovered modal pairs that represent traveling wavelike structures. The most energetic pair consists of two counter-rotating swirls that decay in intensity and move from the inner toward the outer wall while they are convected downstream. The modes belonging to this pair have a dominant wavelength of approximately $7D$, and the power spectral densities (PSDs) of the associated temporal coefficients exhibit a peak at $St \approx 0.16$. The authors argued that this wavelike structure might be a remnant of flow patterns arising in the transition process due to a global instability. Moreover, they demonstrated that applying POD to two-dimensional velocity fields sampled in the cross-flow direction is inadequate for capturing the three-dimensional nature of swirl switching, as it fails to distinguish between temporal variation and convection.

A significant advancement in the investigation of swirl switching was made by Noorani and Schlatter [20], who showed that neither flow separation nor large-scale structures coming from the upstream straight section are the sole cause of the phenomenon. They performed DNS of the fully developed turbulent flow in a toroidal pipe at $Re_b = 11\,700$ and $\delta = 0.01, 0.1, 0.3$, and detected POD modes related to swirl switching only for the two largest curvatures, but not for $\delta = 0.01$. Nevertheless, Noorani and Schlatter [20] could not identify a single dominant structure responsible for swirl switching, as the POD modes are not well separated in energy. They also indicated that the limited size of the periodic computational domain might affect the frequencies associated with the POD modes. They proposed two potential explanations for swirl switching: a linear global instability of the time-averaged flow or an interaction between the secondary motion and near-wall streaks. Swirl switching in continuously curved pipes was also reported in a recent study by Zhang *et al.* [21], who suggested a connection between the phenomenon and VLSM originating in the toroidal pipe, and therefore inherently linked to the curved geometry.

Despite decades of study, the origin of swirl switching remains unclear, with various explanations proposed. While several studies suggested a connection between swirl switching and turbulent structures originating in the upstream straight section, works by Noorani and Schlatter [20] and Zhang *et al.* [21] showed that the phenomenon also occurs in toroidal pipes, where no inflow boundary

is present. However, no studies have investigated swirl switching in spatially developing bent pipes where the flow in the upstream straight section is not turbulent. To address this gap, we employ high-fidelity numerical simulations under various inflow conditions to explore the relationship between swirl switching and upstream turbulence. Furthermore, different bending angles are considered since the impact of this geometrical parameter on the flow characteristics and its connection with swirl switching have not been widely investigated. We conduct DNS for three distinct cases: DNS-90T and DNS-180T for 90°- and 180°-bend pipe flows with turbulent inflow conditions, respectively, and DNS-180L for the flow through a 180°-bend pipe with a laminar velocity field prescribed at the inlet.

The paper proceeds with a description of the numerical framework employed in the three different simulations in Sec. II, followed by a brief theoretical overview of the proper orthogonal decomposition in Sec. III. The main findings are presented in Sec. IV, where the influence of the bending angle and inflow condition on time-averaged (mean) flow characteristics and swirl switching is discussed. This section also illustrates the reduced-order reconstruction based on the most energetic symmetric and antisymmetric POD modes, which is used to pinpoint the region where swirl switching originates. Finally, conclusions are drawn in Sec. V, where the outlook for future work is also discussed.

II. NUMERICAL METHOD

The dynamics of the incompressible flow of a viscous, Newtonian fluid through a bent pipe is described by the incompressible Navier–Stokes equations in nondimensional form,

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \frac{1}{\text{Re}_b} \nabla^2 \mathbf{u}, \quad (1a)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (1b)$$

where $\mathbf{u}(\mathbf{x}, t)$ is the velocity vector and $p(\mathbf{x}, t)$ represents the reduced pressure. The rigid wall of the pipe is modeled as a no-slip and impermeable surface, whereas the natural boundary condition $(-p\mathcal{I} + 1/\text{Re}_b \nabla \mathbf{u}) \cdot \mathbf{n} = 0$, with $\mathbf{n}$ denoting the outward unit normal vector, is imposed at the outlet. For DNS-90T and DNS-180T, a turbulent velocity field generated using the isotropic version of the divergence-free synthetic eddy method (DFSyEM) proposed by Poletto [22] is prescribed at the inlet. Although anisotropic turbulence would be the more appropriate physical boundary condition for these cases, the isotropic formulation recovers the correct Reynolds stresses within a short distance downstream of the inlet (see Fig. 2 in Hufnagel *et al.* [19]). The development length resulting from this approach is significantly shorter than that obtained using other methods for synthetic turbulence generation, as discussed in more detail by Poletto [22]. In contrast, a Hagen–Poiseuille (parabolic) velocity profile is imposed as the inflow condition for DNS-180L. For all cases, a parabolic velocity profile in the streamwise direction s (see Fig. 1) is specified as the initial condition, and the bulk Reynolds number, based on the bulk velocity U_b , the diameter of the pipe cross section D , and the kinematic viscosity ν , is set to $\text{Re}_b = U_b D / \nu = 11\,700$, in line with previous studies on straight [23] and toroidal [6,24] pipe flows.

Direct numerical simulations of the flow are performed by numerically integrating the system (1) supplemented by the boundary and initial conditions mentioned above. The governing equations are formulated in Cartesian coordinates, so no singularity arises at the pipe centerline. In the postprocessing phase, a local reference system $\{s, p, y'\}$ is introduced to express flow quantities. The computational domain consists of two straight sections connected by either a 90° or a 180° bend. In both cases, the radius of curvature of the bend centerline, R_c , is three times the radius of the cross section of the pipe, R_p , i.e., $\delta = R_p / R_c = 1/3$. This curvature value is chosen because it is representative of sharp bends. Indeed, swirl switching has not been observed at low curvatures, e.g., $\delta = 0.01$ [20]. For both bent pipes, the upstream straight section is $10D$ long, sufficient to obtain a fully developed turbulent flow when the inflow condition is prescribed using the isotropic version of the DFSyEM at $\text{Re}_b = 11\,700$ [19], while the downstream part has a length

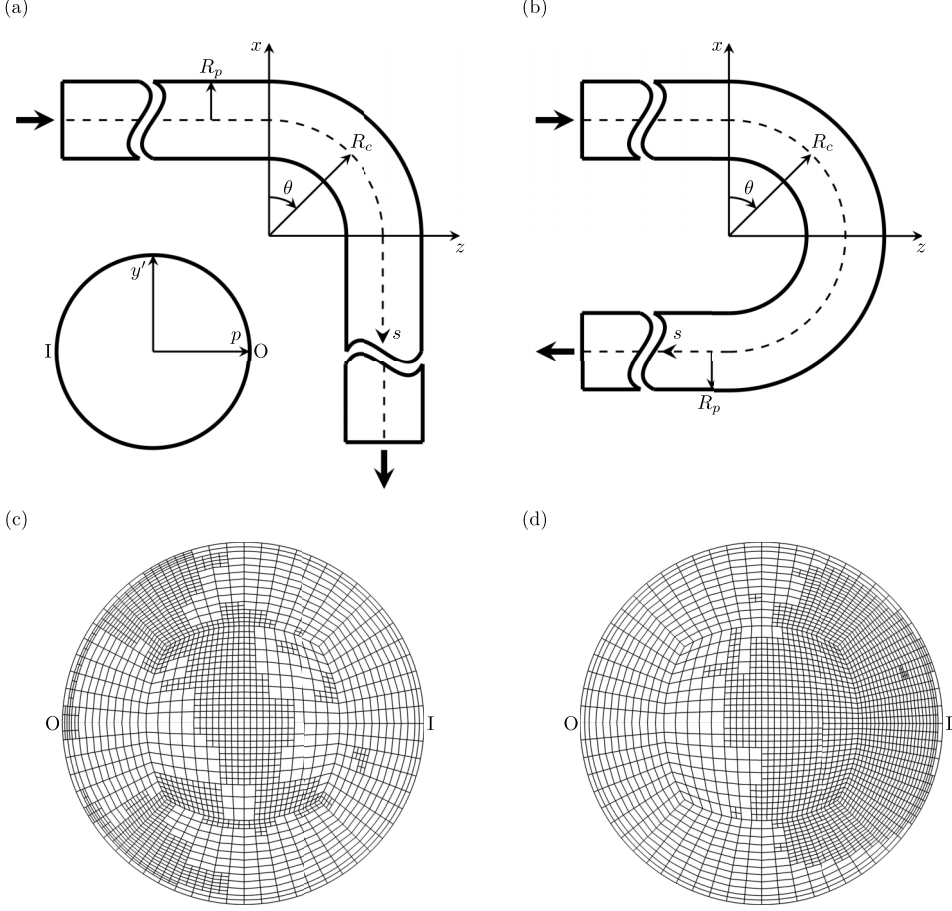


FIG. 1. Top: Sketches of the (a) 90°- and (b) 180°-bend pipes. The Cartesian axes $\{x, y, z\}$ and the reference system used in the postprocessing stage $\{s, p, y'\}$ are also shown. The axis y' has the same direction and orientation as the y axis of the Cartesian coordinate system, but its origin is at the center of the cross section. Bottom: Cross sections of the nonconforming spectral grid at $\theta = 180^\circ$ for the (c) DNS-180L and (d) DNS-180T cases. The inner and outer walls are denoted by I and O, respectively. The black arrows indicate the flow direction.

of 20D. The sketches of the two bent pipes, together with the reference systems, are shown in Fig. 1. The spatial discretization of the equations is based on the spectral element method (SEM) implemented in the open-source code Nek5000 [25]. Within each element, the velocity and pressure fields are discretized using Lagrangian interpolants defined on $N + 1$ Gauss–Lobatto–Legendre (GLL) and $N - 1$ Gauss–Legendre (GL) points, respectively, where $N = 7$ is the polynomial order. This approach corresponds to the $\mathbb{P}_N - \mathbb{P}_{N-2}$ formulation [26] and results in a staggered grid. Additionally, the adaptive mesh refinement (AMR) technique is employed to finely resolve each region of the domain, significantly reducing the computational cost while providing greater flexibility than a conforming mesh. The grid is adapted automatically by applying an isotropic h -type refinement, i.e., the elements with the highest computational error are isotropically split to increase the resolution. The interpolation and quadrature errors are measured using the spectral error indicator (SEI) proposed by Mavriplis [27]. The refinement process terminates when a DNS-like resolution is achieved. Although criteria concerning grid resolution for canonical flows are available in the literature, well-established standards for SEM in more complex geometries are lacking.

Therefore, in addition to a standard mesh convergence study, we compute a statistical estimate of the Kolmogorov length scale to evaluate the mesh quality. The ratio between the largest grid spacing within each element and this length scale is kept below 6 throughout the domain. In the near-wall region, a DNS-like resolution, based on the viscous length scale, is used. Further details are provided in Massaro [28] and the appendices of Massaro *et al.* [29,30]. The use of AMR in high-fidelity DNS has been thoroughly validated and applied to both transitional and turbulent flows [31–33].

The integration in time is performed using an implicit third-order backward differentiation formula (BDF3), with an extrapolation of order three (EXT3) for the nonlinear term, resulting in a semi-implicit scheme. The (nonlinear) convective term is also over-integrated (or de-aliased) by a factor of 3/2 to retain its skew symmetry [34]. The temporal integration is carried out with an adaptive time step Δt during the meshing and transient phases, and a constant Δt when statistics are collected. It is verified that the chosen Δt is suitable for capturing the fastest dynamics and that the Courant number is consistently below 0.4. After discarding the initial transient, flow statistics are collected over at least 200 convective time units (D/U_b) using the framework described by Massaro *et al.* [35].

III. PROPER ORTHOGONAL DECOMPOSITION

The proper orthogonal decomposition of a velocity field $\mathbf{u}(\mathbf{x}, t)$ is given by

$$\mathbf{u}(\mathbf{x}, t) = \sum_{j=0}^{\infty} a_j(t) \Phi_j(\mathbf{x}), \quad (2)$$

where $\Phi_j(\mathbf{x})$ are orthonormal basis functions with respect to the L_2 inner product (in this case), commonly referred to as POD modes, and $a_j(t)$ are their corresponding temporal coefficients. Among the various linear decompositions, POD is optimal (in the least-squares sense) as it captures the highest amount of kinetic energy for a given number of modes [36]. This property makes it suitable for investigating large-scale and energetically dominant motions. Accordingly, POD is employed in the present study to extract spatially coherent structures associated with swirl switching.

Snapshots of three-dimensional velocity fields are first interpolated due to memory requirements and then stacked as column vectors in a matrix $\mathbf{X}$. The effects of the interpolation are carefully assessed, confirming that the conclusions presented here remain unchanged. The averaging operation and the inner product involved in the Fredholm integral equation [37] require the introduction, in the discrete POD formulation, of the matrices $\mathbf{M}$ and $\mathbf{N}$, which account for spatial and temporal weights, respectively. This operation leads to the definition of a new matrix,

$$\hat{\mathbf{X}} = \mathbf{M}^{1/2} \mathbf{X} (\mathbf{N}^{1/2})^\top. \quad (3)$$

The singular value decomposition (SVD) of this matrix is written as

$$\hat{\mathbf{X}} = \hat{\mathbf{U}} \boldsymbol{\Sigma} \hat{\mathbf{V}}^\top, \quad (4)$$

with the matrix of POD modes given by

$$\mathbf{U} = \mathbf{M}^{-1/2} \hat{\mathbf{U}}, \quad (5)$$

and the matrix of corresponding temporal coefficients defined as

$$\mathbf{A} = \boldsymbol{\Sigma} \mathbf{V}^\top = \boldsymbol{\Sigma} (\mathbf{N}^{-1/2} \hat{\mathbf{V}})^\top. \quad (6)$$

Here, $\mathbf{N}$ corresponds to the identity matrix since the snapshots are sampled at a constant frequency, whereas $\mathbf{M}$ contains the quadrature weights arising from the spatial discretization. The superscript $\top$ denotes the transpose operation. The temporal average is not subtracted from the snapshots. Hence, the POD mode 0 corresponds to the mean flow field. Additionally, adopting a physics-informed

approach, the inherent statistical reflectional symmetry about the equatorial plane xz is leveraged, thus ensuring that the resulting POD modes are either symmetric or antisymmetric by construction. The flow reconstruction given only by a selected subset of POD modes can be written in matrix form as

$$\tilde{\mathbf{X}} = \mathbf{U} \mathbf{R}_U \mathbf{R}_A \mathbf{A}, \quad (7)$$

where $\mathbf{R}_U$ and $\mathbf{R}_A = \mathbf{R}_U^\top$ are Boolean restriction matrices for selecting desired POD modes and temporal coefficients, respectively.

Snapshots are collected after discarding the initial transient, using a constant sampling period of 0.5 convective time units, which yields a Nyquist frequency corresponding to $St = 1$. According to Hufnagel *et al.* [19], this sampling rate is adequate for capturing the dynamics of large-scale structures associated with swirl switching. Proper orthogonal decomposition is performed with different numbers of snapshots in the three cases: $N = 1000, 710$, and 483 for DNS-90T, DNS-180T, and DNS-180L, respectively. The convergence of the POD modes is carefully assessed using the criterion introduced by Massaro *et al.* [30].

Note that spectral proper orthogonal decomposition (SPOD) [38] is also applied to the velocity fields in the 90° -bend pipe, yielding large-scale structures similar to those obtained with POD. However, the results from SPOD appear less converged due to the consideration of only one frequency at a time.

IV. RESULTS

In this section, we present the primary outcomes of our investigation on swirl switching in spatially developing bent pipes. Initially, we study the flow through 90° - and 180° -bend pipes with turbulent inflow conditions to explore the impact of differing bending angles. Varying the extent of the bend does not eliminate swirl switching, but changes its characteristics. Notably, different frequencies and mean flow features emerge. To exclude the influence of large-scale motions related to upstream turbulence, we further examine the occurrence of swirl switching in a 180° -bend pipe with laminar inflow conditions. Subsequently, focusing on the latter case, we reconstruct the flow fields using either symmetric or antisymmetric POD modes. Statistical data from these reconstructed fields are then exploited to study the connection between swirl switching and the shear layer within the bend.

A. Influence of the bending angle

The influence of the bending angle on turbulent flows through both 90° - and 180° -bend pipes is investigated by analyzing statistical data from DNS. Figure 2 shows the time-averaged streamwise velocity component $\bar{u}_s$ on the equatorial plane and various cross sections along the pipe for DNS-90T and DNS-180T. Pseudo-streamlines of the time-averaged in-plane velocity field are also shown on the cross sections to highlight swirling motions. In both pipes, the mean streamwise velocity deviates from the axisymmetric profile upstream of the bend inlet as a result of the curved geometry [39]. The length of the bend strongly affects the development of the time-averaged flow within and downstream of the curved section. While the mean flow field evolves similarly in the initial portion of the two bends, differences emerge close to their exits. A similar behavior was also observed for the steady base flow in bent pipes at lower Re_b [7,8].

In the 90° -bend pipe, the mean secondary flow at the bend outlet ($s/D = 0$) consists of a pair of symmetric counter-rotating vortices resembling Dean vortices, with their cores located near the side walls $[(p, y') \approx (-0.07D, \pm 0.35D)]$. Two smaller structures are also present at the inner wall, associated with the mean flow separation occurring close to the exit of the bend [see Fig. 3(a)]. They merge with the primary vortices a short distance downstream of the bend outlet. As one moves further from the bend exit, the cores of the (primary) Dean vortices shift toward the center of the cross section $[(p, y') \approx (-0.05D, \pm 0.24D)]$ at $s/D = 8$, and the cross-sectional mean streamwise

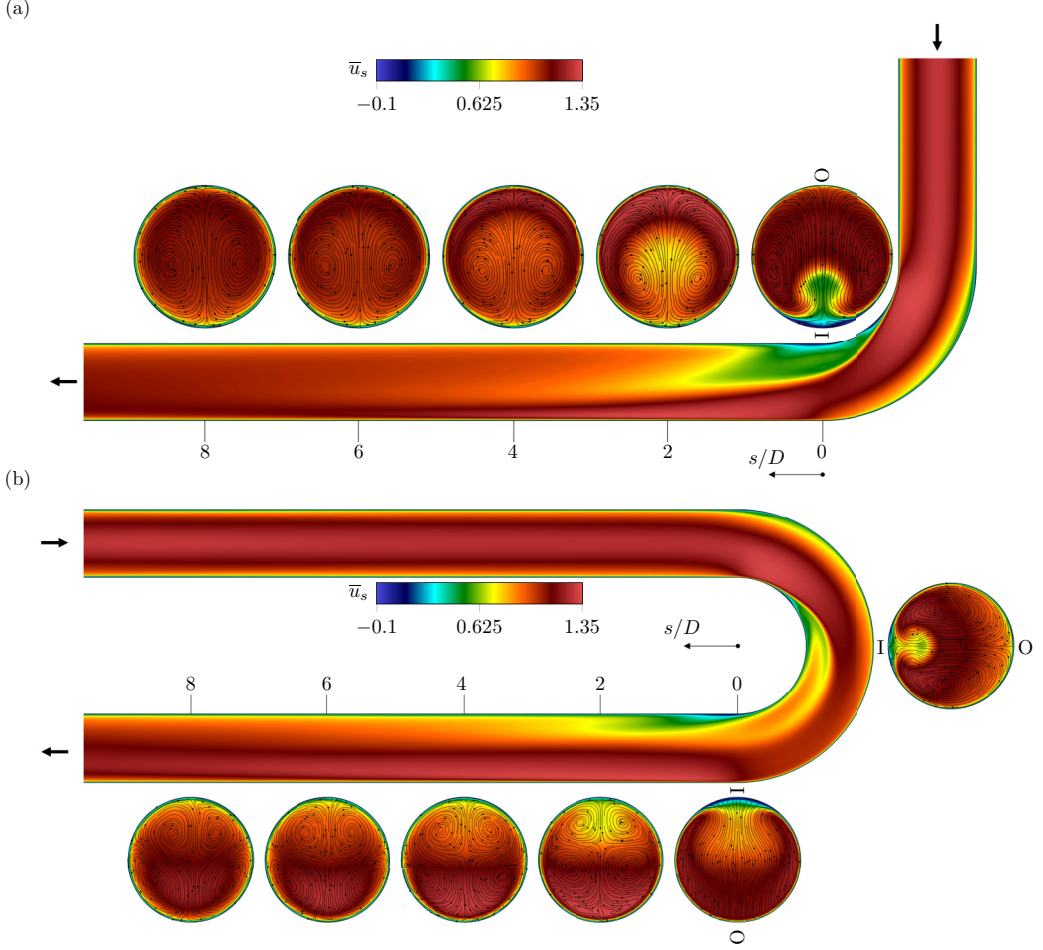


FIG. 2. Time-averaged streamwise velocity $\bar{u}_s$ for (a) the 90°-bend pipe flow with turbulent inflow conditions (DNS-90T) and (b) the 180°-bend pipe flow with turbulent inflow conditions (DNS-180T). In both panels, the planar perspectives of the mean flow are shown at $y' = 0$, $\theta = 90^\circ$, and $s/D = 0, 2, 4, 6, 8$. The pseudo-streamlines of the mean in-plane velocity field are also displayed on the cross sections. The inner and outer walls are denoted by I and O, respectively. The black arrows indicate the flow direction.

velocity profile becomes more uniform due to momentum transfer, gradually approaching that of a fully developed turbulent flow in a straight pipe. However, complete recovery of axisymmetric flow is not achieved even at $s/D = 20$, with the secondary motion still evident at the outlet of the computational domain. Previous studies at higher values of Re_b and different curvatures [16,39] have shown that longer straight sections are needed downstream of the bend for this to occur.

Although similar mean flow development is observed within the 180°-bend pipe for $\theta < 90^\circ$, the influence of the centrifugal force over a longer distance considerably modifies the time-averaged flow topology. Specifically, the shear layer arising due to the velocity difference between the inner and outer walls exhibits different dynamics for the larger bending angle, owing to the longer development length. Consequently, a distinct configuration of swirling motions emerges in the 180°-bend pipe. At $s/D = 0$, a *bulge*, linked to intense turbulent fluctuations [24], develops near the center of the pipe ($p \approx 0.02D$), pushing the core of the Dean vortices toward the side walls. As

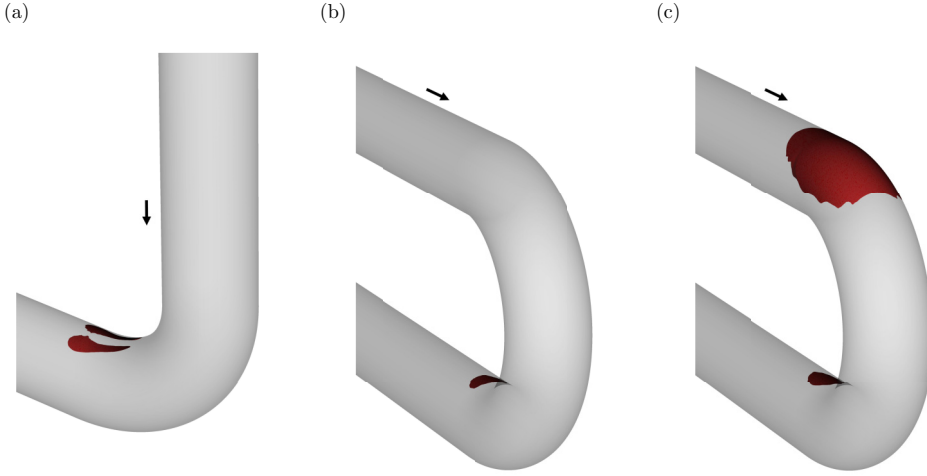


FIG. 3. Mean recirculation regions ($\bar{u}_s \leq 0$) for (a) the 90°-bend pipe with turbulent inflow conditions, (b) the 180°-bend pipe with turbulent inflow conditions, and (c) the 180°-bend pipe with a laminar parabolic velocity profile at the inlet. The black arrows indicate the flow direction.

a result, the mean flow pattern at the bend exit resembles that within a toroidal pipe with similar curvature (see Fig. 9 in Noorani *et al.* [24]). This behavior is not surprising as the flow is expected to approach the fully developed state in a torus, i.e., a continuously curved pipe. However, the straight section downstream of the bend further alters the mean flow topology, giving rise to additional swirling motions. A short distance downstream of the bend outlet, the two vortical structures at the side walls split, each generating a vortex on the inner and another on the outer side of the curved section. In addition, two vortices form in the pipe core. Six vortical structures are present, i.e., three pairs of symmetric, counter-rotating vortices. For $1 \leq s/D \leq 2$, the pair in the center of the cross section nearly merges with that at the outer wall. Hence, there are two main pairs of vortices at $s/D = 2$: one located approximately at the center of the cross section $[(p, y') \approx (0.08D, \pm 0.23D)]$ and the other shifted toward the inner wall $[(p, y') \approx (-0.3D, \pm 0.17D)]$. The two primary vortices present in each half of the cross section have opposite directions of rotation. For $s/D > 2$, the central vortices get pushed to the side walls and are slightly tilted, whereas the other vortex cells expand toward the center of the cross section. For $s/D > 5$, no considerable qualitative changes are observed in the mean secondary flow pattern. Complete recovery of axisymmetric flow is not attained in this case either.

A thin mean separation bubble is present at the inner wall of the 180°-bend pipe with turbulent inflow conditions, close to the bend exit, extending for a shorter distance in both the streamwise and wall-normal directions than the mean recirculation regions observed in the 90°-bend pipe [see Figs. 3(a) and 3(b)]. Additionally, the reversed mean flow areas are topologically different in the two cases. Two distinct mean recirculation regions are present in the DNS-90T case [see Fig. 3(a)], while a single one occurs for DNS-180T, as shown in Fig. 3(b). Consequently, two swirling motions appear at the inner wall of the 90°-bend pipe at $s/D = 0$, confined by the two separation bubbles [see Fig. 2(a)]. In contrast, in the 180°-bend pipe, the mean recirculation area straddles the equatorial plane ($y' = 0$), and the pseudo-streamlines of the mean in-plane velocity field get deflected [see Fig. 2(b)]. In both cases, the absolute value of the reversed mean streamwise velocity within the separation bubbles is lower than 5% of the bulk velocity.

As anticipated earlier, the effect of the bending angle on swirl switching is studied through proper orthogonal decomposition of three-dimensional velocity fields. For both bending angles, the POD modes come in pairs since they correspond to traveling structures [40]. The most energetic modes,

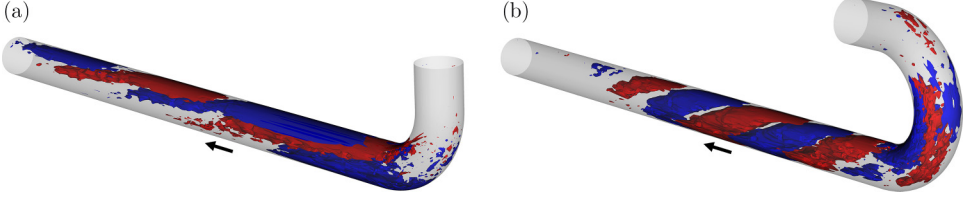


FIG. 4. Isosurfaces of the velocity component normal to the equatorial plane $u_{y'}$ of POD mode 1 for (a) the 90°-bend pipe and (b) the 180°-bend pipe, both with turbulent inflow conditions. Red (blue) isosurfaces correspond to positive (negative) values. The black arrows indicate the flow direction.

i.e., POD modes 1 and 2, are antisymmetric and resemble a three-dimensional wavelike structure in both cases, as shown by the isosurfaces of the velocity component normal to the equatorial plane $u_{y'}$ in Fig. 4. Note that the main (streamwise) wavelength of the dominant modes in the 90°-bend pipe is twice that for the 180°-bend pipe, $\lambda_s \approx 8D$ and $\lambda_s \approx 4D$, respectively, indicating that the most energetic structures in the two cases are characterized by different temporal frequencies (see the discussion below). However, for both bent pipes, the POD modes are not purely periodic in either space or time since such periodicity is not imposed by construction, unlike in other modal decompositions.

A quantitative assessment of the temporal frequencies related to swirl switching is obtained by computing the power spectral density of the temporal coefficients associated with the four most energetic POD modes through Welch's method [41]. For the 90°-bend pipe [see Fig. 5(a)], the most energetic pair of modes exhibits significant energy content at $St \approx 0.12$, in close agreement with the results of Hufnagel *et al.* [19] for the same bending angle and similar curvature. POD modes 3 and 4, i.e., the second most energetic pair, represent the first harmonic of modes 1 and 2, as the PSDs of the corresponding temporal coefficients exhibit a leading peak at $St \approx 0.24$, and their main spatial scale is approximately half of that of the dominant pair (not shown here). Since POD enables the reduced-order reconstruction of the most energetic motions, we consider the superposition of POD modes 1 and 2 with the mean flow field (POD mode 0) for the 90°-bend pipe. A behavior similar to that reported by Brücker [10] and Hufnagel *et al.* [19] is observed: the Dean vortices rotate without one being suppressed by the other, suggesting that the dominant POD modes are closely associated with swirl switching.

In contrast, for the 180°-bend pipe with turbulent inflow conditions, the temporal coefficients associated with the most energetic modal pair, i.e., POD modes 1 and 2, present a peak in their power spectral densities at $St \approx 0.3$ [see Fig. 5(b)]. Interestingly, POD modes 3 and 4 exhibit considerable energy content at $St \approx 0.15$. Indeed, the main (streamwise) wavelength of these modes is nearly twice that of the most energetic pair. The flow reconstruction using POD modes 0, 1, and 2 shows the rotation of both primary pairs of vortices in the cross section, i.e., swirl switching (see GIF

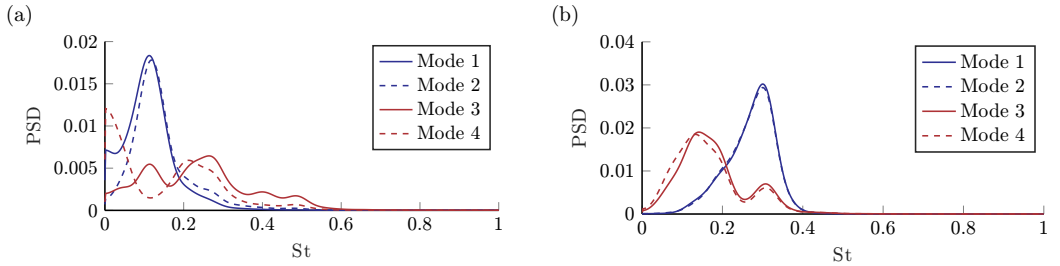


FIG. 5. Power spectral density (PSD) estimate of the temporal coefficients of the four most energetic POD modes for (a) the 90°-bend pipe and (b) the 180°-bend pipe, both with turbulent inflow conditions.

in the Supplemental Material [42]). For $s/D \geq 2$, this oscillation causes the vortices with opposite spinning directions to merge at times, nearly resulting in the suppression of one pair of vortex cells.

The different frequencies associated with the dominant POD modes in the two bent pipes are ascribed to the differing width of the shear layer separating high- and low-speed regions in the mean flow fields at $\theta = 90^\circ$. Despite this discrepancy, swirl switching occurs regardless of the length of the bent section, and the vortical patterns exhibit similar behavior in the two geometries. The topologies of the reconstructed flows appear to be primarily influenced by the different mean fields, which are significantly affected by the extent of the bend, unlike swirl switching. Notably, although proper orthogonal decomposition is carried out using a higher number of snapshots for the 90° -bend pipe (1000 vs 710), the POD modes and the corresponding temporal coefficients are much more separate for the 180° -bend pipe (see Figs. 4 and 5). Indeed, the relative fluctuating energy of the dominant modes, and thus of swirl switching, is considerably higher (by a factor of roughly 1.5) for the DNS-180T case. Hence, the separation of these structures from the surrounding turbulent flow is more evident. This behavior is likely attributed to the connection between swirl switching and the shear layer (see the discussion below), as a larger bending angle allows for more extensive growth of the latter and enhances the vortical coherent motions associated with swirl switching.

B. Influence of the inflow condition

The effect of the inflow condition on the flow topology and swirl switching is studied by prescribing either a laminar or a turbulent velocity field at the inlet of the 180° -bend pipe, as described in Sec. II. Since similar conclusions hold for both bends, we focus on the 180° -bend pipe as it has been barely studied in the existing literature and is more relevant to real-world applications. We aim to shed light on a disputed topic, i.e., the connection between upstream turbulence and swirl switching.

We start by examining the influence of the inflow condition on the mean flow field (see Fig. 6). In the case of laminar inflow conditions [see Fig. 6(b)], the parabolic profile starts to get perturbed slightly upstream of the bend entrance, and the instantaneous velocity fields display chaotic behavior for $\theta \gtrsim 65^\circ$. Consequently, simulations that rely on modeling the fluctuating field should also incorporate a transition model within the bend to accurately capture the complex flow dynamics and predict the onset of turbulence more effectively. The mean flow field at $\theta = 90^\circ$ resembles the steady base flow observed at lower Reynolds numbers [8]. Two primary vortices are present in the core of the pipe, whereas two smaller swirling motions are detected close to the inner side of the bend. Two additional pairs of vortex cells emerge near the outer wall, where the centrifugal force more effectively confines the flow. Owing to lower cross-sectional momentum transfer, the DNS-180L case exhibits a higher variation in the mean streamwise velocity between the inner and outer walls at $\theta = 90^\circ$ compared with DNS-180T. As one moves along the bend, two of the swirling motions identified at $\theta = 90^\circ$ grow in size, occupying the central part of the cross section, and eventually merge with the other vortical structures, giving rise to a bulge region at the bend outlet ($s/D = 0$). These results highlight that the mean flow development within the 180° bend follows distinct routes for the two inflow conditions, although the time-averaged vortical patterns are similar at the bend exit. However, note that the bulge region in the DNS-180L case is more pronounced, as delineated by the pseudo-streamlines of the mean in-plane velocity field. For laminar inflow conditions, the swirling motions at the side walls bring about three vortex pairs for $0 \leq s/D \leq 2$: in proximity to the outer wall, in the central region of the cross section, and at the inner side of the bend (from bottom to top on the cross-sectional panels). At $s/D = 4$, the central vortices give rise to two swirls at the side walls close to the outer side of the bend. Further downstream, these structures merge with the vortex cells in the center of the cross section, resulting in two vortices at the outer wall and another pair near the inner side of the bend at $s/D = 6$ and $s/D = 8$. This pattern shows similarities to the mean secondary flow at the same streamwise locations in the DNS-180T case. Even for laminar inflow conditions, however, the length of the downstream straight section is insufficient to recover an axisymmetric velocity profile.

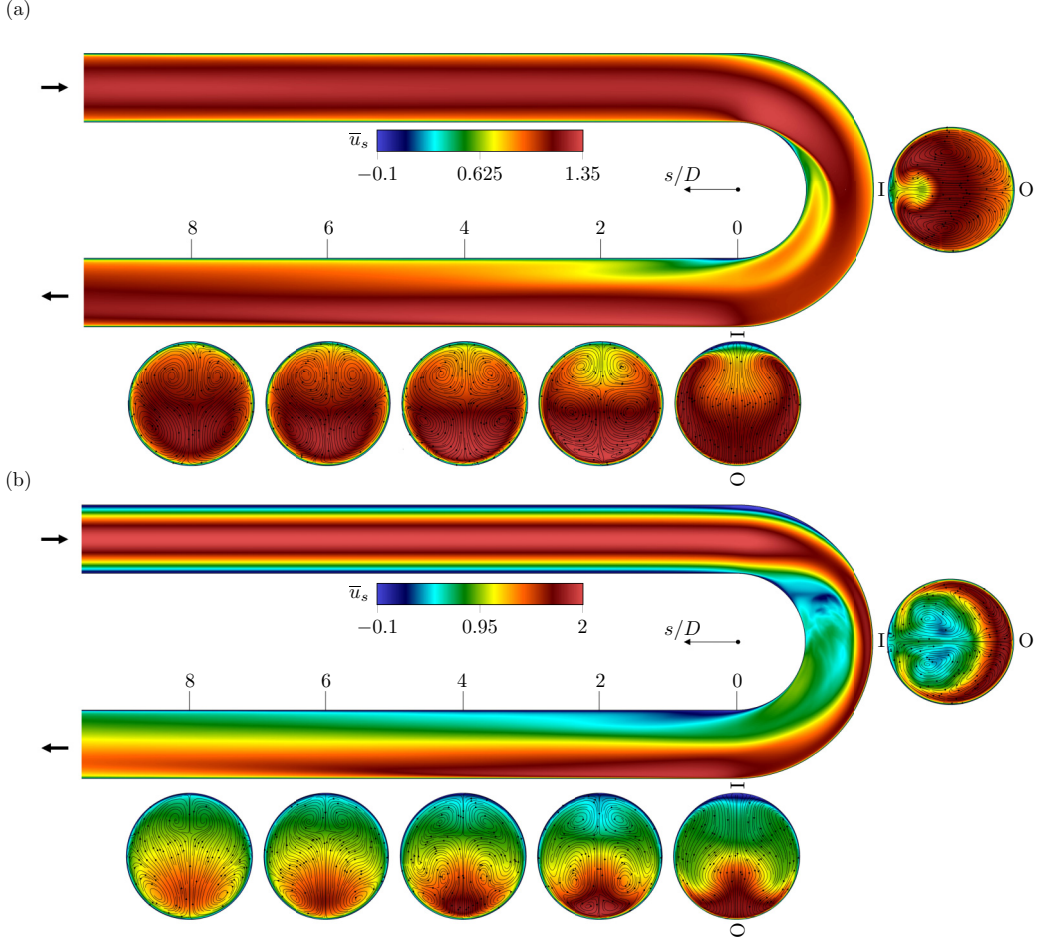


FIG. 6. Time-averaged streamwise velocity $\bar{u}_s$ for (a) the 180°-bend pipe flow with turbulent inflow conditions (DNS-180T) and (b) the 180°-bend pipe flow with laminar inflow conditions (DNS-180L). In both panels, the planar perspectives of the mean flow are shown at $y' = 0$, $\theta = 90^\circ$, and $s/D = 0, 2, 4, 6, 8$. The pseudo-streamlines of the mean in-plane velocity field are also displayed on the cross sections. The inner and outer walls are denoted by I and O, respectively. The black arrows indicate the flow direction.

The different evolution of the swirling motions in the two cases is possibly related to the regions with negative mean streamwise velocity at the exit of the bend [see Figs. 3(b) and 3(c)]. Specifically, the mean recirculation region at the inner wall, close to the bend outlet, is approximately 30% longer for laminar inflow conditions than in the DNS-180T case. Furthermore, in the DNS-180L case, a considerably large area of mean flow separation is found at the outer wall in the initial portion of the bend ($0^\circ \lesssim \theta \lesssim 30^\circ$). Within this area, the negative time-averaged streamwise velocity reaches an absolute value of approximately $0.25 U_b$, significantly higher than the values observed in the mean recirculation regions near the bend outlet in the various cases. Since this separation bubble corresponds to the location where velocity fluctuations first appear in the DNS-180L case, and no reversed mean flow is detected at the same position for the DNS-90T and DNS-180T cases, it is argued that it represents a remnant of the instability that initiates the transition process at a lower Reynolds number [8].

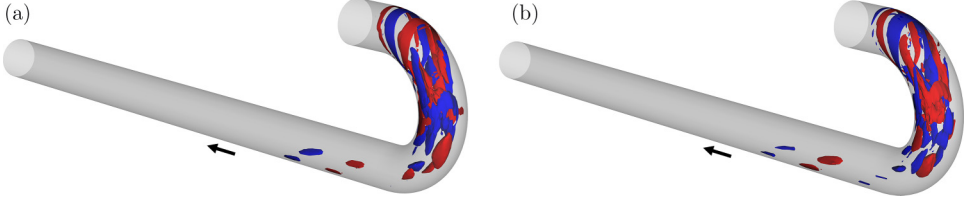


FIG. 7. Isosurfaces of the streamwise velocity component u_s of (a) POD mode 1 and (b) POD mode 2 for the 180°-bend pipe with laminar inflow conditions. Red (blue) isosurfaces correspond to positive (negative) values. The black arrows indicate the flow direction.

The transitional nature of this flow, combined with flow separation and turbulence development, poses significant challenges for accurate modeling. The present dataset also provides a valuable resource for refining Reynolds-averaged Navier–Stokes (RANS) models, which often struggle to accurately characterize turbulent flow in bent pipes [43,44]. Owing to the complexity of the flow topology and its spatially evolving nature, it is unlikely that any single existing model is suitable for the entire domain, highlighting the need for more sophisticated approaches. Novel machine-learned and physics-informed algorithms may provide viable alternatives for this purpose [45,46]. However, the development of suitable turbulence models falls outside the scope of the present work.

Proper orthogonal decomposition of the three-dimensional velocity fields in the DNS-180L case reveals that the most energetic modal pair is symmetric, as shown in Fig. 7. Each of these modes accounts for approximately 6.5% of the fluctuating kinetic energy. They constitute a traveling structure consisting of a ringlike formation at the outer side of the bend inlet, which evolves toward the inner wall. The similarity with the unstable eigenmode at $Re_b = 2550$, related to the transition from the steady to the periodic regime, is striking (see Fig. 6 in Massaro *et al.* [8]). However, it is valuable to note that the amplitude of the unstable eigenmode grows exponentially in time, whereas POD modes are spatially coherent structures extracted from nonlinear data and thus saturate. In addition, the reconstruction obtained by superposing this pair of modes with POD mode 0 resembles the instantaneous flow at $Re_b = 2550$, i.e., provides a reduced-order representation of a limit cycle. Therefore, POD modes 1 and 2 likely represent a footprint of the Hopf bifurcation occurring at $Re_b \approx 2528$ [8]. They are indeed nearly periodic in time, as highlighted by the power spectral densities of the corresponding temporal coefficients (see Fig. 8), which exhibit a relatively sharp peak at $St \approx 0.48$. This value is approximately twice as large as the Strouhal number associated

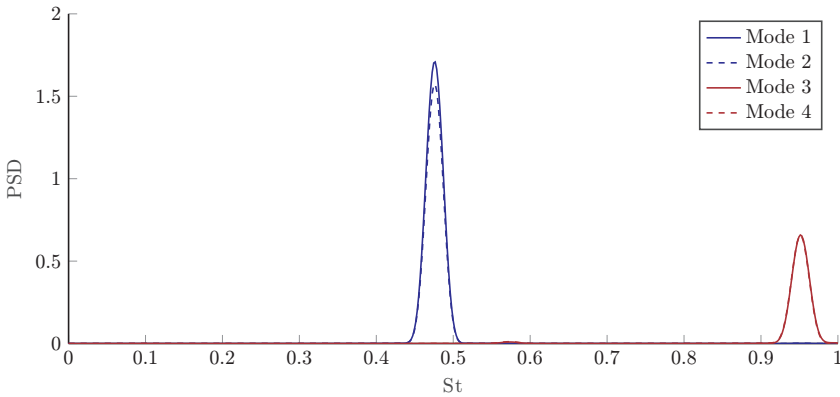


FIG. 8. Power spectral density (PSD) estimate of the temporal coefficients of the four most energetic POD modes for the 180°-bend pipe with laminar inflow conditions.

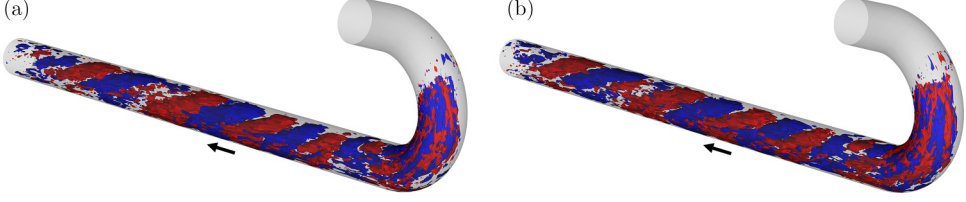


FIG. 9. Isosurfaces of the velocity component normal to the equatorial plane $u_{y'}$ of (a) POD mode 17 and (b) POD mode 18 for the 180°-bend pipe with laminar inflow conditions. Red (blue) isosurfaces correspond to positive (negative) values. The black arrows indicate the flow direction.

with the unstable eigenmode at $Re_b = 2550$ (bear in mind that $Re_b = 11\,700$ in the current study). This shift is expected since the frequency of a limit cycle can vary significantly with the Reynolds number [47]. POD modes 3 and 4 correspond to the first harmonic of the structure described by the most energetic modal pair, as the PSDs of the associated temporal coefficients display a peak at $St = 0.96$. Since both pairs of modes described above are symmetric about the equatorial plane, they do not contribute to swirl switching.

The first POD modes in the kinetic energy ranking exhibiting an antisymmetric behavior are the modes 17 and 18, shown in Fig. 9. Each of them accounts for approximately 0.32% of the fluctuating kinetic energy. They represent a traveling structure similar to that associated with the energetically dominant antisymmetric POD modes observed in the DNS-180T case. Note that the amplitude of these modes is very low in both the upstream straight section and the initial portion of the bend, indicating that they are primarily associated with the chaotic regime, in contrast to POD modes 1 and 2, which are linked to the first global instability. The PSDs of the temporal coefficients associated with POD modes 17 and 18 (see Fig. 10) feature a distinct and narrow peak at $St \approx 0.48$. Additionally, two broader, less prominent peaks are observed at $St \approx 0.23$ and $St \approx 0.3$, in close agreement with the dominant frequency of the most energetic modal pair in the DNS-180T case. The flow reconstruction given by POD modes 0, 17, and 18 clearly highlights the occurrence of swirl switching for $0 \leq s/D \leq 2$, whereas the flow pattern becomes more disordered further downstream. As in the case with turbulent inflow conditions (DNS-180T), the two primary pairs of vortices in the cross section oscillate in opposite directions, i.e., anticlockwise and clockwise directions in the plane $y'p$.

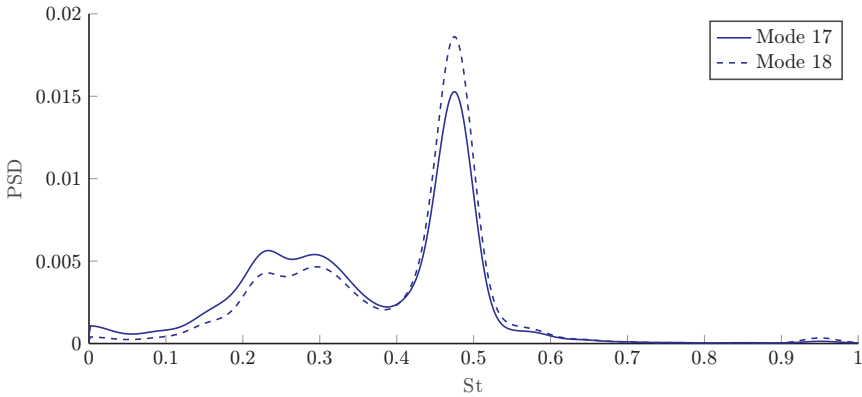


FIG. 10. Power spectral density (PSD) estimate of the temporal coefficients of the most energetic antisymmetric POD modes for the 180°-bend pipe with laminar inflow conditions.

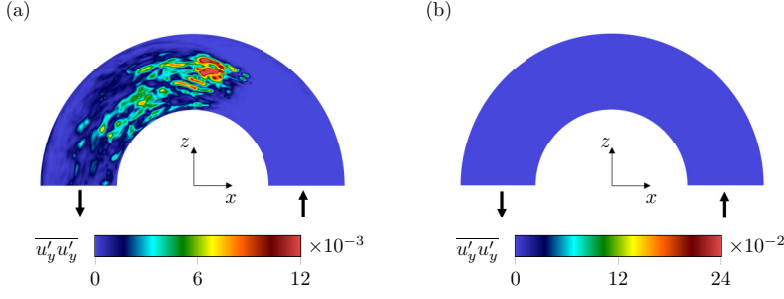


FIG. 11. Normal Reynolds stress in the y direction $\overline{u'_y u'_y}$ on the equatorial plane within the bend. The statistics are computed by employing two different sets of flow fields, which are reconstructed by using (a) symmetric (STAT-S) and (b) antisymmetric (STAT-A) POD modes for the DNS-180L case. The black arrows indicate the flow direction.

These results clearly demonstrate that swirl switching is not strictly dependent on the velocity field imposed at the pipe inlet. It corresponds to the most energetic structure in the case of turbulent inflow conditions, whereas it has a lower kinetic energy than symmetric modes related to the first global instability when a laminar velocity field is prescribed at the inlet. Since the flow in the upstream straight section is not turbulent for the DNS-180L case, it is argued that upstream turbulence and associated structures are not the primary causes of swirl switching. These findings agree with the results of Noorani and Schlatter [20] and Zhang *et al.* [21], who observed the phenomenon in continuously curved pipes, where there is no inflow boundary.

C. Symmetric and antisymmetric flow reconstructions

The DNS-180L case reveals instructive features related to the transition process. In particular, it is effective in detecting symmetric and antisymmetric motions and in isolating the physical mechanisms that contribute to the chaotic regime, both within the bend and downstream of it. To provide a more detailed inspection of swirl switching, the 50 most energetic POD modes for this case are classified as symmetric when $\max(|u_y|) < 10^{-6}$ on the equatorial plane, and as antisymmetric otherwise. Once this categorization is complete, low-order reconstructions are performed using either the symmetric or the antisymmetric POD modes, and time-averaged statistical quantities are computed from the two groups of reconstructed velocity fields. The two sets of statistics are named STAT-S (*symmetric*) and STAT-A (*antisymmetric*). Significant fluctuations of u_y on the symmetry plane are observed for STAT-A, as highlighted by the normal Reynolds stress in the y direction $\overline{u'_y u'_y}$ (see Fig. 11). Turbulent fluctuations are pronounced at $\theta \approx 90^\circ$, especially in the shear layer region, and they contribute to breaking the reflectional symmetry of the flow about the plane xz . In contrast, negligible fluctuations outside the equatorial plane are observed for STAT-S. Although this result is expected due to the inherent symmetric/antisymmetric classification and reconstruction, Fig. 11 provides a crucial suggestion: STAT-A can help identify the regions within the bend where swirl switching initiates. Since this phenomenon appears to be connected with the chaotic regime, the production of turbulent kinetic energy (TKE), $\mathcal{P}_k$, is used to highlight the areas where the POD modes contribute the most to the turbulent fluctuations (see Fig. 12). This physical quantity is selected because it represents the dominant term in the TKE budget.

For STAT-S, the production of TKE is noticeable at $\theta = 30^\circ$, particularly near the outer and side walls. As one moves along the bend, the peak of TKE production shifts toward the inner wall. This spatial evolution resembles the unstable (symmetric) ring-shaped eigenmode reported by Massaro *et al.* [8]. For STAT-A, instead, the production of turbulent kinetic energy is negligible in the first portion of the bend, becoming significant in the middle of the cross section around $\theta \approx 65^\circ$, where strong fluctuations of the streamwise velocity within the shear layer are also observed. Even at

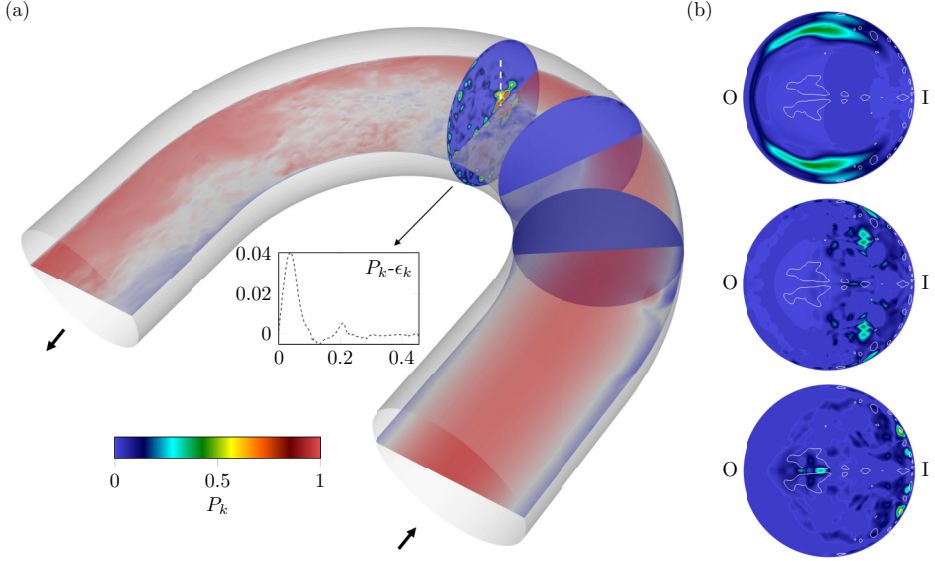


FIG. 12. (a) Instantaneous streamwise velocity on the equatorial plane with the production of turbulent kinetic energy from STAT-A in the cross sections at $\theta = 30^\circ, 60^\circ,$ and 90° . The black arrows indicate the flow direction (a portion of the domain is shown). The difference between the production and dissipation of turbulent kinetic energy along the white dashed line in the plane $y'p$ at $\theta = 90^\circ$ is also reported. (b) Production of turbulent kinetic energy ($\mathcal{P}_k$) from STAT-S in the cross sections at $\theta = 30^\circ, 60^\circ,$ and 90° . The white isolines indicate 50% of $\mathcal{P}_k$ from STAT-A at $\theta = 90^\circ$. The production of turbulent kinetic energy is normalized by its maximum value. The inner and outer walls are denoted by I and O, respectively.

$\theta = 90^\circ$, regions of high $\mathcal{P}_k$ coincide with areas of significant shear rates in the instantaneous and mean velocity fields. Hence, the spatial distribution of TKE production for STAT-A indicates a relationship between swirl switching and the shear layer, as it traces the radial evolution of the latter through the bend from $\theta \approx 65^\circ$ to $\theta \approx 90^\circ$.

Note that the onset of transition in 180° -bend pipe flows with $\delta = 1/3$ is triggered by a global instability of the shear layer. Specifically, a Hopf bifurcation occurs at $\text{Re}_b \approx 2528$, leading to a symmetric periodic flow [8]. Assuming that the system follows the Ruelle–Takens–Newhouse route to turbulence for $\delta = 1/3$ [48,49], it is likely that the shear layer undergoes a symmetry-breaking bifurcation at a Reynolds number lower than that of the present study, leading to a state in which swirl switching occurs. Then, the antisymmetric POD modes identified here would represent a remnant of this instability. This conjecture is further supported by the observation of a footprint of the global instability of the initial steady state in the symmetric POD modes extracted for the case with laminar inflow conditions. Further investigations, particularly an analysis of the secondary instability, are required to validate this hypothesis. However, a wide range of Reynolds numbers needs to be examined to identify the possible onset of this bifurcation, and this is outside the scope of the present work.

To further characterize regions of substantial antisymmetric TKE production and clarify the underlying statistical kinetic energy transfer, Fig. 13 shows the Reynolds stresses involved in the x component of the Reynolds-averaged momentum equation at $\theta = 90^\circ$ for STAT-A. It is not surprising that they attain high absolute values in the same regions of the cross section where $\mathcal{P}_k$ for STAT-A is significant. In these areas, substantial kinetic energy is extracted from the mean flow and transferred to the antisymmetric fluctuating velocity field. Drawing an analogy with strong fronts in transitional straight pipe flows [50–52], it is argued that swirl switching is sustained by this kinetic energy transfer in regions where TKE production exceeds dissipation (see the inset in Fig. 12).

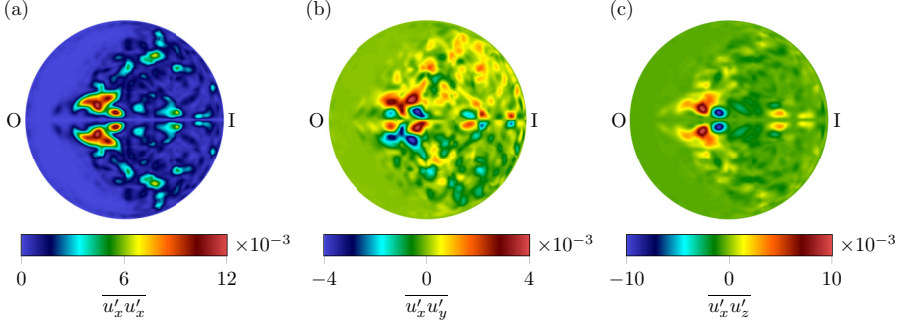


FIG. 13. Reynolds stresses (a) $\overline{u'_x u'_x}$, (b) $\overline{u'_x u'_y}$, and (c) $\overline{u'_x u'_z}$ from STAT-A in the cross sections at $\theta = 90^\circ$. Note that $\overline{u'_x u'_y}$ and $\overline{u'_x u'_z}$ need to be zero on the equatorial plane due to symmetry. The inner and outer walls are denoted by I and O, respectively.

V. CONCLUSIONS AND OUTLOOK

High-fidelity direct numerical simulations of the flow at $Re_b = 11\,700$ through 90° - and 180° -bend pipes with curvature $\delta = 1/3$ are performed in the present study. The main focus of the work is investigating swirl switching, a phenomenon reported in the literature on curved pipe flows [10,12,20] whose origin remains unexplained despite several suggested hypotheses. To understand the connection of swirl switching with turbulent structures originating in the upstream straight section, both turbulent and laminar velocity fields are prescribed at the inlet of the computational domain.

Large-scale spatially coherent structures are extracted via proper orthogonal decomposition of three-dimensional velocity fields. Flow reconstructions based on POD modes reveal swirl switching for both bending angles and inflow conditions, even though the phenomenon does not correspond to the most energetic structure when a laminar velocity field is prescribed at the inlet of the pipe. In this latter case, the most energetic POD modes are symmetric and presumably represent a footprint of the instability occurring at $Re_b \approx 2528$ [8]. In the cases with turbulent inflow conditions, the POD modes associated with swirl switching are significantly stronger and more distinct in the 180° -bend pipe than in the geometry with smaller bending angle. This observation locates the origin of the phenomenon within the curved section, where significant changes in the mean flow field may contribute to this strengthening. The occurrence of swirl switching even when neither turbulence is prescribed at the inlet nor chaotic behavior arises in the upstream straight section further suggests that the phenomenon does not necessarily require upstream turbulence and is intrinsically related to curvature, as speculated by Noorani and Schlatter [20].

This study employs an innovative approach to track the evolution of swirl switching by examining statistical data derived from the flow fields reconstructed using only the antisymmetric POD modes (STAT-A) extracted for the 180° -bend pipe with laminar inflow conditions. These statistics show considerable turbulent kinetic energy production within the bend, starting from the location that marks the onset of chaotic behavior and is characterized by significant shear rates ($\theta \approx 65^\circ$). These observations, combined with the association of symmetric POD modes with earlier instabilities, suggest that the antisymmetric modes contributing to swirl switching may be linked to a bifurcation that breaks the symmetry of the flow about the equatorial plane and is part of the route to turbulence. It is posited that this instability is related to the shear layer arising because of the curved geometry. Given these considerations, swirl switching would be a characteristic phenomenon of both transitional and turbulent flows.

Although the present study rules out upstream turbulent fluctuations as the primary cause of swirl switching, it does not address whether the phenomenon can arise when the flow does not reach a chaotic state, e.g., in a quasiperiodic regime. Investigating this aspect could help establish

a lower threshold of Re_b for the onset of swirl switching. Subsequent stability analysis in the neighborhood of this Reynolds number could then assess the link between swirl switching and shear layer instability. However, this approach would require accurate tracking of the bifurcation cascade and computational tools for studying the stability of periodic and quasiperiodic flows.

While industrial applications typically involve flows at Reynolds numbers higher than those considered here, swirl switching is still observed and contributes to pipe vibrations and fatigue [53]. Therefore, identifying its spatial origin, as analyzed in this study, may provide valuable insight into its suppression and control in practical contexts.

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Correction: Figure 1 contained duplicate panels and has been replaced with the correct version.