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Hydrodynamics and Length-Scale Distributions of a Random Cylinder

Array

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ABSTRACT

In vegetated flows a reliable estimation of flow scales is crucial to understand and model mixing processes. This study presents velocity maps obtained using Particle Image Velocimetry (PIV) within a cylinder array (diameters $4 \leq d \leq 20$ mm) designed to mimic real emergent vegetation. Tests were undertaken over a comprehensive range of stem Reynolds numbers ($100 \leq Re_d \leq 900$), intended to characterise time-dependent hydrodynamic features, including their interactions. Time-averaged flow heterogeneities are found to be independent of Re_d . Vortex dynamics are seen to dominate turbulent fluxes of momentum, and are the relevant coherent structures driving mass transport. The range of characteristic time- and length-scales from these coherent structures was quantified and shown to be determined by the distribution of spaces between cylinders. This is due to: (i) neighbouring cylinders forming clusters, leading to larger flow structures, and (ii) the maximum size of the flow structures being constrained by the inter-stem space. It is concluded that the Delaunay criterion provides practitioners with a good approximation to the distribution of flow scales in vegetated flows.

24 **Practical Applications**

25 This study presents the quantification of the scales of flow structures generated in a vegetated
26 flow. These structures play an important role in the quantification of mass transport processes,
27 and estimates of the sizes of these flow structures are necessary to understand the rate of solute
28 transport and therefore provide reliable model for pollutant mixing in vegetated flows. Using
29 state-of-the-art equipment to characterise velocity fields, the present study found that the size of
30 these flow structures is determined by the spacing between cylinders. The author's recommend
31 that for practical applications, engineers quantify the spacing between plant stems using the criteria
32 presented in this paper.

INTRODUCTION

Literature Review

Aquatic vegetation in natural streams dominates a wide range of physical, biochemical and restoration processes. It influences sediment dynamics (Righetti and Armanini 2002), which impacts stream geomorphology (Simon et al. 2004). Vegetation elements affect flow resistance (Jalonen and Järvelä 2014), govern the rates of mass and momentum exchange (Nepf 2012), and influence the rates of nutrient uptake and biochemical reactions (Nishihara and Terada 2010). The consequences of these processes are fundamental for stream restoration, conservation, biota reproduction, water quality control, and stormwater management (Shilton 2000).

In open channel flow, bed effects govern the transfer of mass and momentum. For emergent vegetation, experimental results have shown that bed effects are confined to a smaller bed region (Nepf et al. 1997b) and the vertical transfer of momentum, and vertical gradients of streamwise velocities (dU/dz), are negligible over the flow depth (Ricardo et al. 2016b). Therefore, emergent vegetation flows can be considered a special case of shallow 2D flows (Jirka and Uijtewaal 2004).

From experiments using cylinder arrays to simulate the stems of emergent vegetation, the time-averaged flow fields are characterised by cylinder-induced features: wakes, boundary layers and advective acceleration regions (White and Nepf 2003; Nepf 2012). These features create a heterogeneous flow field with zones of high and low velocities (differential advection) that contribute to the proportional spread of mass along vegetated reaches (Sonnenwald et al. 2017). Cylinder wakes are divided into near- and far- regions (called secondary wakes in White and Nepf 2003). The length of near-wakes (cf. formation regions) is a function of diameter, d , and local Reynolds number, Re_d , and independent of array density, φ . Measurements of the formation region length, obtained from single-cylinder flow experiments, have yielded estimates between $1d$ to $2d$ (Gerrard 1978).

Cylinder-induced turbulence overshadows that generated from the bed, and the difference increases proportionally with stem density, φ (Nepf 1999; Nepf et al. 1997a). Ricardo et al. (2014a) quantified the terms of the Turbulent Kinetic Energy (TKE) equation from local measurements

60 using Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA). Vortex dynamics
61 were found to be the main drivers of Turbulent Kinetic Energy (TKE) production, in the inter-stem
62 space. A local peak in TKE production occurs the limit of the near-wake, and turbulent diffusion
63 and fluxes are subsequently directed downstream into the far-wake. No local production-dissipation
64 equilibrium was found in the inter-stem space (Ricardo et al. 2014a). Further, turbulent stresses
65 were found to adapt to local density and are therefore independent of longitudinal stem density
66 gradients ($d\varphi/dx$) (Ricardo et al. 2016b).

67 Experimental limitations have precluded comprehensive analyses on the range of flow scales
68 existing in cylinder arrays. Quantifying the sizes of the dominant coherent structures in these
69 environments is a key component in the hydrodynamic characterisation of obstructed flows. These
70 structures represent the integral scales and thus govern the rates of turbulent mass and momentum
71 transfer, and are key in the determination of mixing lengths. In cylinder arrays these relevant scales
72 are connected to the rates of lateral spread due to mechanical dispersion (Nepf 1999; Tanino and
73 Nepf 2008b; and Tanino and Nepf 2009); and the extent of the advective zone, which is the distance
74 necessary for a scalar to lose correlation with its initial position and disperse in a Fickian manner
75 (Shucksmith et al. 2007). Further, a characteristic scale that represents the effects of cylinder arrays
76 on the flow, at the reach scale, is necessary to apply dimensional analysis on obstructed flows and
77 formulate closure models for numerical experiments (Ricardo 2014; Juang et al. 2008).

78 For engineering practice, it is desirable to obtain estimates of these flow scales, directly from
79 the morphology of the cylinder array. Conventionally, the main flow scales in cylinder arrays
80 are estimated as the smaller between the mean diameter, d , and the average space between each
81 cylinder and its nearest neighbour, s_n (Nepf 2012). Flow features are assumed to scale with the
82 mean diameter, d , since turbulence is generated in the wakes of each cylinder (Nepf 1999). In
83 dense arrays, however, these flow structures will be dissipated in the spaces between cylinders, at
84 scales smaller than the diameter (Tanino and Nepf 2008a).

85 Ricardo (2014) presented estimates of length scales within the inter-stem space in cylinder
86 arrays, using spatial autocorrelations of mean velocity. This approach suggested flow scales to be

87 proportional to the mean transverse distance between adjacent cylinders. Also, Ricardo (2014)
 88 concluded that the integrational approach to estimate length scales from temporal features (Taylor
 89 1922) does not apply for coherent flows, as the periodicity can generate unrealistic estimates and
 90 even negative values (Csanady 1973). The dominant period in these coherent functions is seen to
 91 be a more appropriate estimate of time scales.

92 The use of the minimum of either d or s_n (Nepf 2012) presupposes that the flow field is the result
 93 of linear superpositions of the effects of individual cylinders. This overlooks the existence of flow
 94 structures larger than those generated from single elements (Sumner 2010). Further, the method
 95 presented in Ricardo (2014) tends to mask the temporal variation (i.e. characteristic periods) of
 96 travelling structures, as it removes the coherence component of the velocity series analysed. In
 97 summary, previous physical assumptions for the definitions of d and s_n as relevant scales need to
 98 be reviewed experimentally. A unified methodology for the determination of a spacing distribution,
 99 that considers a wider range of flow scales, from cylinder interactions, is needed. These challenges
 100 will be explored in this study, using time-dependent velocity statistics from the comprehensive
 101 velocity maps obtained, and appropriate formulations for the estimation of relevant flow scales,
 102 based on array morphology will be given.

103 **The Double-Average Framework**

104 Equations for the momentum, mass and energy balance serve as a starting point to study the
 105 way in which instantaneous flow variables are related. Averaging frameworks simplify the analysis
 106 of flow equations by removing degrees of freedom that, due to experimental limitations, cannot be
 107 quantified directly (Nikora et al. 2007). The analysis presented here is based on the momentum
 108 equation, which expresses a balance between flow acceleration and the forces acting on the flow
 109 field. Using index notation, the general momentum equation is defined as

$$110 \quad \frac{\partial}{\partial t} u_i + u_j \frac{\partial}{\partial x_j} u_i = \frac{\partial}{\partial x_j} \left(-\frac{1}{\rho} p \delta_{ij} + \nu \frac{\partial}{\partial x_j} u_i \right) + f_i \quad (1)$$

111 where p is the instantaneous pressure, i and j are the indices indicating each spatial direction,

112 δ_{ij} is the Kronecker delta, ν the kinematic viscosity for the fluid and ρ its density, and f_i the
 113 external force term (Hinze 1975). Similar to the framework for the RANS equation (Pope 2000), a
 114 double-average framework can be applied to generate virtual stress terms that represent the effects
 115 of the vegetation-induced temporal and spatial fluctuations (Nikora et al. 2013).

$$\epsilon \langle \overline{u_j} \rangle \frac{\partial}{\partial x_j} \langle \overline{u_i} \rangle = \frac{\partial}{\partial x_j} \epsilon \left(-\frac{1}{\rho} \langle \overline{p} \rangle \delta_{ji} + \left\langle \nu \frac{\partial \overline{u_i}}{\partial x_j} \right\rangle - \langle \overline{u_i'' u_j''} \rangle - \langle \overline{u_i' u_j'} \rangle \right) +$$

(2)

$$\epsilon \langle \overline{f_i} \rangle + \left(\frac{1}{\rho} \right) \frac{1}{V_f} \int_{S_C} n_i p dS - \frac{1}{V_f} \int_{S_C} n_j \nu \frac{\partial u_i}{\partial x_j} dS$$

117 The overbar, $\overline{\cdot}$, represents a time average, and the operator $\langle \cdot \rangle$ represents a spatial average
 118 over an area large enough to be representative of the reach scale. Each instantaneous variable u_i
 119 is replaced by its double-averaged decomposition, $u_i = \langle \overline{u_i} \rangle + \overline{u_i''} + u_i'$ (Nikora et al. 2013). The
 120 terms n_i represent each component of the unit vector normal to each cylinder surface, V_f is the
 121 averaging volume, and S_C is the surface of each cylinder. Eq. (2) includes the effects of pressure
 122 (form) and viscous drag (6th and 7th terms on the RHS) on the momentum balance as independent
 123 terms. The velocity heterogeneities are summarised in the covariance term $\langle \overline{u_i'' u_j''} \rangle$, and referred
 124 to as form-induced stresses (Giménez-Curto and Corniero Lera 1996) or dispersive fluxes (Raupach
 125 et al. 1986). The effects of turbulence are expressed in the covariance term $\langle \overline{u_i' u_j'} \rangle$, called turbulent
 126 stresses (Nikora et al. 2013), and ϵ represents the porosity ($\epsilon = 1 - \phi$).

127 The interpretation of the terms $\langle \overline{u_i'' u_j''} \rangle$ and $\langle \overline{u_i' u_j'} \rangle$ as stresses comes from the idea that their
 128 effect on a fluid volume is similar to that of viscous stresses as a representation of molecular
 129 momentum transfer (Pope 2000). Similarly, these terms express the average flux of directional
 130 momentum due to turbulence and flow heterogeneities, between flow layers, over the area of
 131 analysis, and can therefore be also interpreted as turbulent and dispersive momentum fluxes. These
 132 momentum fluxes can help describe characteristic dispersive length scales due to turbulence and
 133 differential advection. For consistency and simplicity, these terms will be referred to as turbulent

134 and dispersive fluxes throughout the paper.

135 **Objectives**

136 To date, experimental limitations have precluded the possibility of obtaining detailed charac-
137 terisations of vegetated velocity fields. As a step forward in the characterisation of hydrodynamics
138 in vegetated flows, this study presents the results of velocity field measurements, using a Particle
139 Image Velocimetry (PIV) system that allowed for the illumination of a Field of View (FoV) large
140 enough to cover the reach-average morphological parameters of a random cylinder array, with a res-
141 olution that also permitted the study of velocities over small areas around individual cylinders. This
142 new cylinder array, named RandoSticks, incorporates a diameter distribution, designed to mimic
143 the distribution of stem sizes (diameters) and spacing observed in characterisations of winter *Typha*
144 *Latifolia* (Sonnenwald et al. 2017).

145 The aim of this study is to provide a full description of vegetated hydrodynamics in an artificial
146 array, to estimate turbulence structures, and describe mass and momentum fluxes. This research
147 focuses on the variation of these quantities with Reynolds number, Re_d , for a single physical
148 configuration. The results offer a complete picture of inter-stem hydrodynamics, and of the
149 influence of cylinder interactions on the size and behaviour of flow structures. These new insights
150 will provide practitioners with relevant, physically-based information to determine appropriate
151 distributions of length scales to model mass transport in vegetated flows. The following specific
152 objectives will be explored:

- 153 • Identify the main spatial features of the vegetated flow field, via qualitative analysis of 1st
154 (temporal mean) and 2nd order (deviations from the mean) velocity maps, e.g. wakes, zones
155 of turbulence production. Characterise the changes in these quantities with Reynolds number,
156 and identify the physical processes generating these features.
- 157 • Quantify the fluxes of mass and momentum in a double-averaged (DA) sense, and relate them
158 to the general morphological parameters of the cylinder array and the different flow regimes
159 considered during the experiments.

- Quantify the main flow scales driving the transport of mass, and relate them to the morphological descriptors of the RandoSticks array.

The Methodology Section outlines the experimental system, and the techniques used, which are presented in more detail in [Corredor-Garcia et al. \(2022\)](#) and [Corredor-Garcia \(2023\)](#). The Results Section shows horizontal 2D maps of time-averaged velocity fields, from which the relevant double-averaged quantities are obtained. Finally, time-dependent velocity statistics are analysed to obtain the characteristic shedding frequencies and length scales at representative points within the flow field. New insights into the range of flow structures and their generation mechanisms are provided.

METHODOLOGY

Experimental Facilities

The experiments were performed in a 14 m-long by 1 m-wide flume in the Water Engineering Laboratory at the University of Sheffield, which had a fixed slope of $\beta = 0.138\%$. The flow for the experiments was provided by a constant-head tank, and controlled using an inlet valve. The temperature during the experiments was on average $17.8\text{ }^{\circ}\text{C}$ (kinematic viscosity, $\nu = 1.06 \cdot 10^{-6}\text{ m}^2/\text{s}$). All tests were conducted with a reference water depth of 150 mm in the PIV Field of View (shown as a \times in Figure 1b). Photos and a detailed description of the equipment, calibration and preparation methods are presented in [Corredor-Garcia et al. \(2022\)](#) and [Corredor-Garcia \(2023\)](#).

RandoSticks Configuration

The RandoSticks diameter distribution ($d = 4, 8, 12, 15, 20\text{ mm}$), was designed to replicate real measurements from winter *Typha Latifolia* ([Sonnenwald et al. 2017](#)), and is presented in Figure 1a. The cylinders comprising the distribution were organised in a $1.0 \times 1.0\text{ m}^2$ pattern of randomly located PVC cylinders (Figure 1b), replicated over 9 m along the flume. The average physical parameters of the RandoSticks array in the area of study (PIV Field of View, Figure 1c) are: mean diameter, $d = 10.35\text{ mm}$; solid volume fraction, $\varphi = 0.05$; stem number density, $n = 506\text{ stems}/\text{m}^2$; frontal facing area per unit volume of vegetation $a = 5.08\text{ m}^{-1}$.

186 The RandoSticks array started 2.92 m downstream from the flume inlet, and covered a total
187 of 9 m downstream. Seeding particles for PIV were injected 2 m downstream from the start of
188 the RandoSticks array (i.e. 4.92 m from the flume inlet), to allow the flow to stabilise before
189 the injection and measurement areas. The injection location is chosen as the origin of the global
190 coordinate system (X_{rs}, Y_{rs}) in the streamwise location, i.e. $X_{rs} = 0$. The PIV Field of View (FoV),
191 with dimensions $\Delta X = 0.32$ m and $\Delta Y = 0.52$ m, was centred at $X_{rs} = 1.50$ m downstream from
192 the seeding injection location, and at a lateral distance $Y_{rs} = 0.57$ m from the right wall of the
193 flume. To allow visualisation from underneath the flume, the FoV was fitted with a glass window
194 below a 0.33×1.00 m² acrylic plate. This acrylic plate was perforated to place glass cylinders and
195 tubes such that the laser plane needed for the PIV measurements, located at mid-depth (75 mm),
196 was able to illuminate between cylinders. The location of this acrylic plate, relative to the injection
197 point, and the PIV Field of View are shown in Figures 1b and c. Figure 1c also shows the locations
198 and labels of the points used to illustrate the differences in autocorrelation periods, and thus length
199 scales, presented in the Shedding Frequency and Length Scales sections below. These points
200 represent the locations of the end of the recirculation region, along cylinder wakes, estimated from
201 previous studies (Gerrard 1978). The ellipses around each selected cylinder represent the length of
202 the recirculation zone, and the points where the velocity series were analysed are denoted with a ‘×’
203 symbol. The dotted rectangle in Figure 1c is the reference area chosen to illustrate the definitions
204 of inter-stem spacing given in Figure 7.

205 PIV Set-up

206 Glass tubes ($d = 12, 15, 20$ mm) and rods ($d = 4, 8$ mm) were used to allow visualisation
207 within the Field of View shown in Figure 1c. These were made of borosilicate glass 3.3 (refractive
208 index of 1.473; Schott 2017). In total, 6 tests were performed with the following mean velocities:
209 $U = 12.8, 26.2, 34.3, 42.2, 68.3,$ and 88.6 mm/s; and the corresponding diameter Reynolds
210 numbers: $Re_d = 125, 256, 335, 412, 667,$ and 865 .

211 The value of the Reynolds number, Re_d reported is based on the mean cylinder diameter,
212 $d = 10.35$ mm, within the Field of View (Figure 1c). The camera used in the PIV set-up is a

213 Blackfly BFS-U3-23S3 machine vision (FLIR 2018), fitted with a short focal-length (i.e. 48 mm)
214 lens (Computar 2018), to capture the relatively large FoV. The illumination system consisted of a
215 CNI, 10 W laser, operating at 532 nm, fitted into a scanning laser sheet generator (scanning periods
216 in the range: 225 - 750 μs), that created a horizontal plane 75 mm from the channel bed, to measure
217 x and y components of the mid-depth velocity field. To avoid secondary scanning effects in the
218 images, the camera shutter times, frame rate and laser scanning box rate were synchronised (i.e.
219 multiples of each other). The seeding used was polyamide 12 (density, 1.05 g/cm³) with combined
220 diameters of 20 and 100 μm .

221 For each test, 16000 images, with a resolution of 1996 \times 1258 pixels, were taken. Note that
222 due to the short focal-length lens used, image distortion occurred, and areas around cylinders
223 were blocked due to perspective errors. A piecewise linear transformation was used to correct
224 lens distortion (Higham and Brevis 2019). The camera allowed for an acquisition frequency of
225 65 fps. Four passes with interrogation windows of 120, 60, 32 and 16 pixels, with an overlap
226 of 50% between consecutive frames, were used for the calculation of velocities. Pre-processing,
227 calculation and post-processing of the displacement information was done using PIVlab (Thielicke
228 and Stamhuis 2014; Thielicke and Sonntag 2021). An additional pre-processing algorithm to
229 account for the glass-generated illumination heterogeneities was applied to equalise the intensity
230 response in all areas of the PIV images (Corredor-Garcia et al. 2022).

231 RESULTS

232 Velocity Characterisation in the RandoSticks Configuration

233 *Mean velocities (1st order quantities)*

234 Figure 2a and 2b show the time-averaged streamwise and lateral velocity maps ($U(x, y) = \bar{u}$
235 and $V(x, y) = \bar{v}$), normalised by reach-averaged velocity ($U^*(x, y) = U(x, y) / \langle \bar{u} \rangle$). Wakes can be
236 identified in Figure 2a as the zone of low velocities ($U^*(x, y) < 1$) behind individual cylinders, and
237 are more noticeable for cylinders that tend to group together, as shown in the area circled as A.
238 Preferential paths of high velocity ($U^*(x, y) > 1$) are generated between groups of stems, as can be

239 seen in circle *B* of Figure 2a. The normalised, time-averaged lateral velocity map, V^* (Figure 2b)
240 shows larger magnitudes of lateral displacement within groups of stems than around isolated ones.

241 The time-averaged features were found to be consistent for all Re_d tested. This is corroborated
242 by the probability distributions of the mean velocity maps $U^*(x, y)$ and $V^*(x, y)$ presented in Figure
243 2c and d, respectively. The probability distributions show that the spread of low and high velocity
244 areas in the time-averaged velocity maps remain constant with Re_d . For all Re_d tested Figures
245 2c and d show that the average maps have the same proportion of wakes, recirculation zones and
246 acceleration gaps for $U^*(x, y)$, and the same pattern of lateral displacements for $V^*(x, y)$. In other
247 words, first-order hydrodynamic features are independent of Re_d in the RandoSticks configuration.

248 *Turbulent Kinetic Energy (2nd order quantities)*

249 Employing the Reynolds decomposition on the velocity maps, ($u_i = U_i + u'_i$), an estimation of
250 the 2D TKE is obtained by time-averaging the squares of the turbulent fluctuations of velocity:
251 $k = (\overline{u'^2} + \overline{v'^2})/2$. The magnitudes of this quantity show the combined effects of ‘random’ turbulence
252 and coherent motions generated by vortex shedding, particularly their energy. Figure 3a shows that
253 non-dimensional TKE values, $k^* = k/\langle \bar{u} \rangle^2$, reach local peaks downstream from the stems, at
254 lengths that match the $\sim 1d$ distance reported by [Ricardo et al. \(2014a\)](#) and [Ricardo et al. \(2014b\)](#).
255 This distance also matches the end of the recirculation region reported by [Gerrard \(1978\)](#). These
256 peaks are expected near the sources of turbulent energy, which is transferred from the mean flow
257 through cylinder drag.

258 The magnitude and spatial extent of the peaks of k^* are proportional to cylinder size, Re_d , and
259 the presence of cylinders downstream. Figure 3a shows larger TKE peaks for isolated cylinders,
260 compared with those closely followed by other cylinders, suggesting that the growth of coherent
261 structures is constrained by the space between cylinders and increasing decay at larger Re_d .

262 Shear Reynolds stresses, $\tau_{xy} = \overline{u'v'}$, indicate momentum and mass transfer between flow layers
263 ([Pope 2000](#), [Hinze 1975](#)), particularly around obstructions. Understanding this transfer within
264 the entire flow field helps interpret wake interactions in obstructed flows. Nondimensionalising
265 shear Reynolds stresses by total turbulent momentum, $\tau_{xy}^* = \tau_{xy}/(u^+v^+)$, represented here by the

266 root-mean-square of the streamwise and lateral turbulent fluctuations ($u_i^+ = \sqrt{u_i'^2}$), provides a
 267 clearer visualisation of tangential momentum transfer at each point. Figure 3b shows the spatial
 268 distribution of this non-dimensional version of shear Reynolds stresses, τ_{xy}^* . Interacting wakes with
 269 opposite signs show no transfer, while those with the same signs coalesce. This is evident within
 270 the rectangle in Figure 3b, where the negative portion of an 8 mm wake coalesces with similar areas
 271 from 4-mm cylinders downstream. Similarly, the positive wake areas from three consecutive 4-mm
 272 cylinders merge together. However, when the negative transfer area from the 8 mm-cylinder wake
 273 encounters the positive area the three consecutive 4-mm cylinders, no shear momentum transfer
 274 between the wakes occur. This behaviour resembles collision-coalescence as reported by **Ricardo**
 275 **et al. (2016a)** and **Ricardo et al. (2016c)** for vorticity fluxes. Non-dimensional shear Reynolds
 276 stresses serve as a good indicator of wake extent, magnitude, and deformation. It is hypothesised
 277 that the cancellation of momentum transfer between adjacent wakes, when τ_{xy} has opposing signs,
 278 is an indication of no net momentum transfer between interacting wakes.

279 Contrary to the time-averaged maps shown in Figure 2a and b (i.e. $U^*(x, y)$ and $V^*(x, y)$,
 280 respectively), the maps of second order velocity statistics change with Re_d , as is evidenced in the
 281 probability distributions of k^* and τ_{xy}^* presented in Figure 3c and d. In particular, the distribution
 282 for $Re_d = 125$ shows k^* to be a more prominent than for the other tests. As will be explained
 283 in the section on Turbulent and Dispersive Fluxes, these variations are related to the changes in
 284 vortex dynamics that are dependent on Re_d . However, the results should only be considered from
 285 a qualitative perspective, as small displacements at $Re_d = 125$ tended to mix velocity fluctuations
 286 with noise inherent with PIV experiments. Note that in Figure 3a, not all cylinders of the same
 287 diameter show the same magnitudes for the peaks of Turbulent Kinetic Energy (TKE) production.
 288 This is caused by the effect of neighbouring cylinders on local turbulence production.

289 *Turbulent and Dispersive Fluxes in the RandoSticks configuration*

290 In the double-averaged momentum equation (Eq. 2), and the 2D flow assumption, horizontal
 291 instantaneous variables (u and v) are replaced by net momentum fluxes acting over the averaging
 292 area, i.e. the PIV Field of View. These fluxes are the velocity correlation terms $\langle \overline{u_i' u_j'} \rangle$ and $\langle \overline{u_i'' u_j''} \rangle$,

293 which represent the net turbulent and dispersive momentum fluxes acting on the obstructed reach.
294 The first term comprises random and coherent turbulent motions, and the second term represents
295 the effects of (time-averaged) flow heterogeneities caused by the presence of cylinders. Figure 4
296 shows the variation of these fluxes with Re_d for all the tests conducted.

297 Normal Reynolds stresses, $\overline{u'_i u'_i}$, are an estimation of the square of the turbulent length scale for
298 each point in the flow field. Their spatial average, $\langle \overline{u'_i u'_i} \rangle$, gives a representative turbulent scale
299 for the cylinder array analysed, i.e. they represent the magnitude of the average coherent scales
300 for the entire array. It can be seen from Figure 4 that normal turbulent momentum fluxes can
301 be considered isotropic (i.e. equal magnitude in the x and y direction), while momentum fluxes
302 ($\langle \overline{u'v'} \rangle$ and $\langle \overline{u''v''} \rangle$) are clearly negligible in a double-averaged sense.

303 Non-dimensionalising turbulent and dispersive fluxes using the square of the mean velocity, $\langle \overline{u} \rangle^2$
304 (Figure 4b) shows that turbulent momentum fluxes decrease with Re_d , in the range ($125 < Re_d <$
305 300). Above this range, non-dimensional turbulent momentum fluxes remain relatively constant for
306 the rest of the tests conducted ($300 < Re_d < 900$). Within this dataset, a local peak at $Re_d = 667$
307 can be seen. As will be pointed out below, this local peak is connected to transverse seiching for
308 that test (i.e. periodic motions caused by a synchronisation between water surface fluctuations and
309 cylinder shedding frequencies, Defina and Pradella 2014), and cannot be concluded to be universal.

310 A physical interpretation of the results for normal turbulent momentum fluxes, $\langle \overline{u'_i u'_i} \rangle$, in
311 the range $125 < Re_d < 300$, may be made based on the results from single cylinders. The
312 maximum value of turbulent momentum fluxes measured ($Re_d = 125$) is close to theoretical
313 maximum value as it coincides with the onset of periodic vortex shedding (Gerrard 1978). Close
314 to this value, it is known that the flow is dominated by a periodic vortex shedding regime, where
315 turbulence production comes from a combination of vortex decay and a transition to turbulence in
316 the wakes as they travel downstream (Roshko 1954; Gerrard 1978). The decreasing trend after this
317 maximum can be attributed to a transition to three-dimensional, small-scale vorticity for $Re_d \approx 190$
318 (Williamson 1991), which is coupled with an accelerated break down of vortices due to the presence
319 of downstream cylinders, and an increasing shedding frequency caused by shear (Kiya et al. 1980).

320 Non-dimensional dispersive fluxes show a moderate inverse proportionality with Re_d , which,
 321 in the case of $\langle \bar{u}''\bar{u}'' \rangle$, indicates a reduction of the size of the boundary layers and recirculation
 322 zones behind stems. Dispersive fluxes are anisotropic, as they do not represent the same scales.
 323 Streamwise dispersive fluxes, $\langle \bar{u}''\bar{u}'' \rangle$, represent the differences between boundary layers, trapping
 324 zones and wakes behind and around stems; and advective acceleration zones between cylinders.
 325 Transverse dispersive fluxes, $\langle \bar{v}''\bar{v}'' \rangle$, are proportional to the size of the cylinders, and as such are
 326 predominantly dependent on array morphology (Tanino and Nepf 2008b).

327 **Shedding frequency in the RandoSticks configuration**

328 As described in the Section on Turbulent and Dispersive Fluxes, the variation of reach-scale
 329 hydrodynamic quantities in the RandoSticks configuration is governed by vortex dynamics. Vortices
 330 are the dominant structures in cylinder flows, since both their frequency and characteristic length
 331 scale are expected to dominate the transfer of mass and momentum along cylinder arrays (Nepf
 332 1999; White and Nepf 2003).

333 A sample of points was analysed to obtain representative values of the shedding frequency, f_s .
 334 The points were located at the end of the recirculation region ($\sim 2d$ downstream from the cylinder
 335 centre along the wake centreline, Gerrard 1978), for 32 different cylinders, chosen randomly. Figure
 336 1c shows the RandoSticks FoV, with the location of a subsample, consisting of two cylinders, A and
 337 B per diameter, of the original 32-cylinder sample. The dominant flow structures within cylinder
 338 arrays are the vortices shed by the cylinders. To better visualise the coherence of the vortices
 339 contained within the array, a velocity autocorrelation function was calculated for all points. Note
 340 that these points are referred to specific cylinders, but as will be seen below, these vortices are not
 341 solely determined by their reference cylinders in an array. The transverse velocity series was used,
 342 as this is shown to better reveal the vortex periods along the wake centrelines (Roshko 1954). For
 343 reference, the velocity autocorrelation function, R_{vv} , for a velocity series at a specific point in
 344 steady flow, is defined as:

$$345 \quad R_{vv}(\tau) = \frac{\overline{v'(t) v'(t - \tau)}}{\overline{v'^2}} \quad (3)$$

346 Figure 5 shows the autocorrelation functions for the subsample of cylinder pairs (A and B), for
 347 a test at $Re_d = 335$. By virtue of the position relative to each cylinder, a strong periodic signal,
 348 representative of the vortex shedding process, was obtained. It is expected that cylinder interactions
 349 will affect the dominant frequencies of each cylinder diameter, in contrast to single cylinders. To
 350 illustrate this difference, a Single Cylinder Prediction (SCP) curve, based on the Strouhal number,
 351 S_t (Roshko 1954) is included for each diameter. The Strouhal number, S_t , non-dimensionalises
 352 shedding frequency using the cylinder diameter and mean reach-scale velocity, $\langle \bar{u} \rangle$

$$353 \quad S_t = \frac{f_s d}{\langle \bar{u} \rangle} \quad (4)$$

354 The variation of R_{vv} for each pair of cylinders (see Figure 1c) clearly shows that the characteristic
 355 periods are not comparable. This suggests that the structures captured in these periodic signals do
 356 not depend on their reference cylinders alone, but reflect the effect of surrounding cylinders.

357 Analysing the R_{vv} curves presented in Figure 5, the location of each cylinder with reference
 358 to the map for $U^*(x, y)$ (see Figure 2a) reveals important information about the coherence of each
 359 sampled point. Cylinder A for $d = 4$ mm is relatively isolated, which explains the smaller period,
 360 when compared with B , which is located directly downstream from a larger cylinder (12 mm), and
 361 thus shows a larger period.

362 For the $d = 8$ mm cylinders, A is located downstream from a group of larger cylinders, and B
 363 is isolated. The frequency (i.e. reciprocal of the dominant period) of B is larger than that for A , as
 364 expected, but also larger than the Single Cylinder Prediction (SCP). The autocorrelation function
 365 for cylinder $d = 12$ mm- A , does not show a strong coherent component, but its location is close to
 366 that of cylinder $d = 15$ mm- A , which has a larger characteristic period than its SCP. This suggests
 367 that cylinders $d = 12$ mm- A and $d = 15$ mm- A are interacting and thus generating a larger coherent
 368 structure. In contrast, cylinders $d = 12$ mm- B and $d = 15$ mm- B , are both isolated, but the first
 369 has a characteristic period similar to the SCP while the second has a higher frequency than the
 370 SCP. Cylinder $d = 20$ mm- A has a larger period than $d = 20$ mm- B , though both are smaller than
 371 the SCP. The periods shown in Figure 5, highlight the inadequacy of single cylinder predictions to

372 characterise flow structures in cylinder arrays, and emphasise the influence of cylinder interactions
373 on the temporal features of flow structures.

374 Figure 6a shows the shedding frequencies, f_s , obtained as the dominant component of the Power
375 Spectral Density function for all 32 reference cylinders, using Welch's method (Cryer et al. 1987)
376 for all Re_d tested. A proportionality trend between the shedding frequency and Re_d , confirms a
377 faster mass exchange between recirculation regions and far wakes, for increasing values of Re_d .
378 It should be noted that the shedding frequency values presented in Figure 6a result from cylinder
379 interactions and cannot be linked to a specific diameter. If the estimated shedding frequencies
380 are non-dimensionalised using the diameter of each reference cylinder, the distribution of Strouhal
381 numbers shown in Figure 6b is obtained. The variability of St suggests that reference cylinder
382 diameter is not an appropriate length scale to non-dimensionalise the shedding frequency and
383 scale of vortices from interacting cylinders. Even though the separation mechanism still obeys
384 the same principle (instability and separation of a laminar boundary layer, Schlichting and Gersten
385 2017). Interacting cylinders behaving as single bluff bodies have a complex, non-linear behaviour
386 that depends on more factors than a single reference diameter: orientation, distance and diameter
387 ratio of the interacting cylinders. Indeed finding appropriate length scales to non-dimensionalise
388 shedding frequencies from interacting cylinders is important to characterise cylinder arrays. This
389 question is addressed below by exploring the connection between these periodic features, flow
390 scales and the RandoSticks morphology.

391 Further, Figure 6a shows that the scatter in the estimates of f_s seems to increase with Re_d
392 within the range $100 < Re_d < 500$. For $Re_d \approx 665$, almost all sample points have the same
393 shedding frequency, confirming the existence of the transverse seiching. Seiching is defined as
394 transverse surface waves in cylinder flows, when the vortex shedding frequency comes into phase
395 with the natural standing wave frequency of the channel, determined by its geometry (Defina
396 and Pradella 2014). The predominant in-phase frequency ($Re_d \approx 665$) is divided into multiple
397 dominant frequencies at $Re_d = 865$.

398 Note that the existence of a dominant frequency due to seiching does not preclude the existence

399 of other relevant coherent structures; just that the seiching frequency is the strongest signal captured
400 by the velocity series. Further analyses are needed to decompose the main frequencies from these
401 velocity series, as multiple shedding frequencies are usually found from cylinder-pair interactions
402 (Sumner 2010). It can be seen that even for cylinders that can be considered isolated, there is little
403 agreement between estimated shedding frequencies and single-cylinder predictions (see Figure 5).
404 The variability in estimates of f_s , particularly for $Re_d < 500$, suggest a broader distribution of
405 dominant frequencies, and therefore time scales, for the flow structures passing through the area of
406 analysis. These results suggest that cylinder interactions influence the characteristic time scales of
407 the flow structures. Single cylinder predictions of characteristic periods using the Strouhal number,
408 based on the reach-average velocity, $\langle \bar{u} \rangle$, clearly overlook the range of flow structures generated
409 by cylinder interactions. Consequently, any meaningful characterisation of flow structures in
410 obstructed flows should consider the local velocity field. The local velocity is used to quantify the
411 Strouhal number, as shown in Figure 6b. The variability in the estimation supports the idea that
412 interacting cylinders and isolated ones are not scalable. A way of characterising the length scale of
413 flow structures generated by interacting cylinders is necessary and presented in this paper.

414 **RandoSticks length scales**

415 In engineering practice, it is useful to connect the characteristic length scale of the flow structures
416 to morphological descriptors of the vegetated array. Contrary to previous hypotheses proposing the
417 characteristic flow scale to be the representative diameter in cylinder arrays (Nepf 1999, White and
418 Nepf 2003), Figures 5 and 6a shows no correlation between cylinder diameters and the estimated
419 shedding frequencies for the RandoSticks configuration. The variability in the estimates of f_s
420 clearly suggests a range of flow scales broader than the diameter distribution.

421 As an alternative, Tanino and Nepf (2008b) suggested that the average edge-to-edge distance
422 between a cylinder and its nearest-neighbour is the relevant flow scale, provided such distances are
423 smaller than the representative diameter. Physically, flow structures are constrained by the space
424 between cylinders, and only considering a nearest neighbour overlooks the existence of larger flow
425 structures, resulting from cylinder interactions, as the results from Figure 6a suggest. A nearest-

426 neighbour can be an interacting element and not a spatial constraint. Hence, if inter-stem spacing
427 is the relevant constraint limiting the size of flow structures, a way to define spacing that considers
428 the range of possible flow structures generated from element interactions is needed.

429 This study proposes the use of a Delaunay criterion (De Loera et al. 2010) to define the edge-to-
430 edge spacing distribution between neighbouring cylinders. This criterion defines valid spaces (i.e.
431 neighbours) as any group of 3 cylinders (cf. points) that can have a circumscribed circle without
432 containing any other interfering cylinder. The concept of a circumscribed circle as the space that
433 can contain a flow structure is justified by the results from Turbulent momentum fluxes (see Figure
434 4), which shows that these fluxes are isotropic in a double-averaged sense, i.e. turbulent scales have
435 on average, the same dimensions in the streamwise and transverse direction.

436 An area of the PIV Field of View (dotted rectangle in Figure 1c), is chosen to illustrate the
437 difference between the nearest-neighbour (NN) and Delaunay (DN) definition of inter-stem (edge-
438 to-edge) spacing, and shown in Figure 7a and 7b, respectively. It can be seen that the NN spacing
439 distribution is a subset of the DN distribution. The Delaunay spacing considers larger spaces
440 that can contain flow structures generated by interacting cylinders. The probability density and
441 cumulative distribution for both spacing definitions, for the entire RandoSticks array is shown in
442 Figure 7c. As expected, a wider range of spacing is obtained using the Delaunay criterion.

443 As shown in the previous section, shedding frequency and length scale estimates for the
444 characterisation of array morphology should consider cylinder interactions, the local velocity field,
445 and their effects on the flow structures that are generated. To describe the range of flow structures
446 existing in the RandoSticks configuration, the reciprocal of the shedding frequencies presented
447 above (i.e. the characteristic time scale of the integral structures) is multiplied by the travelling
448 velocity of the vortices, as suggested by Taylor's frozen turbulence hypothesis (Taylor 1938), to
449 obtain the characteristic length scales, Λ_t , of the RandoSticks configuration.

450 Following these assumptions, the characteristic time scales, $T = 1/f_s$ (i.e. periods) of each
451 dominant frequency shown in Figure 6a, are multiplied by a velocity scale, u_l to obtain an estimate
452 of the characteristic length scale of the RandoSticks distribution.

$$\Lambda_t = Tu_l \quad (5)$$

The next question is how to define u_l to compute length scales. For single-cylinder studies, the approach velocity is commonly used. However, [Maryami et al. \(2020\)](#) argues that this is not an appropriate velocity scale to non-dimensionalise shedding frequencies in single cylinders. Similarly, the use of a reach-scale mean velocity, $\langle \bar{u} \rangle$, does not represent the actual local travel velocities of the vortices whose shedding frequencies are presented in Figure 6a. It is proposed to specify u_l as the velocity at the end of the recirculation region, to scale the shedding frequency, as it better represents the local travel velocity of the vortices ([Maryami et al. 2020](#); [Roshko 1955](#)). Following this approach, the distribution of length scales for all 32 cylinders presented in Figure 8a is obtained.

The variation of the mean Λ_t with Re_d shows that the distribution of length scales is independent of Reynolds number, at least for the range of flows tested. Physically, the consistency in the estimation of larger flow structures confirms the existence of cylinder interactions, and the formation of flow structures from multiple cylinders acting as clusters. The characteristic length scales presented in Figure 8a are larger than those expected from the RandoSticks cylinder diameter distribution.

To illustrate this, Figure 8b compares the morphological scales measured directly from the RandoSticks configuration, namely, the diameter distribution; the nearest-neighbour (NN) and Delaunay (DN) spacing distributions; and those obtained from the statistical analysis of the velocity series, using the local velocity field, and the ‘global’ velocity scale ($\langle \bar{u} \rangle$). The length scales obtained using local velocities have a broader range than those obtained from the distribution of cylinder diameters, and nearest-neighbour (NN) spacing; but show remarkable agreement to those from the Delaunay (DN) distribution.

This confirms that the characteristic length scales of flow structures in the RandoSticks configuration are determined by cylinder interactions, and constrained by the space available between neighbouring obstructions, not the nearest elements or stem diameters. This agrees with the results

479 presented in [Stovin et al. \(2022\)](#), where numerical simulations of dispersion in different cylin-
480 der arrays, with different diameter distributions, showed that dispersion coefficients scale more
481 consistently with cylinder spacing than cylinder diameter.

482 The RandoSticks configuration presented here, and those analysed in [Stovin et al. \(2022\)](#)
483 are representative of a wide range of vegetation species, consequently the Delaunay criterion is
484 expected to apply for configurations with similar density and diameter distributions. However,
485 for cases outside of this range, i.e. sparse $\varphi \rightarrow 0$ and dense $\varphi \rightarrow 1$, the present results cannot
486 be directly extrapolated. For sparse configurations, cylinders behave independently as distances
487 prevent interactions. For dense arrays the space between elements is not large enough to allow
488 the formation of coherent structures. The relevant length scales in this cases are, therefore, the
489 diameter d , for sparse configurations; and the nearest-neighbour spacing s_n for dense arrays.

490 Based on the previous considerations, the RandoSticks configuration belongs to a range of
491 intermediate vegetation densities wherein cylinders are close enough to interact and affect the
492 formation of flow structures. Within this intermediate range, the most appropriate estimation
493 of the range of flow structures can be obtained via a Delaunay triangulation. Therefore, for
494 engineering practice, in vegetated arrays of similar reach-average characteristics to the RandoSticks
495 configuration (e.g. winter *Typha latifolia*) the quantification of inter-stem spacing using a Delaunay
496 criterion, should be used to estimate flow scales.

497 **CONCLUSIONS**

498 This paper presents the results from a comprehensive study of velocity fields, using non-intrusive
499 optical techniques, in a random cylinder array designed to mimic the features of natural species.
500 The maps of time-averaged streamwise and transverse velocities show the location and extent of
501 obstructed flow features, specifically, wakes, recirculation and acceleration zones. These were
502 found to have minimal variation with Reynolds number, such that the time-averaged flow field is
503 constant with Re_d .

504 The same RandoSticks configuration was tested for an extensive range of flow regimes, charac-
505 terised by the interaction of the obstructions with the flow field. The results show that the variation

506 of turbulent momentum fluxes with Re_d is governed by vortex dynamics. A decreasing trend for
507 turbulent momentum fluxes, $\langle \overline{u'_i u'_i} \rangle$ in the range $Re_d < 300$ suggests turbulent production caused
508 by vortex decay and a transition to three-dimensional turbulence. For $Re_d > 300$, the behaviour
509 of turbulent momentum fluxes supports previous hypotheses of a transition to 3D turbulence in
510 the cylinder wakes. This increase in small-scale turbulence and the transition to turbulence in the
511 formation region is in agreement with the decrease in streamwise dispersive fluxes as the extent of
512 the recirculation region tends to decrease.

513 Based on the characterisation of average momentum fluxes, it was found that turbulent momen-
514 tum fluxes can be considered isotropic in a double-average framework. Normalised longitudinal
515 dispersive fluxes are significantly higher than transverse fluxes, and both are primarily determined
516 by array morphology. Shear turbulent and dispersive fluxes are negligible in a double-average
517 sense, but are a good indicator of local momentum and mass transfers, particularly the absence of
518 momentum transfer between wakes with opposing signs in the Reynolds stress. Wake interactions
519 can be interpreted depending on the sign of local shear virtual stresses.

520 An in-depth analysis of the range of characteristic flow scales, based on estimations of the
521 main periodic component from velocity series over the flow field, reveals the existence of flow
522 structures with a broader range of scales than those associated with the diameter distribution.
523 The distribution of flow structures was found to resemble closely the distribution of edge-to-edge
524 spacing between neighbouring cylinders, defined using a Delaunay criterion. The range of flows
525 structures measured indicates that the size of coherent structures is determined by a variety of
526 non-linear cylinder interactions, from isolated elements, to interacting cylinders forming clusters.
527 The size of these structures is limited by the inter-stem spacing. Estimates of flow structures using
528 a Delaunay criterion are expected to be valid for an ‘intermediate’ range of vegetation densities,
529 similar to the RandoSticks configuration. For the range of flows tested, the range of flow scales
530 is independent of Re_d . For engineering applications, such as estimating dispersion coefficients
531 for pollutant transport, characterising flow resistance, and non-dimensionalising hydrodynamic
532 parameters, it is proposed that practitioners employ a distribution of inter-stem spacing using a

533 Delaunay criterion.

534 **Data Availability Statement**

- 535 • All data, models, or code that support the findings of this study are available from the
536 corresponding author upon reasonable request.

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546

APPENDIX I. NOTATION

547

The following symbols are used in this paper:

548

Latin Symbols a = Frontal Facing Area of Vegetation per Unit Volume [m^{-1}]; d = Cylinder Diameter [m]; f_s = Shedding Frequency [1/s]; g = Acceleration due to gravity [m/s^2]; h = Flow depth [m]; k = Turbulent Kinetic Energy [m^2/s^2]; n = Cylinder Density [cylinder/ m^2]; p = Pressure [N/m^2]; R_{vv} = Autocorrelation function of the transverse velocity [-]; Re_d = Cylinder Reynolds Number [-]; s = Mean edge-to-edge Spacing using a Delaunay Criterion [m];

549

 s_n = Mean edge-to-edge Spacing to nearest neighbour [m]; S_t = Strouhal number [-]; T = Characteristic Time Scale obtained from the Autocorrelation function [s]; $U(x, y)$ = Time-averaged Streamwise Velocity $\bar{u} \equiv U(x, y)$ [m/s]; U = Double-Averaged Velocity $U \equiv \langle \bar{u} \rangle$ [m/s]; u_i = Instantaneous Velocities in Tensor notation, $(u_1, u_2, u_3) \equiv (u, v, w)$ [m/s]; u_l = local velocity scale at the end of the recirculation region [m/s]; $V(x, y)$ = Time-averaged Transverse Velocity $\bar{v} \equiv V(x, y)$ [m/s]; X_{rs} = Streamwise Distance from Seeding Injection Point [m]; x_i = Coordinates in Tensor notation, $(x_1, x_2, x_3) \equiv (x, y, z)$ [m]; Y_{rs} = Lateral distance of the flume [m];

550

Greek Letters β = Flume Slope [-]; ΔX = Longitudinal Dimension of the PIV Field of View [m]; ΔY = Transverse Dimension of the PIV Field of View [m]; δ_{ij} = Kronecker Delta [-];

551

 ϵ = Porosity [-]; Λ_t = Flow Length Scale obtained from the Autocorrelation function[m]; ν = kinematic viscosity [m²/s]; ρ = water density [kg/m³];

552

 φ = Solid Volume Fraction [-];

553

Mathematical symbols and operators $\overline{\cdot}$ = Time Averaging [-]; $\langle \cdot \rangle$ = Volume Averaging [-];

554

 θ^+ = Standard Deviation of the time series represented by the variable θ , $\theta^+ = \sqrt{\overline{\theta'^2}}$ [-]; θ^* = Normalised version of the dimensional quantity θ [-]; $\langle \overline{u_i'' u_j''} \rangle$ = Dispersive Fluxes cf. form-induced stresses [m²/s²]; $\langle \overline{u'u'} \rangle$ = Turbulent Fluxes cf. Reynolds stresses [m²/s²];

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670

List of Figures

671

1 **a)** RandoSticks Diameter distribution **b)** RandoSticks plate and location of the PIV FoV using global coordinates (X_{rs}, Y_{rs}) . **c)** Detailed view of the PIV FoV with reference cylinders (marked by ellipses) for flow scales analysis using local coordinates (x, y) , and reference area (dotted rectangle) for inter-stem spacing illustration. The \times symbols represent the points marking the limit of the recirculation area, based on the location reported in single cylinders studies. 31

672

673

674

675

676

677

2 Non-dimensional **a)** time-averaged streamwise velocity, $U^*(x, y)$ and **b)** time-averaged transverse velocity, $V^*(x, y)$ for $Re_d = 335$. Probability distribution of the time-averaged maps of non-dimensionalised **c)** streamwise and **d)** transverse velocities, for all Re_d 32

678

679

680

681

3 Non-dimensional **a)** Turbulent Kinetic Energy, $k^*(x, y)$ and **b)** shear Reynolds stresses, $\tau_{xy}^*(x, y)$ for $Re_d = 335$. Probability distribution of the time-averaged maps of non-dimensionalised **c)** Turbulent Kinetic Energy and **d)** Shear Reynolds stresses, for all Re_d 33

682

683

684

685

4 Variation of **a)** dimensional dispersive (-) and turbulent (- -) fluxes; and **b)** dispersive (-) and turbulent (- -) fluxes fluxes, normalised by mean velocity, with Re_d 34

686

687

5 Transverse velocity autocorrelation functions for a sample of cylinders, at $Re_d = 335$, and comparison with their respective Single Cylinder Predictions (SCP). 35

688

689

6 **a)** Variation of shedding frequency, f_s , from the velocity spectra. **b)** Variation of Strouhal numbers, from shedding frequencies, using the reference cylinder diameter and local velocities as length and velocity scales, respectively. 36

690

691

7 **a)** Nearest-neighbour (NN) and **b)** Delaunay (DN) inter-stem spacing distributions. **c)** Probability and cumulative functions for NN and DN spacing distributions. 37

692

693

694

8 **a)** Variation of point-based estimates of length scales, Λ_t , with respect to stem Reynolds number, Re_d , and **b)** density and cumulative Distribution functions for Λ_t , for local and global estimates of velocity. 38

695

696

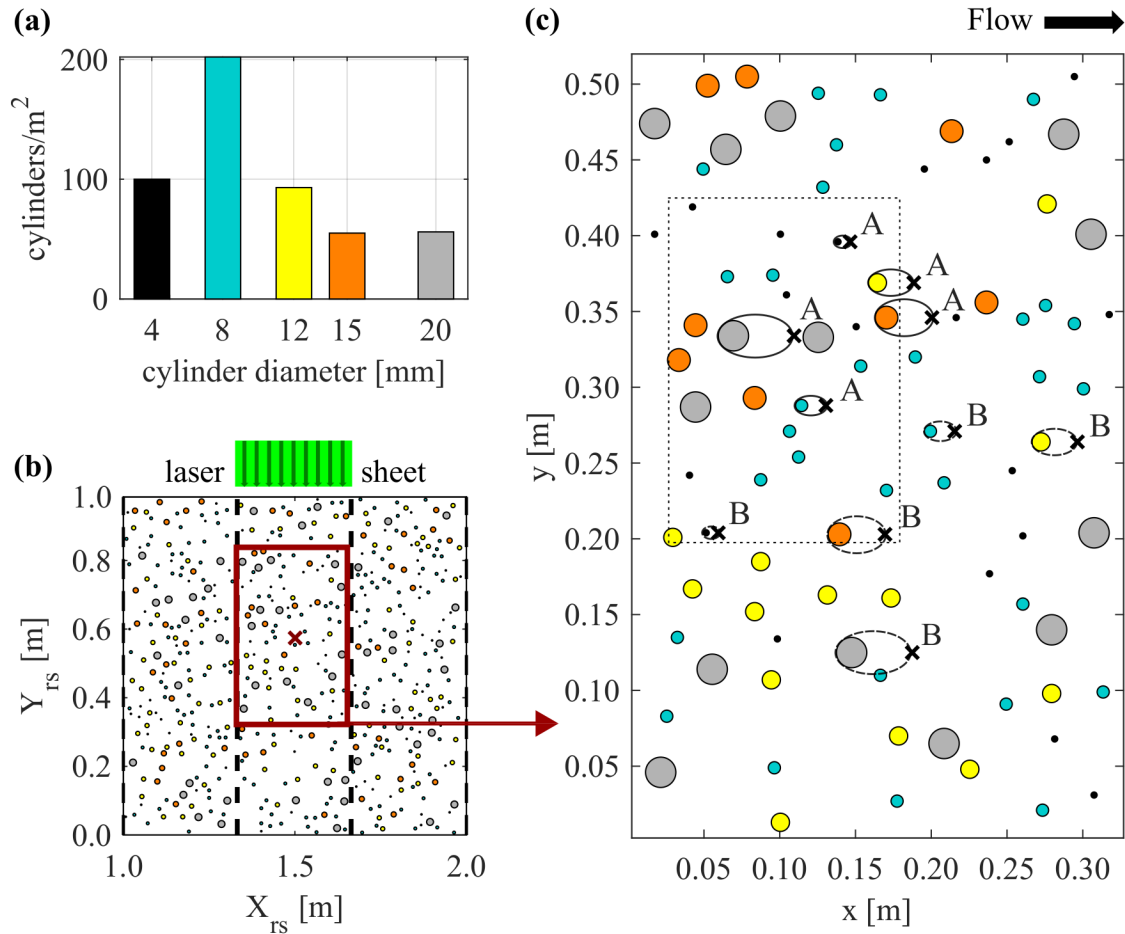


Fig. 1. **a)** RandoSticks Diameter distribution **b)** RandoSticks plate and location of the PIV FoV using global coordinates (X_{rs} , Y_{rs}). **c)** Detailed view of the PIV FoV with reference cylinders (marked by ellipses) for flow scales analysis using local coordinates (x , y), and reference area (dotted rectangle) for inter-stem spacing illustration. The \times symbols represent the points marking the limit of the recirculation area, based on the location reported in single cylinders studies.

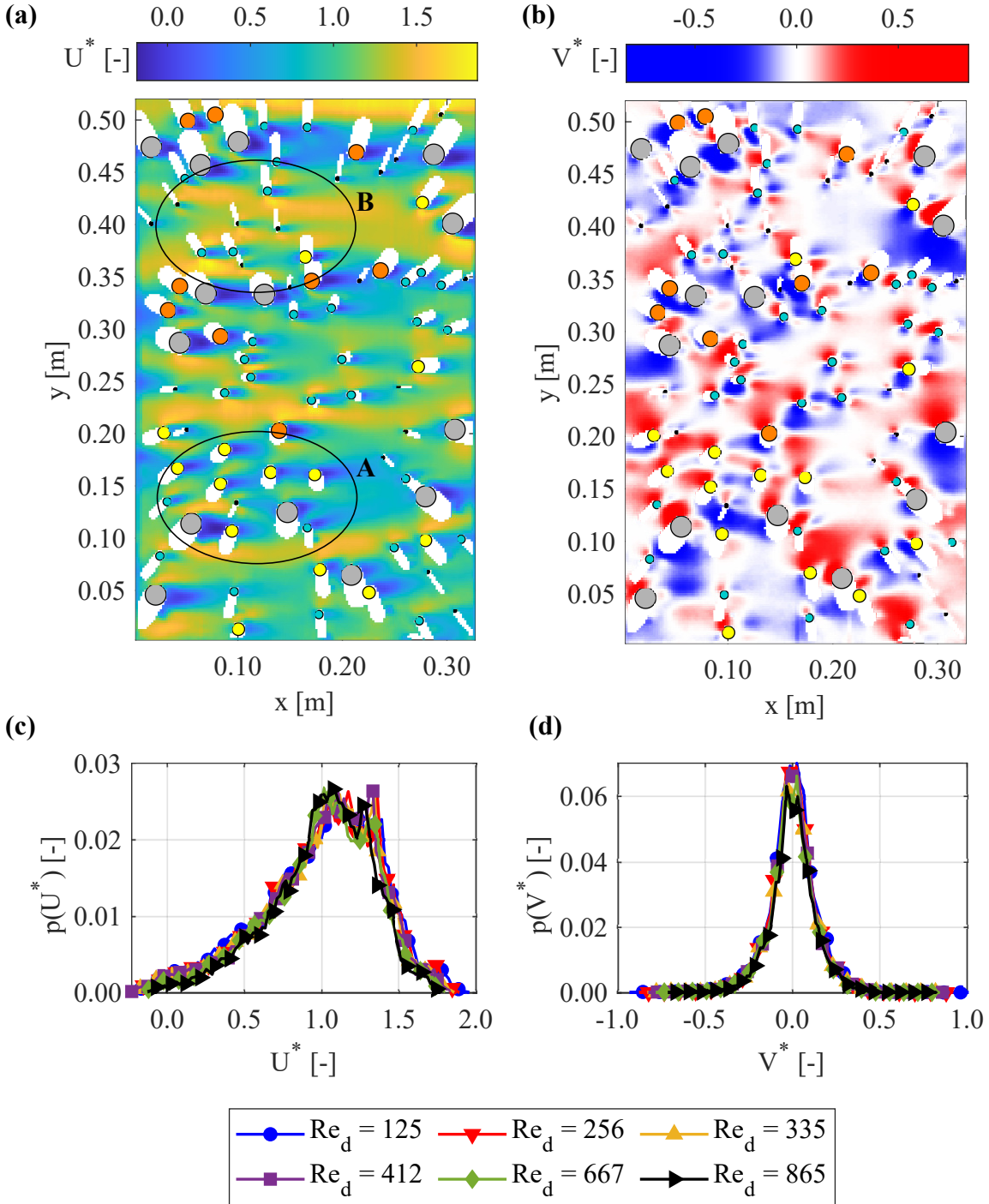


Fig. 2. Non-dimensional **a)** time-averaged streamwise velocity, $U^*(x, y)$ and **b)** time-averaged transverse velocity, $V^*(x, y)$ for $Re_d = 335$. Probability distribution of the time-averaged maps of non-dimensionalised **c)** streamwise and **d)** transverse velocities, for all Re_d

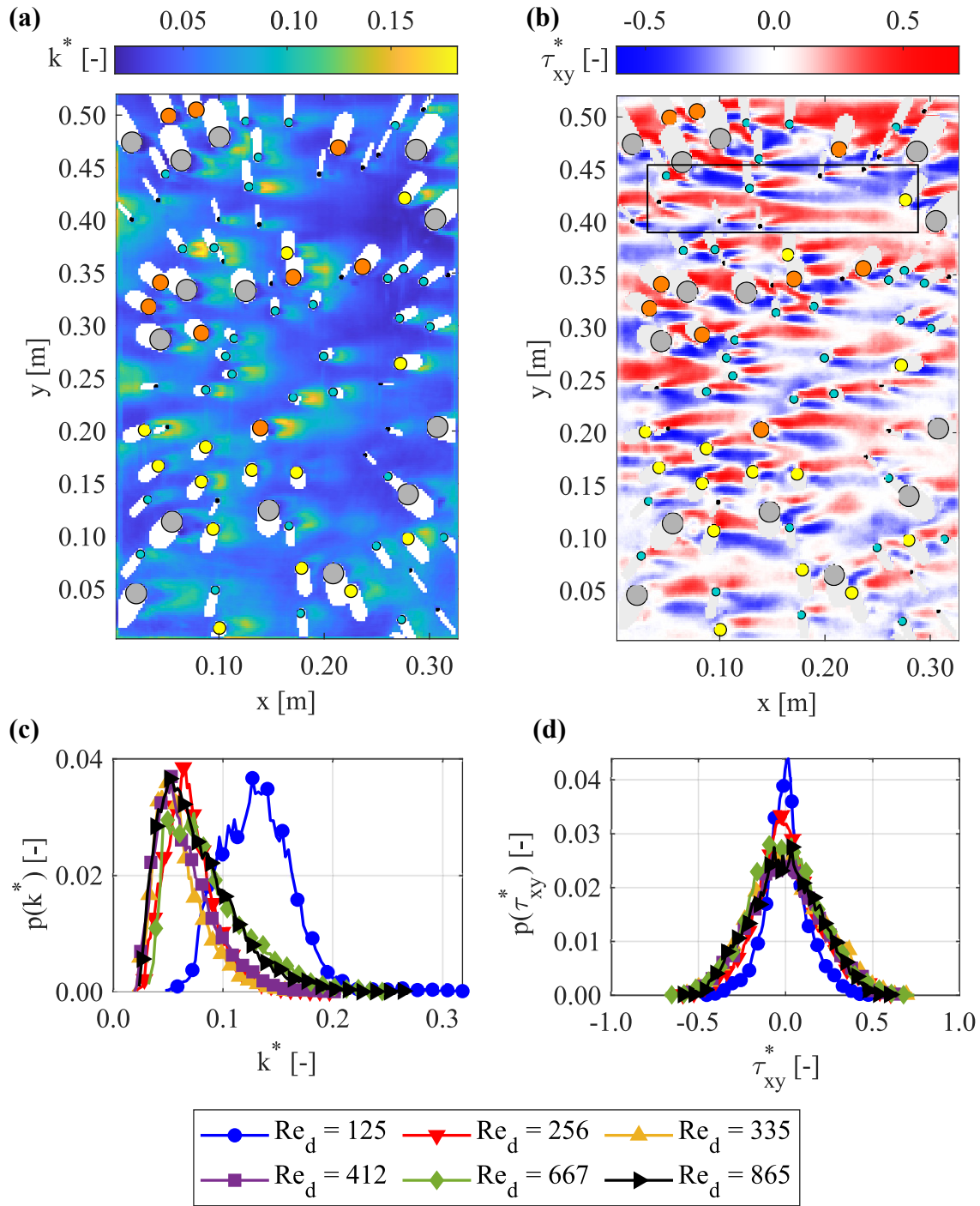


Fig. 3. Non-dimensional **a)** Turbulent Kinetic Energy, $k^*(x, y)$ and **b)** shear Reynolds stresses, $\tau_{xy}^*(x, y)$ for $Re_d = 335$. Probability distribution of the time-averaged maps of non-dimensionalised **c)** Turbulent Kinetic Energy and **d)** Shear Reynolds stresses, for all Re_d

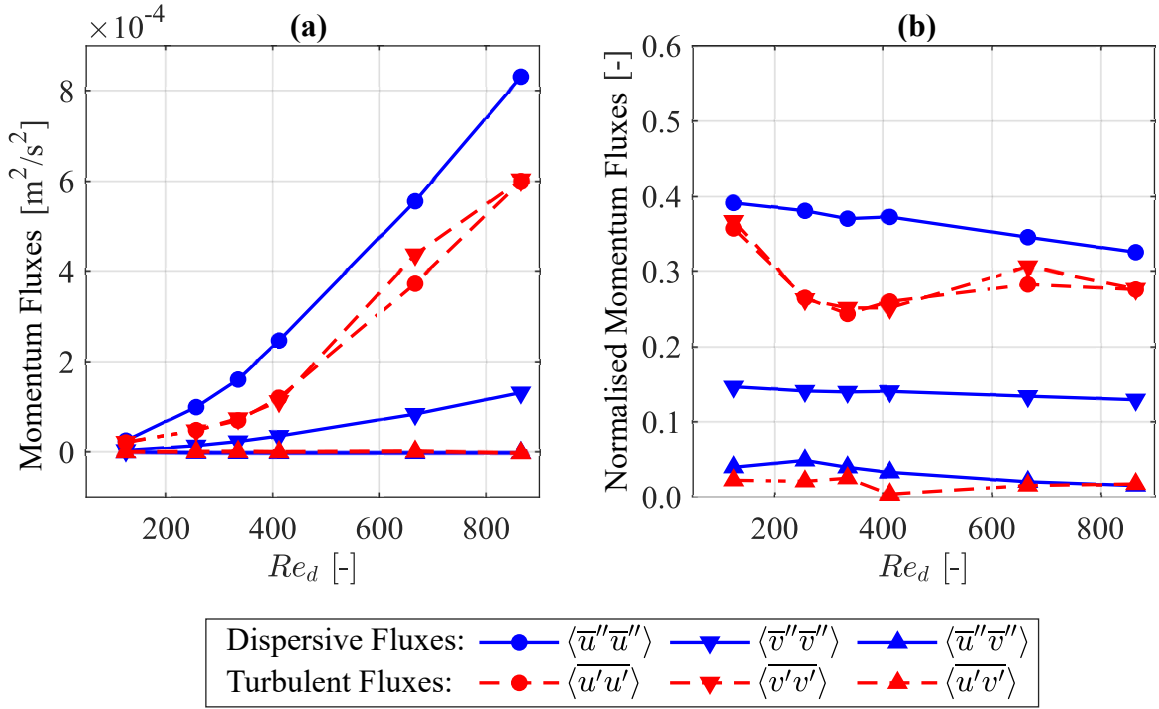


Fig. 4. Variation of **a)** dimensional dispersive (-) and turbulent (- -) fluxes; and **b)** dispersive (-) and turbulent (- -) fluxes, normalised by mean velocity, with Re_d

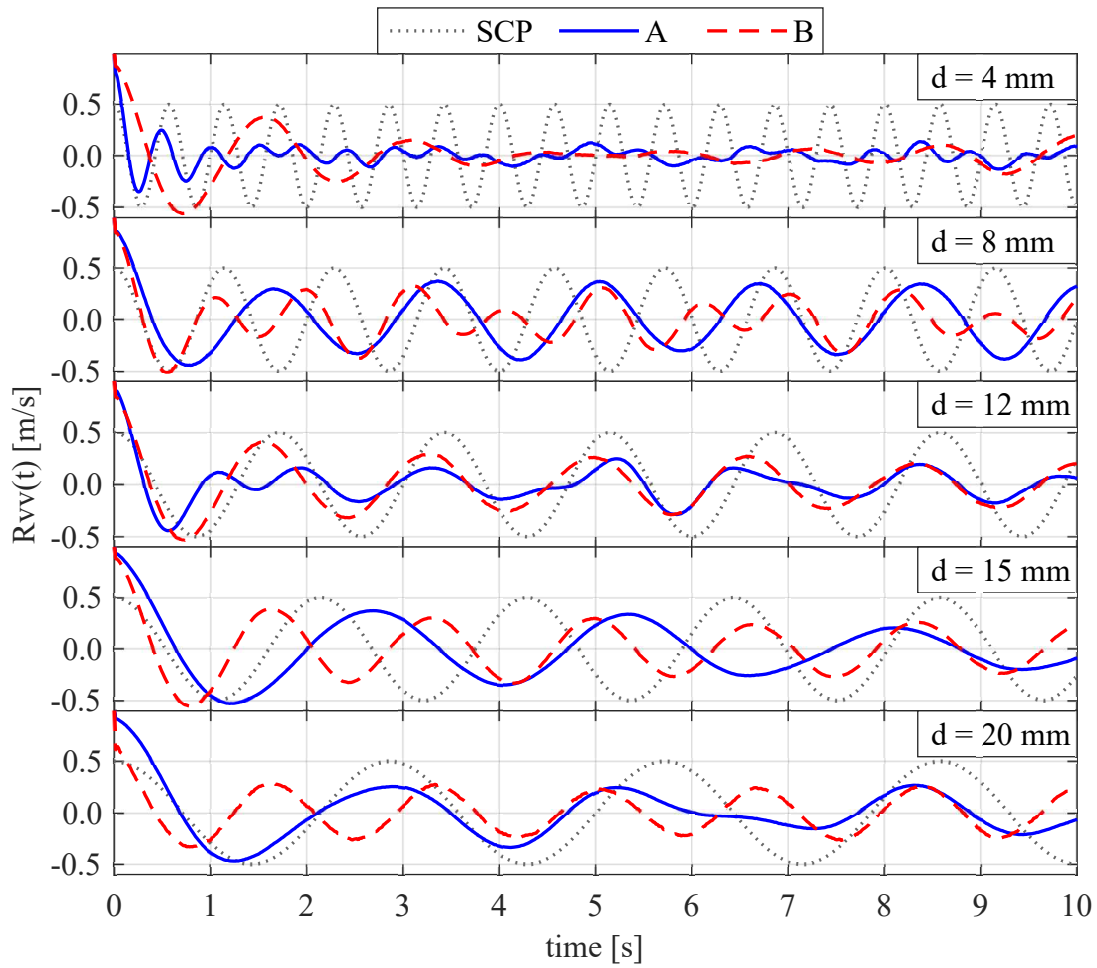


Fig. 5. Transverse velocity autocorrelation functions for a sample of cylinders, at $Re_d = 335$, and comparison with their respective Single Cylinder Predictions (SCP).

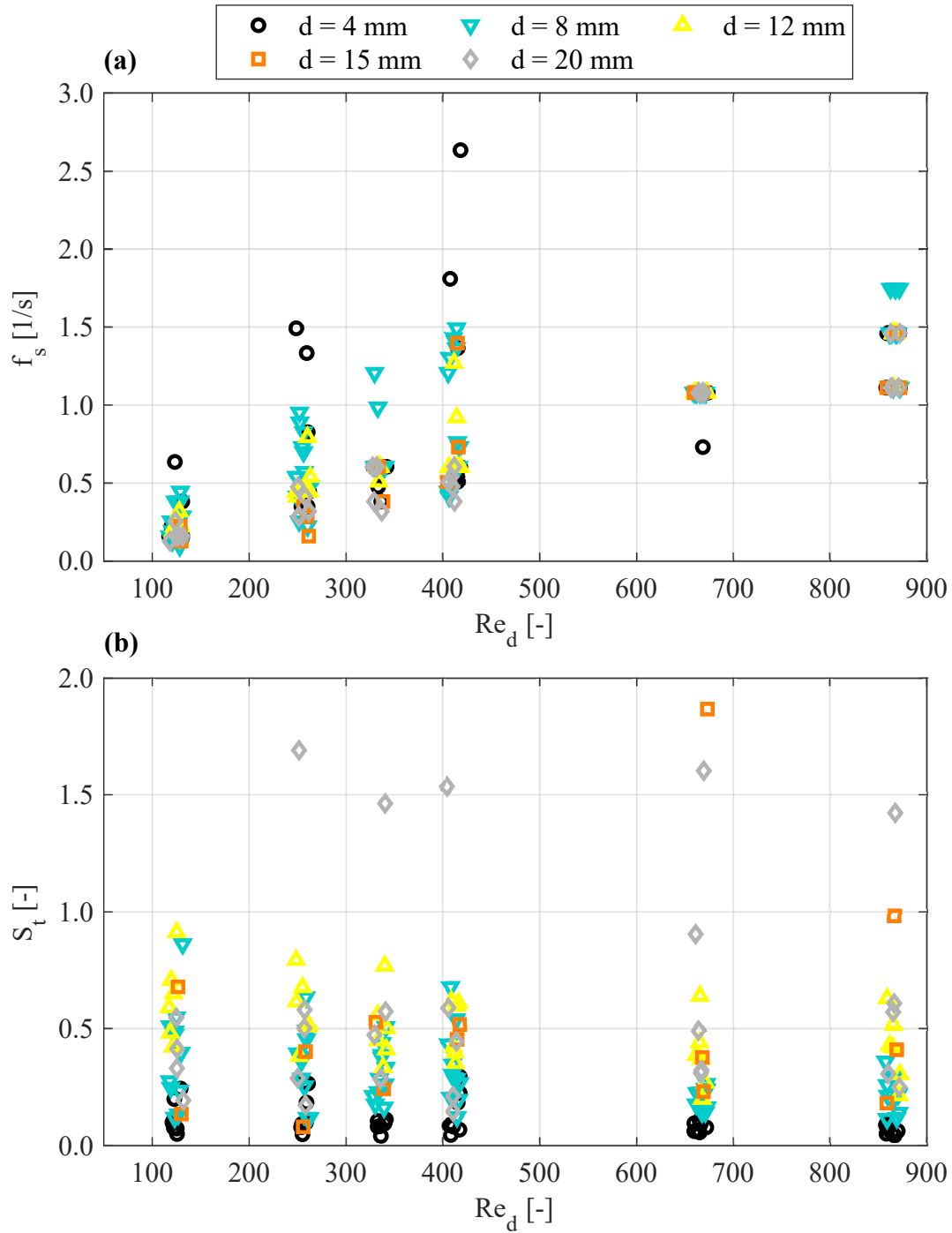


Fig. 6. a) Variation of shedding frequency, f_s , from the velocity spectra. b) Variation of Strouhal numbers, from shedding frequencies, using the reference cylinder diameter and local velocities as length and velocity scales, respectively.

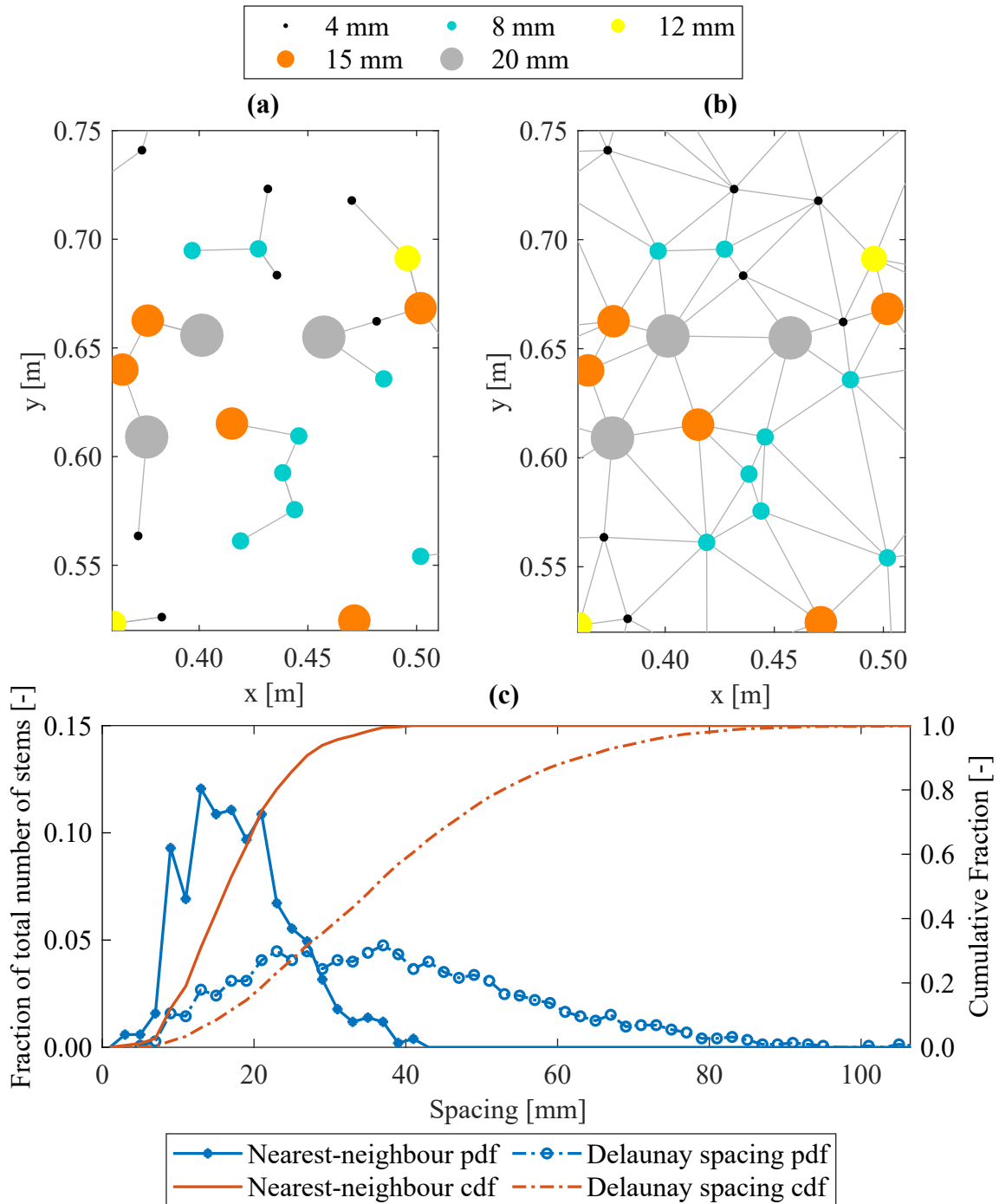


Fig. 7. **a)** Nearest-neighbour (NN) and **b)** Delaunay (DN) inter-stem spacing distributions. **c)** Probability and cumulative functions for NN and DN spacing distributions.

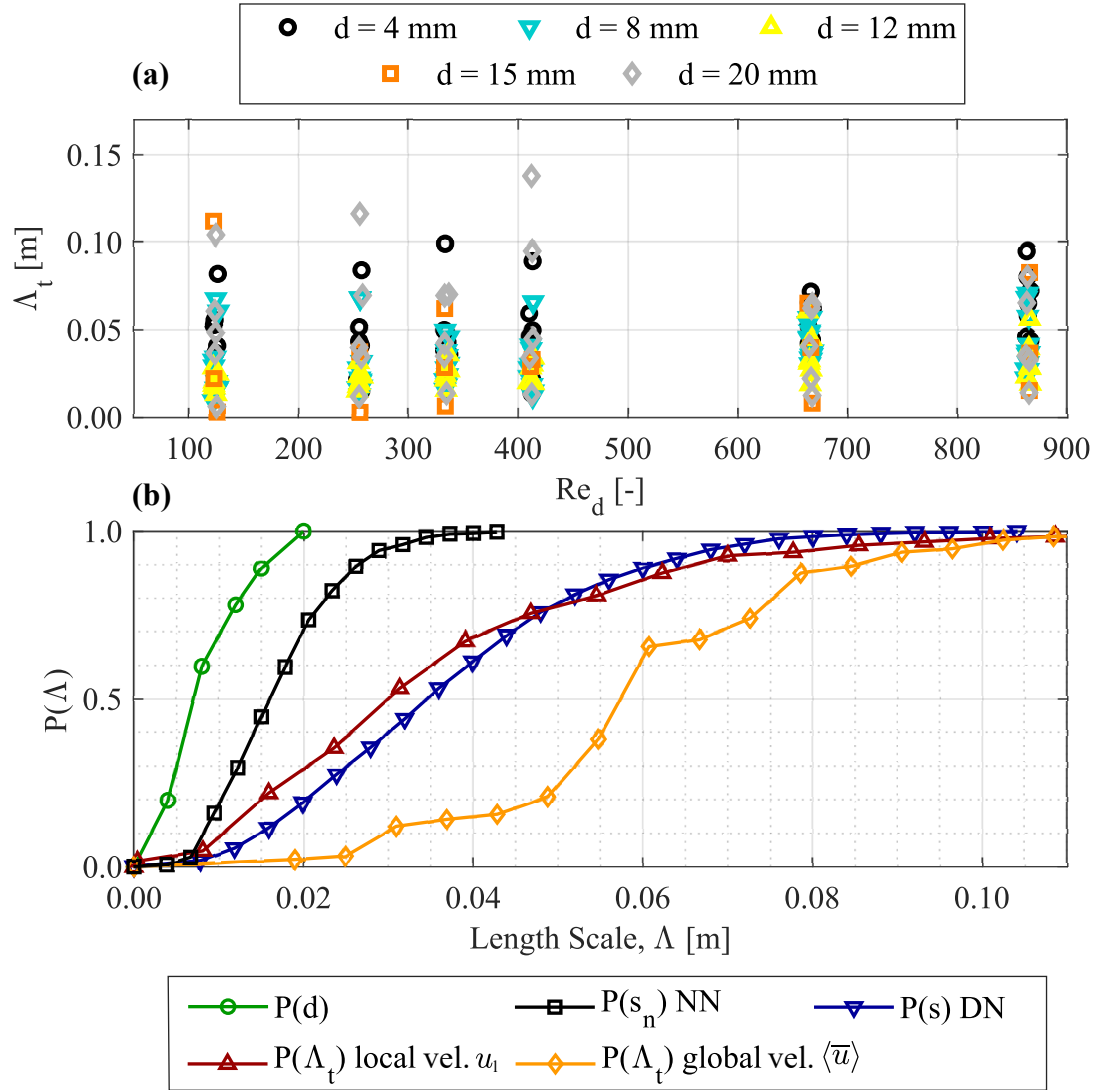


Fig. 8. a) Variation of point-based estimates of length scales, Λ_t , with respect to stem Reynolds number, Re_d , and b) density and cumulative Distribution functions for Λ_t , for local and global estimates of velocity.