Near-wake analysis of perforated disks with varying hole topology

R. Theunissen¹*, R. Worboys¹, A. Masullo¹
¹: Dept. of Aerospace Engineering, University of Bristol, UK
* Correspondent author: r.theunissen@bristol.ac.uk

Keywords: near-wake, porosity, disk, drag, LDA, PIV

ABSTRACT

Porous disks are encountered in multiple applications such as fluidic damping and chemical mixing and are commonly used in experimental studies pertaining wind turbines and parachute deployment. Although it is commonly assumed that solely porosity dictates the disk’s associated drag coefficient, experimental studies presented within this paper have indicated both porosity and hole topology to be pivotal and an explicit relation is derived. To further understand the underlying flow dynamics, near-wake surveys have been performed on a variety of perforation layouts using two component Laser Doppler Velocimetry, two-component Particle Image Velocimetry and Hot-wire anemometry. Based on the evolution in downstream centerline velocity deficit the ensemble of tested disks could be grouped in 5 categories. For disks with a pore-spacing to disk radius below 0.01 individual jets would merge along the centerline eliminating the appearance of the typical rear stagnation point and with features distinct from those encountered in studies related to planar parallel jet merging. Despite the potential absence of an encapsulated near-wake in the temporal averaged velocity field, spectral analyses of the collected velocity data have evidenced the existence of a near constant low frequency near-wake motion for all disk tested and a larger scale motion related to vortex shedding which increases in frequency in a near quadratic tendency with porosity. Furthermore, probability distributions of velocities for lower porosities show clear signs of bi-modality caused by this low frequency motion. The near-wake velocity field remains highly random in 3 dimensions with strong coupling between the shear-layers originating from the disk circumference and pore jets, making it impossible to distinguish dominant modes. Nevertheless, mean velocity fields illustrate the complexity of the near-wake with the presence of flow features involving multi recirculation zones and axial a-symmetry depending on porosity and pore topology.

1. Introduction

When modelling wind turbines the main region of interest is the far wake (excess of approximately 6-7 turbine diameters downstream) in which the velocity field can be assumed to have reached self-similarity. In this region the wake can be presumed to have only a weak memory of how it was generated and porous disks can be used to simulate to most important wind turbine wake characteristics (Sforza et al., 1979). In line with this common approach, Theunissen et al. (2015) investigated the suitability of several disk layouts as wind turbine analogue and reports a
dependency of the wake recovery not only on porosity, $\beta$, defined as the ratio between the open and closed area, but also on the topology of the perforations. The origin of these variations will be the topic of interest in this paper.

Medici and Alfredsson (2005) compared the vortex shedding from slotted disks of varying porosity and rotating turbine models and concluded that disks gave rise to large-scale vortex shedding with a frequency nearly independent of porosity. Moreover, shedding was noted to become less distinct with increasing porosity. The latter is in agreement with Castro (1971) who stated that no ring vortex is developed when the porosity of the plate is larger or equal to 0.3. Castro’s sketches further suggest the appearance of a recirculation area behind the disks which delays the merging of the outer shear-layers. This plays an active role in subsequent wake development as the more rapid the shear-layers are able to communicate the faster self-preservation in mean velocity sets in (Huang and Keffer, 1996). These findings imply that the wake development can be influenced by the near-wake region, which in turn is influenced by the disk’s porosity. The flow visualization experiments of Cannon et al. (1993) indeed show that disks with high porosity produce jet-like wakes. Perera (1981) for example reported the absence of recirculating regions behind fences with porosities above 30%. These findings are corroborated by Cannon et al. (1993) who shows that for a fixed Reynolds number an increase in porosity corresponds to a decrease in normalised wake deficit with the eventual disappearance of the region of reverse flow attached to the body. Theunissen et al. (2015) on the other hand did not observe this correlation but found wake recovery to be strongly dependent on pore topology. In fact, Roberts (1980) reasoned that the jet phenomenon, and therefore the near-wake, is pivotal in the wake flow behind slotted disks. With decreasing porosity Roberts found the extension of the reverse flow region to increase. More importantly, only the wake behind the most porous case (ratio of 1) remained axisymmetric whereas other wakes showed three-dimensional oscillations. Kim and Lee (2001) investigated the effect of hole diameter for fences with fixed porosity and similarly reported that holes of smaller diameter, and hence smallest spacing, showed the largest reduction of streamwise velocity in the wake behind the fence and accordingly the fastest wake growth. This again instigates pore layout to be influential. Roberts (1980) drew a similar conclusion in that the drag coefficient of a porous disk was not uniquely determined by the porosity and Reynolds number alone, but also the slot arrangement. Castro (1971) investigated the drag of porous plates in function of porosity for two Reynolds numbers and reported, as to be initially expected, an increasing drag coefficient with decreasing porosity. However, according Roberts increasing porosity could even lead to drag coefficients higher than that for a solid disk.

The foregoing literature indicates an unambiguous coupling between porosity, pore topology and wake development, whereby the characteristics of the near-wake play a dominant role. This in
turn will influence the disk’s drag coefficient. Though insightful, results are somewhat inconclusive as to what the mechanisms driving the wake generation of a porous disk are and a precise understanding of the coupling is lacking. In particular the macroscopic examinations of the flow fields neglect an important phenomenon which relates to the microscopic flow structure behind the adjacent small elements within a porous body; the resultant merging of the jets emanating from the pores seems to govern the overall flow (i.e. wake recovery and drag coefficient). The current work therefore aims to identify the physical processes through which pore topology alters the wake characteristics.

After presenting the experimental setup, this paper will illustrate the dependency of the drag coefficient of a porous circular disk on the hole topology by means of drag measurements. Laser Doppler Anemometry (LDA) measurements are subsequently performed along the wake centreline to identify merging and stagnation point enabling a classification of the discs in distinct categories. Spectral analysis of the recorded LDA data is performed revealing the presence of near-wake oscillations and larger scale vortex shedding. Hot wire anemometry on the other hand indicates the strong interaction between the outer shear-layers and pore jets. Full field velocity fields obtained through PIV are subsequently utilised to investigate the larger wake structure and complement the LDA-based characteristics of the near wake flow.

2. Experimental facility

2.1 Disk Geometries

Four geometric features of the disks with radius $R$ have been identified to represent the hole topology; hole center spacing $S$ defined as the shortest distance between the centers of two adjacent holes, hole center radius $r_p$ pore radius $h$ and number of pores $N$. The geometric parameters are related through the following equations;

$$h = \left(\frac{\beta}{N_p}\right)^{0.5} R \quad \text{and} \quad S = 2 \cdot r_p \cdot \sin(\pi/N_p)$$  \hspace{1cm} (1)

Note that the maximum distance between two holes is thus given by $2r_p/R$. These parameters were varied under constant porosity to produce a group of six disks (A, B, C, D, E, F) with different topologies, which are tabulated in Figure 1. The number of holes $N$, was selected to be either four or six. These numbers were chosen to provide the lowest number of holes generating a disk with at least two orthogonal planes of symmetry thus preserving as much rotational symmetry as
possible. The radius of the holes was determined as a result of obtaining the correct porosity once the number of holes was selected as per equation 1. The hole center radius $r$, was varied to enable a matching of the spacing ratio $S/h$ for disks across different porosities as well as varying the radius ratio $r/R$. Disks were 3D-printed out of ABS-M30 for manufacturing practicality with a thickness $t$ of 6mm yielding a thickness to diameter ratio of 0.1.

![Pore topologies](image)

<table>
<thead>
<tr>
<th>Topology</th>
<th>$N_h$</th>
<th>$r_p/R$</th>
<th>$h/R$</th>
<th>$S/R$</th>
<th>$S-Zh/R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 6</td>
<td>0.51</td>
<td>0.09</td>
<td>0.51</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>B 36</td>
<td>0.36</td>
<td>0.09</td>
<td>0.36</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>C 4</td>
<td>0.51</td>
<td>0.11</td>
<td>0.73</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>D 4</td>
<td>0.36</td>
<td>0.11</td>
<td>0.51</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>E 4</td>
<td>0.41</td>
<td>0.11</td>
<td>0.58</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>F 4</td>
<td>0.45</td>
<td>0.11</td>
<td>0.65</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 (Top Left) Pore topologies (Top Right) Parameters for various topologies tested (Bottom) Overview of the geometrical parameters defining the disks selected for further LDA and PIV investigation. Dark gray indicate excluded disk topologies due to unphysical parameter values. Light gray cells indicate the disk types exhibiting pore jet merging.

### 2.2 Wind tunnel facility

Experiments were performed in the low turbulence wind tunnel of the department of Aerospace Engineering at the University of Bristol. This is a closed circuit tunnel capable of speeds up to 100m/s while providing a flow of high uniformity and low turbulence intensity (<0.09%). The working section has a rectangular cross-section of 0.8m×0.6m. Given the dimensions of the disk, a negligible blockage of 0.6% was obtained. All disks were subjected to a freestream velocity $U$ of 30m/s equating to a diameter-based Reynolds number $Re_D=1.2\cdot10^5$. This Reynolds number was selected as drag coefficients became constant beyond.

When performing velocity measurements an aluminum ring located at the center of the test section was attached through four 3mm metallic poles allowing a secure fit when the disk was inserted (yielding a total diameter of 60mm) and minimize system vibrations (Figure 2-left). Given their small radius with respect to the disk diameter, the influence of the rods on the wake structure was considered marginal.
2.3 Data acquisition

Force measurements were performed by means of a SMD load cell equipped with a 5N capacity strain-gauge connected to a 16bit A/D board. Each measurement consisted of 1800 samples collected at a frequency of 30Hz, which were analyzed by means of statistical bootstrapping (Theunissen et al., 2008) to return statistical moments and uncertainty estimates at 95% confidence level.

![Image: Disk mount in the test section of the University of Bristol's low turbulence wind tunnel (Middle) LDA centerline measurements (Right) PIV setup.]

Wake velocities along the disk centerline were characterized using a Dantec Dynamics two-component Laser Doppler Anemometry system (LDA) adopting a lens with 600mm focal length. Sampling was conducted with a resolution of 0.05· D (3mm) between 0.3≤X/D≤4.3 and 0.17· D (10mm) between 4.3≤X/D≤8.3. The principle beams had a diameter of 2.2mm and were separated 38mm prior to passing through a beam expander of ratio 1.98 yielding maximum measurement volume dimensions of 0.179mm and 2.8mm perpendicular and parallel to the flow direction respectively. The two orthogonal planes spanned by the two laser beam pairs were orientated at an angle of 45 degrees with respect to the freestream direction to maximize the data rate in coincident mode. The laser probe was mounted on a computer controlled traverse system capable of incremental displacement steps of 0.5mm. At each spatial sampling location typically 8000 instantaneous measurements were collected at a typical data rate of 0.8kHz. Transit times, defined

† The initial non-zero measurement location was due to the mounting structure obstructing the LDA laser paths.
† coincident mode refers to the validation of a burst signal only when the signal recorded by all channels (i.e. directions) is considered valid.
as the difference in tracer particle arrival times, were used as weighting in the calculation of statistical moments to reduce bias errors (Hösel and Rodi, 1977).

**Fig. 3** Exemplary schematic depicting the orientation of the three 2D2C PIV measurement planes together with the adopted coordinate systems.

Full-field wake surveys were obtained using a two-dimensional two-component Dantec Dynamics Particle Image Velocimetry (PIV) system. For each disk tested with PIV, three orientation measurement planes were taken; a vertical one crossing two pores, a diagonal plane between pores and an offset plane across two pores (Figure 3). Seeding was generated by atomizing a mixture of PEG-80 and water producing 1μm tracer particles. Illumination was provided by a Litron 200mJ laser with a repetition rate of 15Hz and optically transformed into a 1mm thick laser sheet. The CMOS sensor of the SpeedSense M340 consisted of 10μm pixels arranged in a 2560×1600 array. With a calibration factor of 15.5 pixels/mm the corresponding field of view covered approximately 2.75 disk diameters downstream and 1.72·D in vertical direction. The separation between laser pulses was set at 40μs, producing a maximum particle image displacement of approximately 20 pixels at the pores. Images were a-priori enhanced using a minimum intensity background subtraction (Wereley et al., 2002) followed by a spatial low-pass filtering adopting a Gaussian kernel with 1 pixel standard deviation. In total 1936 image recordings were analyzed with a standard PIV processing routine incorporating iterative correlation window size reduction and image deformation. Final correlation window sizes were 32×32 pixels (~2.1mm×2.1mm) with an overlap of 75% resulting in a structured vector field with approximately 0.5mm grid spacing. Constant temperature hot wire anemometry (HWA) was performed with a Dantec Dynamics Streamline Pro system. The probe consisted of single 5μm wire of 1.25mm length oriented perpendicular to the freestream direction. At each measurement location 2.4 million velocity readings were accrued at a sampling frequency of 40kHz to allow noise reduction by block-averaging spectra.
3. Results

3.1 Force measurements
The evolution in wake-blockage-corrected drag coefficient* with Reynolds number is depicted in Figure 4 and shows the drag coefficients to attain constant values beyond $Re_\infty$=1.2×10^3. Drag values in function of porosity are tabulated and illustrated in Figure 5. In comparison, the drag coefficient for a circular solid disk is typically measured to be approximately 1.17 for Reynolds numbers of 1.3×10^3 (Blackmore et al., 2014), which is in agreement with the depicted results considering the limit of $\beta \rightarrow 0$. As reported by Roberts (1980), careful selection of porosity and pore topology may actually yield drag coefficients exceeding the one of the solid disk, which is also observed here. While the simplistic equation $C_D = 16 \cdot \beta^2 \cdot (1 - \beta) \cdot (5\beta^2 - 2\beta + 1)^2$ of Taylor (1983) relating the drag coefficient with porosity fits well for higher porosities, it is only valid for porosities in excess of 1/3. The dashed line represents a fit to the present data and shows the typical tendency of increasing drag coefficient with decreasing porosity. However, with error bars indicating 95% confidence levels, the variation in drag coefficient for a given porosity is clearly due to underlying flow dynamics, irrefutably demonstrating drag to be influenced by both porosity and topology combined. Furthermore, for a given porosity no topology (A-F) can be assimilated with a higher drag coefficient indicating a flow-dictated interaction between porosity and topology (Figure 5a). Craze (1977) stipulates that for a fluff body with relatively fixed separation point, which in case of the disk will be on its outer perimeter, the drag coefficient is controlled by the behavior of the outer free shear-layer. In particular, the characteristic thickness, entrainment length and velocity of the shear-layer are the dominant characteristics. Since the shear-layer will be turbulent once separated, the length of the entrainment region will be Reynolds number independent. This justifies limiting the performed investigations to a single $Re_\infty$. Recently Nedic et al. (2013) investigated the wake shed from plates with fractal edges and stipulated the drag coefficient to be related to the wake volume and dissipation of turbulent kinetic energy in the wake. Furthermore, Huang and Keffer (1996) state that the outer shear-layers play an active role in the subsequent wake development. The more rapid the outer shear-layers are able to communicate the faster self-preservation in mean velocity sets in. From this perspective the near-wake behind the perforated disks can be thought to be most influential to the shear-layer behavior and deserves further investigation.

---

* the corrected drag coefficient $C_{D,c}$ has been calculated as $C_{D,c} = C_D \cdot (1 + nC_D A / A_t)^{-1}$, where $A_c$ is the frontal area of the disk, $A_t$ the cross-sectional area of the wind tunnel and $n$ the blockage factor according Gould (1970).
3.2 Temporal averaged centerline velocity

Of the original 30 disks, all porosities up to and including 0.25 were selected for further LDA measurements as these indicated the largest variation in drag. Analysis of the centerline velocity deficits $\Delta u_m=1-U/U_\infty$ with downstream distance indicates the presence of 5 general tendencies across the different topologies, which are depicted in Figure 6. The first type involves the presence of a large recirculation area ($\Delta u_m>1$), which is only obtained for the lowest porosity ($\beta=0.05$). Note that the solid disk belongs to this category. Among the three topologies (A, C, F) differences become marginal beyond 2-3 disk diameters. Indeed, the rear-stagnation point, identifiable as $\Delta u_m=1$, indicates the location where the outer shear-layers merge and terminate the near-wake. Figure 7 presents an overview of the near-wake extents together with a graphical representation.
Among each porosity group a large variation in the location of the merging or stagnation point can be noted and a direct correlation between wake extent and drag coefficient is missing.

This limited extent of the near-wake can be observed across the five regimes. In the second regime the flow tends to initially have a velocity lower than freestream and gradually decelerates (increase in $\Delta u_m$) to give rise to a recirculation zone ($\Delta u_m$>1) after which ($X/D$>2.5) the bulk wake starts to recover. Differences between the different topologies are again limited to the near-wake region ($X/D$<2.5). In the third regime, which is predominantly encountered for a porosity of 0.1 (2nd porosity group) a large recirculation area is formed directly behind the perforated disk, which is also the case in the fourth mode. The latter is mainly ascribed to the disks with a porosity of 0.2. Velocities in the recirculation zone are quasi-constant, fluctuating around $\Delta u_m/U_{\infty}$~1.3-1.4, contrary to those depicted in Figure 6d where the magnitude of the reverse velocity component gradually decreases with downstream distance. Finally, the fifth regime categorizes disks where the flow displays no recirculation at all; the outer shear-layers do not merge as this event would be identifiable by the appearance of a stagnation point ($\Delta u_m/U_{\infty}$=1). Surprisingly, in this category the

![Fig. 6](image-url)
disk with topology D and porosity of 0.25 (i.e. disk 4D) shows the presence of a pocket of flow with a higher speed than the freestream ($\Delta u_->0$). For these higher porosities tested ($\beta=0.2$, 3rd porosity tested, and $\beta=0.25$, 4th porosity tested) the flow accelerates (decreasing $\Delta u_m$) then reaches a maximum within 1 disk diameter downstream, after which deceleration takes place. In case of disk 2B (i.e. $\beta=0.1$ with topology B) this deceleration can go as far as a reverse flow ($\Delta u_m>1$).

Wake recovery can be mathematically modelled as $\Delta u_m/U_\infty \sim (X/D)^n$. When tested on velocity data for $4 \leq X/D \leq 8.3$, no tendency with respect to topology can be observed (Figure 8) nor is there evidence of a linear evolution in power per topology. It is interesting to note that a porosity of 0.05 shows the least fluctuations around a power of 1.3. Indeed, at low porosity all topologies, with exception of topology B, yield wake centerline evolutions of the same category (cf. Figure 6). The power $n$ generally decreases with increasing porosity nevertheless, implying a longer downstream distance before reaching freestream velocity. These LDA findings are in accordance with those of Cannon et al. (1993) albeit only for particular perforations; altering the pore topology for a given porosity influences the wake recovery and can be made faster than a lower porosity. The variation in $n$ among the disks of the same porosity also suggests that the wake downstream does depend on upstream conditions.

No general conclusion can be drawn with respect to centerline velocity evolution in terms of the combined effect of porosity and topology. The results do show however that the number of holes $N$, does not influence the centerline velocity evolution. Moreover, as the porosity increases, so does the flow mode; small porosities are assimilated with flow regimes one and two for example (cf. Figure 6). Neither can a direct correlation between wake deficit or wake structure and drag
coefficient be identified from these LDA measurements. On the other hand, the velocity profiles pertaining all the regimes with exception of the 5th regime, show a close resemblance to those in case of parallel jets (Tanaka, 1974); flow decelerates (Δu increases) and a zone of recirculating flow (Δu>1) precedes the merging point (i.e. the point of zero velocity, Δu=1) after which the velocity increases (Δu decreases) to attain a maximum (lowest Δu) and the flow starts to decelerate (Δu increases). This could imply that the flow ejected from the disk pores coalesce and demonstrate a behavior resembling that of parallel jet flow. However, this supposition will be refuted by the PIV measurements.

![Graph showing evolution in wake decay parameter n with porosity (evaluated for X/D>4) combined with linear trendlines.](image)

**Fig. 8** Evolution in wake decay parameter n with porosity (evaluated for X/D>4) combined with linear trendlines.

### 3.3 Pore exit velocity

Based on the LDA measurements performed on the perforations’ centerline nearest to the disks (X/D=0.3) the variation in exit velocity U is plotted in Figure 9. Depending on the topology of the perforations the measurement location ranged between 1.5 and 3.3 pore diameters downstream. While for a single jet this still falls within the potential core, Figure 9b shows the presence of strong longitudinal gradients decelerating the exit flow. This in turns signals the jet trajectories to be already curving, either inside or outside at the measurement location (Anderson *et al.*, 2002).
Exit velocities can exceed the freestream velocity although no correlation can be deduced with either the disk centerline velocities or the derived velocity gradients. As porosity is augmented, a general tendency of the pore exit velocity to increase with $\beta$ can be observed. Disks with topologies A and C seem not to follow this trend although this is most likely caused by the jets having deviated too strongly already at the initial LDA measurement location. Indeed, topologies A and C are the disks with the perforations distanced furthest from the centerline and are thus expected to rapidly interact with the outer shear-layers.

Based on the estimates of pore exit velocity a tentative relationship is sought with the drag coefficient. For parallel jets several studies report a linear dependence between the jet merging point and the jet spacing (Lin and Sheu 1990, Villermaux and Hopfinger 1994, Durve et al. 2012). Although such a linear tendency was not observed here, the volume of the wake must be influential in the establishment of the drag coefficient and the near-wake extent must concomitantly be considered through the average spacing $\bar{S}/D$. The total force acting on the perforated disk must simultaneously be the remainder of the difference between the pressure force acting on the base and the thrust produced by the jets. The latter is given by the momentum difference $\rho \cdot N \cdot h \cdot \vec{U} \cdot (\vec{U'} - \vec{U})$, which, involving the observed tendency in pore velocity with porosity, allows scaling as $Re \cdot N \cdot \beta$. Indeed, introducing the parameter $\zeta = Re \cdot N \cdot \beta \cdot \bar{S} \cdot D$ a linear relationship between $C_D$ and $\zeta$ is obtained for disks evincing an enclosed near-wake (Figure 10);

$$C_D = -0.214 \cdot 10^{-4} \cdot \zeta + 1.23 \quad \text{with} \quad \zeta = (Re_p \cdot \frac{\bar{S}}{D} \cdot N_p \cdot \beta^{0.5})^{-1}$$

(2)
For sufficiently low disk-based Reynolds number, the drag coefficient will undoubtedly depend also on this number. For sufficiently large Reynolds numbers however, the results currently presented provide, to the best of the authors’ knowledge, a first time explicit proof of the stipulated interrelation between drag coefficient, perforation layout and Reynolds number. In case of the solid disk, $\beta$ and $Re$ are zero in which case the line fit results in a $C_D$ of 1.23, which is remarkably close to that of a solid disk found in related studies. Note that along the pore centerline at $X/D=0.3$ topology C did not follow the general trend in pore velocity with porosity and as such deviates from the trendline.

3.4 Centerline longitudinal and transversal turbulence intensity
Studies performed by Tanaka on the interference of two-dimensional parallel jets (1974) indicate the horizontal turbulence intensity to attain two local maxima with downstream distance, which are attributed to the merging of the jets. An overview of the evolution in horizontal and vertical turbulence intensities along the centerline for the various disk topologies is presented in Figure 11. Here a Savitzky-Golay filter has been applied to the data to reduce randomness of the data and improve readability. The first observation is that while for the solid disk the turbulence intensity in the horizontal direction ($\sqrt{u'^2}/U_{\infty}$) is lower than its orthogonal counterpart ($\sqrt{v'^2}/U_{\infty}$), the relative peak intensities are highly pendent on porosity and topology. For porosities of 0.05 and 0.1 (porosity groups 1 and 2) the turbulence intensity in the vertical direction peaks at the nearwake extent. Because of the interaction of the shear-layers the lateral velocity fluctuations exceed those in the longitudinal direction, which in agreement with intermingling jets (Lin and Sheu, 1990). As porosity increases, extrema in vertical turbulence intensities generally decrease in magnitude with highest values for the solid disk. Moreover, differences in downstream evolution
of $\sqrt{\langle v'v' \rangle/U_*}$ are marginal across the topologies for $\beta=0.05$ and become larger with increasing porosity. However, generally a similar tendency can be observed across the topologies for a given porosity with peaks in $\sqrt{\langle v'v' \rangle/U_*}$ coinciding with the near-wake extents. For the lowest porosity considered ($\beta=0.05$) the magnitude of the horizontal fluctuations attains a maximum before 1 diameter and here a tendency related to the spacing ratio can be noted; with increasing $S/h$ ratio (B; D; E; A; F; C), the peak in horizontal turbulence intensity shifts upstream and reduces in amplitude. Although the reduction in amplitude is analogous to parallel jet studies, longitudinal distribution of turbulence intensity typically peaks further downstream with increasing spacing. Surprisingly disks 3D ($\beta=0.2$), 4D and 4E ($\beta=0.25$) display distinctly different tendencies in turbulence intensities compared to the disks of the same porosity and exactly these disks did not exhibit a closed recirculation area. It will be shown from the PIV measurements that these disks produce merging pore jets along the centerline, even though the tendencies in turbulence bear no resemblance to those of merging jets. Further tell-tale signs are the absence of recirculation and an acceleration of the flow instead (Figure 6) combined with high peaks in $\sqrt{\langle u'u' \rangle/U_*}$. It can be therefore concluded that when the pores are positioned close to the center, i.e. $r/R<0.5$, with sufficiently small spacing ($S/h<2.5$) the jet flows issued from the pores merge along the centerline though with particular characteristics distinct from parallel jet theory. Nevertheless, this cannot be assimilated with a larger or smaller drag coefficient.
3.5 Velocity probability density distribution bi-modality

Hartigan’s unimodality test was applied to the 8000 instantaneous LDA samples along the centerline for both velocity components (Hartigan and Hartigan, 1985) yielding dip test statistics $f_u$ and $f_v$. After smoothening the spatial distribution of the heuristics using a sliding averaging to minimize noise influence, the location of the maximum was extracted. While the magnitudes of parameters $f_u$ and $f_v$ do not infer explicit information about the amplitude of the fluctuations, higher values indirectly imply the fluctuation modes to be more distinct as illustrated in Figure 12 for disk 1B. In case of an oscillation for example, this would correspond to a higher amplitude. Higher $f_u$ and $f_v$ values will typically be accompanied by higher turbulence intensities (cf. Figure 11) as the bi-modal shape will cause the probability distribution to widen. However, the inverse relationship needs not to hold as can be verified by the lower value of $f_v$ in Figure 12 at $X/D=2.25$ for disk 1B, which is accompanied by a higher transversal turbulence intensity.

To distinguish spatially local events, crest factors are introduced. While high crest-factors related to parameters $f_u$ and $f_v$ indicate resemblance of the local velocity probability density function to a

\[ C(f) = \frac{f(x)}{\sigma} \]

where $\sigma$ has been derived based on the triangular threshold method (Zack et al., 1977) applied to the probability density function of $f$. 

\* the crest factor $C$ of each parameter $f$. has been defined as $C = \frac{(f(x))_{\text{max}}}{\sigma}$ where $\sigma$ has been derived based on the triangular threshold method (Zack et al., 1977) applied to the probability density function of $f$. 

---

Fig. 11 Evolution in longitudinal (top row) and transversal (bottom row) turbulence intensity for different porosities (left to right) $\beta=0.05$, $\beta=0.1$, $\beta=0.2$ and $\beta=0.25$. 

---
bi-modal distribution, low crest values can have multiple causes. The most straightforward reason is a low bi-modality in the probability density functions, due to either the absence oscillations or indistinct modes. Alternatively, a low crest value may imply that no definite extremum in the spatial variation of factors \( f \) or \( f' \) along the centerline can be identified. In other words, the probability density function of the velocity components does not alter spatially. However, since outer shear flows merge at approximately \( X/D = 2.5 \) and LDA measurements extend to \( X/D = 8.3 \), a bulk of the sampling location are in fully turbulent flow in which no bi-modality is to be expected and a spatial variation of \( f \) and \( f' \) must be present. As such, crest-factors below \( \sim 1.2 \) evince low reliability in the test heuristics.

The location of the peaks with porosity is depicted in Figure 12b together with the crest-factors reflected by the marker size and accompanying numbers. In comparison, the strongest bi-modalities for the solid disk were observed at \( X/D = 0.32 \) and \( X/D = 2.65 \) for the horizontal and vertical velocity components respectively with accompanying crest factors of 1.36 and 1.49. It is known from a solid disk that vortex shedding appears at regular intervals, although the circumferential location of the shedding is random (Miau et al., 1997). This can explain the observed spatial motion of the near-wake since the irregular vortex shedding causes the near-wake to oscillate at random frequency giving rise to bi-modal velocity distributions. Figure 12b depicts the location of the strongest bi-modal distribution in vertical velocity component to correspond approximately with the location of the extent of the near-wake region. The horizontal velocity on the other hand seems to be strongly bi-modal near half a disk diameter, which corresponds with the peaks in longitudinal fluctuating velocity intensity. This bi-modality is especially eminent with

---

**Fig. 12** Probability distributions in flow velocities for disk 1B (\( \beta = 0.05 \)) at identified locations producing peaks in bi-modality parameters \( f^0 \) or \( f^c \). (black filled circles with a horizontal line indicate the location of the stagnation points)
only the lower porosities. As the porosity increases, the dominance of the peaks decreases signifying that potential periodic oscillations reduce in amplitude. Disks 4D and 4E (β=0.25) exhibit the highest crest factor for that porosity family. These disks display dominant peaks in longitudinal turbulence intensities of which the location corresponds with those derived from Figure 12b.

### 3.6 Near-wake pumping and vortex shedding

Information regarding wake flow periodicity was obtained by analyzing the spectral content of the instantaneous LDA samples. While turbulent spectra can be derived from LDA measurements (Nobach 2015, Benedict et al. 2000), the focus here lies on the dominant lower frequencies for which a simplistic, yet reliable procedure is preferred. For this reason the residence-time weighted burst-mode method as proposed by Velte and George (2010) has been implemented selecting a frequency resolution \( \Delta f = (f_m-f_m)/K \) where the minimum and maximum frequencies considered, \( f_m \) and \( f_m \), were originally selected as 0.1Hz and 10Hz respectively. The number of frequencies \( K \) was related to the overall record time \( T_\text{r} \) and a typical value \( \Delta t \) for the transit times by \( K=T_\text{r}/\Delta t \), yielding typical values for \( K \) in the order of 10. The transit time scale \( \Delta t \) was calculated as the median of all transit times. The resulting exemplary spectra for the solid disk at \( X/D=8.3 \) are presented in Figure 13a. Spectra below a diameter-based Strouhal number of approximately 0.003 depict unphysical drops and can be discarded.

For a given disk, the dominant spectral peak in each velocity component was extracted at each of the 111 downstream locations. A probability distribution is then constructed from the 111 peak frequencies adopting the average shifting histogram (ASH) technique as discussed by Scott (2010) with a bi-weight kernel function. The number of bins \( N \), in the histogram was selected as per Sturje’s rule; \( N=\text{1+log}(N) \) where \( N \) denotes the number of data samples (approximately 8000 in this case). The sub-bin width for the ASH routine was calculated iteratively, starting from the initial estimate defined as the ratio between the range of sample data and \( N \), to yield at least 400 smaller width bins.
The output of these routines is exemplified in Figure 13 for the case of the solid disk. For the vertical velocity component the probability density function indicates the presence of 2 dominant frequencies with corresponding Strouhal numbers of $St=0.132$ and $St=0.038$. The former is well-known and attributed to the regular vortex shedding (Miau et al., 1997). The latter is linked to the pumping motion, i.e. regular shrinking and enlarging, of the near-wake region with a typical frequency of $St=0.05$ (Lee and Bearman 1992, Kiya et al. 2000, Berger et al. 1990). The present findings that the near-wake is governed by both large and low frequency motion as can be seen in Figure 13b corroborates the findings of Zhong et al. (2014), who further attributed a Strouhal number of 0.035 to the low frequency peak. Also the absence of a distinct spectral peak related to vortex shedding when measuring along the centerline is in agreement with Zhong et al. Surprisingly, whereas the foregoing related studies utilized single wire hot wires, making it impossible to distinguish contributions from the individual flow components, the present results indicate that the near-wake oscillations are mainly observed in the vertical velocity component. The horizontal velocity component shows a peak at a Strouhal number of 0.015. This peak is too low to be due to the mounting rods (Fey et al., 1998) and is believed to be due to small longitudinal oscillations of the disk as this peak is observed for all porosities and shows only a very shallow increase with porosity. Moreover, pore Reynolds numbers were above 4000 and sufficiently large to exclude the potential appearance of self-sustained oscillations of the pore jet merging distance as reported by Villermaux and Hopfinger (1994). For this reason the following investigations will concentrate on the transversal velocity.
Fig. 14 Evolution in Strouhal number based on the transversal velocity component measured along the centerline of disks of varying porosity and hole topology. Symbols have been offset in the horizontal direction for clarity. Marker sizes reflect the dominance of the spectral peaks.

The evolution in detected Strouhal number peaks with porosity for the different disk layouts is presented in Figure 14. Error bars are deduced from the width of the probability density peak at 75% amplitude as illustrated in Figure 13c. The lower frequency mode attributed to the near-wake pumping is present for all disks and is fairly constant despite some variations for each porosity. This is surprising as previous studies on parallel planar jets have reported the appearance of periodic events whereby the periodicity decreases with increased jet spacing (Anderson et al., 2002). In the case of the perforated disk, the smallest spacing between pores is given by $S-2h$ with the pore radius $h$ related to porosity as $\beta^\gamma$. Increasing porosity would thus imply a reduction in spacing and lead to a larger frequency fluctuation, which is not observed here. However, the frequency related to vortex shedding does show a dependency on porosity in line with findings of Castro (1997), following a near-quadratic tendency. Disks with no rear-stagnation point (Disks 3D, 4E, 4F), seem not to follow this trend and have higher Strouhal numbers. Still, despite the absence of downstream stagnation in average, these disks contain a recurring low-motion frequency. The bi-modality tests indicated the amplitudes to be low such as to create a unimodal velocity density function. This would suggest that the supposed merging of the inner pore-jets does not take place constantly but can take place randomly. In other instances the pore-jets will thus merge with the outer shear-layers, creating an “enclosed” near-wake.
To further investigate the presence of periodic phenomena and compare with the adopted methodology for LDA data analysis, hot-wire anemometry was applied to the solid disk, disk 2B (topology B for $\beta=0.01$) and disk 4C (topology B for $\beta=0.25$). The $E_1$ power spectrum (PS) of the horizontal velocity component for the solid disk shows a distinct peak at a Strouhal number of 0.14 which is consistent with literature (Figure 15a). Moreover, all disks tested show the presence of smaller peak at a fluctuation of $St\sim0.02$, corroborating the LDA findings. For disk 2B with a porosity of 0.01 the dominant peak shifts towards a Strouhal number of 0.3 but simultaneously broadens. As the porosity is further increased disk 4C (porosity of 0.25) no distinct peak can be identified but elevated spectral levels are noticeable around a Strouhal number of approximately 0.2. Both Strouhal numbers have been identified from LDA data.

Positioned 0.2 disk diameters downstream along the centerline of the pore ($r_p/R=0.31$, Figure 15b), the spectrum for disk 2B shows a re-energizing of flow structures at $St\sim2$. Moving towards the
disk edge a similar spectrum is observed whereas the spectrum near the lower edge of the pore ($r/R=0.23$) this re-energizing has disappeared. A Strouhal number of 2 would correspond to a frequency of 1000Hz, which is in accordance with the Kelvin-Helmholz frequency reported by Bunderson and Smith (2005) for a jet at a Reynolds number of 21,000 (compared to 6,100 in the current study). For a solid disk Berger et al. (1990) report a high frequency instability of the outer shear-layer at a Strouhal number of 0.162. It is thus highly probable that the observable plateauing of the spectrum at St~2 is due to an interaction of the jet originating from the pore and the outer shear-layer of the disk. Such a plateauing of the spectrum has been observed also in flow related to forest canopies whereby the steep spectral slope at higher Strouhal numbers (larger than $2/3$) is attributed to the conversion of large-scale, shear-produced kinetic energy into smaller scale motions which are quickly dissipated (Baldocchi and Meyers, 1988). This again implies a strong interaction between the jet pore and disk shear-layer. At a distance of 1 disk diameter (Figure 15d), the spectra resemble that of a turbulent flow with marginal inter-discrepancies. The outer spectra ($r/R\approx 0.36$) again show again a slight peak at St~0.3, indicating again the correlation with the outer shear-layer. Disk 4C on the other hand only shows a non-conform spectral evolution at 0.3 diameters downstream (Figure 15c) when measuring near the top edge of the pore. This spectrum shows a plateau similar to disk 2B whereas the spectra in the other radial locations continuously decrease.

Despite the presence of strong peaks in the longitudinal and transverse spectra, the flow does not behave periodic in the temporal sense. Miau et al. (1997) emphasized that vortex shedding is not periodically arranged circumferentially. When applying Proper Orthogonal Decomposition to the 1936 velocity fields obtained with PIV in the vertical planes of the disks presented in Figure 16, none of the POD modes are dominant. This supports the statement that the flow is not periodic. The relative information content, defined as the normalized cumulative sum of the eigenvalue attributed to each POD mode (Tropea et al., 2007) is similar for all the disks but does imply that a low rank approximation is possible (Berger et al., 2010).

### 3.7 3D wake topology

To gain deeper understanding of the flow field PIV measurements behind a disk of each flow regime identified in Figure 6 are combined in a 3D layout and mean flow fields are depicted in Figure 17.
Overall wake topologies tend to be axi-symmetric with exception of topology C. Planes covering a pore show the presence of recirculating zones between the pore and outer disk edge. Such zones are not present in the bisecting plane between the pores of 4C. As the holes are moved outwards, the recirculation bubble within the near-wake reduces in size. This ring vortex is formed by the pore jets, which forms a first stagnation point for disk 1D. Not so for disk 1F (cf. Figure 6). A secondary recirculation forms further downstream which is no longer bounded by the outer shear-layer. The large recirculation no longer reaches the disk surface. Instead the pores entrain sufficient air to create a secondary stagnation point within the near-wake of the disk. In both cases 1D and 1F the jets bend outwards towards the outer shear-layer originating from the disk edge. Enlarging the holes slightly (case 2B) the momentum through the pores increases and the stagnation point nearest to the disk is moved from 0.5 diameters to 1.2 diameters downstream. The extent of the near-wake region however does not move dramatically; from 2.43 diameters to 2.18. As a result the wake area is more deformed; the wake diameter is visually reduced, the center of the ring vortex is moved further downstream and closer to the centerline and a secondary smaller ring is formed at a radial distance nearly equal to the disk’s radius. In addition, streamlines can be seen to converge towards the centerline indicating jet merging. As the pores are moved slightly outwards (case 2A), axial symmetry is lost again. The diagonal plane between pores shows the presence of two recirculation zones and jets diverge outwards. One may thus conclude that axial symmetry in the wake is only present when the flows

---

**Fig. 16** Convergence of the Relative Information Content of the POD modes related to the velocity field in the vertical plane of the disks presented in Figure 17.
Fig. 17 Mean velocity fields and streamline pattern obtained with PIV (a) Disk topology D for porosity of 0.05 (c) Disk topology F for porosity of 0.05 (d) Disk topology A for porosity of 0.1 (e) Disk topology B for porosity of 0.1 (f) Disk topology C for porosity of 0.25 (e) Disk topology D for porosity of 0.25. Insets indicate the corresponding 2D orientation of the planes.
Fig. 18 Velocity profiles in longitudinal velocity component and normalized turbulent kinetic energy dissipation obtained with PIV (Left) in across planes (b) in vertical planes (cf. Figure 3). Note that pores in the across plane are located at $\eta/D=\pm \frac{1}{2}S/D=\pm \frac{1}{4}S/R$ (cf. Figure 1)
emanating from the pores merge along the centerline, i.e. the 5\(^\circ\) regime in Figure 6. Enlarging the pores (increasing porosity) leads to either a loss in axial symmetry (4C) or the absence of a well-defined near-wake (4D). While in 4C the pore jets bend outwards to interact with the shear-layer the jets in 4D bend inwards to create a single jet of sufficient moment to destroy the typical encapsulated near-wake region. Contrary to 4C the flow regains symmetry in azimuthal direction. Details of the near-wake velocity fields for the disks considered are provided in Figure 18 for the measurements along the vertical plane (along the centerline crossing 2 pores) and the plane across (off-center crossing 2 pores). In addition, plots of the dissipation of turbulent kinetic energy \(\varepsilon\) across the planes are shown, which was defined as

\[
\varepsilon_K = v \left( \frac{\partial u_i}{\partial x_j} \right)^2 = v \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_i}{\partial x_j} \right)^2 = v \left( \frac{\partial u_i}{\partial x_j} \right)^2 - v \left( \frac{\partial u_i}{\partial x_j} \right)^2
\]

and can accordingly be calculated solely on the basis of instantaneous gradients in a single iteration (contrary to two iterations whereby one calculates the average gradients). Instantaneous gradients were calculated using the derivative kernel of quintic B-splines fit to velocity fields of the individual velocity components (Unser et al., 1993).

Differences between longitudinal velocity distributions in the vertical and across plane of the tested disks are marginal and indicate that in all cases, except disks 2B and 4D deviate outwards. Even though pore jets are spaced closer in the across plane, merging must take place in all planes. Near the base of the disk, the solid disk shows a small amount of back flow, which grows in amplitude with downstream distance. The profiles reveal that disk 4C exhibits the strongest reverse flow along the centerline whereas 2B only shows signs of reverse flow for downstream distances beyond one disk diameter as do disks 1D and 2A. The perforated disks display a damping of the recirculation with downstream distance and disk 4D shows no presence of reverse flow. These findings are in line with the LDA findings presented in Figure 6. Due to the smaller distance between the pores in the across plane, pore jets merge more rapidly for disks 2B and 4D. Contrary to the case of disk 4D, the combined nozzle momentum for disk 2B is insufficient to maintain the outer shear-layers separated. As a result the longitudinal velocity along the centerline is decelerated up to a point of reverse flow such that a secondary stagnation point, indicating the

\[ \eta / D = \pm 0.448, \text{ topology A; } \eta / D = \pm 0.475, \text{ topology B; } \eta / D = \pm 0.466, \text{ topology C; } \eta / D = \pm 0.483, \text{ topology D; } \eta / D = \pm 0.478, \text{ topology E; } \eta / D = \pm 0.472, \text{ topology F.}\]
termination of the near-wake forms. Indeed, PIV data corroborates that 4D produces a nozzle flows with velocities exceeding freestream. Once the jets have merged in both planes, the velocity profiles show marginal topological differences implying axial-symmetry.

For X/D<1 across the outer shear-layers the longitudinal velocity changes sign. For disks with a porosity of 0.05 (1D, 1F) these shear-layers are pushed furthest outwards and the least for porosities of 0.25 (4C, 4D).

As to be expected, the majority of kinetic energy dissipation takes place in both the pore jets and outer shear-layers. The solid disk however shows a near zero dissipation in the central region and tends to increase (in absolute value) towards the outer shear-layers. The magnitude of the dissipation overall is however almost an order of magnitude smaller than for the perforated disks. Because of the larger jets, a double bi-modal distribution is obtained near each pore jet with 4D and a non-zero dissipation is obtained for a longer downstream distance. Moreover, dissipation is concentrated in the near-wake region and is near-zero and uniform for downstream distances beyond 2.5 disk diameters, resembling that of a solid disk. Given that the dissipation is pivotal in the determination of the drag coefficient as suggested by Nedic et al. (2013), it is not surprising that the drag coefficients for perforated disks are different from those of the solid disk.

**Conclusions**

It is generally assumed that the drag coefficient of a porous disk is dictated solely by porosity. In this report near-wake analyses involving force measurements, LDA, hot wire and PIV techniques of combinations of porosity and hole perforations have been performed. While a general evolution with porosity was noted, drag measurements irrefutably indicated the above hypothesis to be untrue. Instead, combining force measurements and velocity data, a linear relationship was obtained between the disk drag coefficients and a parameter $Re \cdot N \cdot \beta \cdot \bar{S} \cdot D$, incorporating the ejected flow momentum from the pores (through the pore Reynolds number) and geometrical variables. For those disks exhibiting an enclosed recirculation region, increasing pore nozzle velocity, porosity or number of perforations lead to a decrease in drag coefficient.

For the disks tested, average velocity profiles along the centerlines of the disks established the existence of 5 different flow regimes depending on the extent of the evolution of the velocity in the near-wake region. This region typically extended 2.5 disk diameters and was shown to generally decrease with porosity. In average the flow along the centerline within the near-wake region flows upstream. However, depending on porosity and topology a stagnation point within the near-wake can be formed. In addition, disks with pores closest to the centerline displayed the absence of any recirculation as a result of the jet emanating from the pores to merge. Only disks having a pore spacing less than 0.01 disk radii produced jet merging. In all other cases merging took place with
the outer shear-layers. For low porosities a further correlation was observed between the appearance of peaks in longitudinal turbulence intensity and the location of the rear stagnation point whereby the peak would shift upstream as pore spacing increased. Disks not exhibiting such a stagnation point showed distinctly different evolutions in turbulence intensity. Along the centerline the distribution of instantaneous velocities showed bi-modal shapes with the largest bi-modality in longitudinal velocity for the lowest porosity disks at X/D~0.5. For these porosities, peaks in bi-modality in transverse velocity distributions corresponded again with the location of the rear-stagnation point. With increasing porosity the bi-modality reduced. Nevertheless, periodicity was observed by deriving Strouhal numbers from collected LDA data. Strongest spectral peaks were observed in the transverse velocity readings corresponding with regular vortex shedding from the disk perimeter and a near-wake pumping. While the former showed a near-quadratic dependency with porosity, the latter remained constant. LDA data further demonstrated the influence of large scale vortex shedding in the near-wake. Despite this perceived periodicity, POD analysis of near-wake velocity fields showed the absence of dominant modes, indicating the near-wake to be highly random as reported in literature. Spectral analysis with hotwire anemometry revealed a strong interaction between the outer shear-layers and pore jets causing a plateauing in spectra. Also the average velocity fields obtained with PIV showed a strong coupling between these flow features returning a near-wake with a highly 3 dimensional complexity. In case of perforations dissipation in turbulent kinetic energy was consistently higher than that of the solid disk, peaking at the location of shear-layers. Overall differences between the various combinations of porosity and hole perforations were concentrated in the near-wake, implying that it is the near-wake that dominates the creation of drag, as corroborated by the derived drag coefficient dependency.

Acknowledgement
The authors would like to thank Mr. Maximillian Dixon and Mr. Ewan Calder for their assistance during the experimental campaign.

References


Gould R W F (1970) Wake blockage corrections in a closed wind tunnel for one or two wall-mounted models subject to separated flow. Aeronautical research council reports and memoranda


Velte C M, George W K (2010) Efficient estimation of burst-mode LDA power spectra. 15th Int. symp. on Application of laser techniques to fluid mechanics, Lisbon, Portugal, 05-08 July