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Brief Communication

# Voronoi analysis of beads suspended in a turbulent square channel flow

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## Introduction

Particles commonly occur in industrial and environmental turbulent flows (Crowe et al., 1996) where they tend to be preferentially distributed depending on particle/flow properties such as Stokes number, $\tau_p^+ = \tau_p/\tau_f$, i.e. the ratio between particle response time, $\tau_p = \rho_p d_p^2/(18\rho_f v)$, and a relevant flow time scale, e.g. the viscous time scale, $\tau_f = v/u_\tau^2$; $u_\tau$ denotes friction velocity, $\rho$ material density, $v$ kinematic viscosity and "+" inner wall scaling; subscripts "*p*" and "*f*" denote particle and fluid, respectively. In the past decades, numerical and experimental studies revealed inertial particle clustering in turbulent flows (Fessler et al., 1994; Marchioli and Soldati, 2002). In turbulent boundary layers, particle transport by coherent near wall structures (sweep/ejections) is a broadly accepted mechanism (Soldati, 2005; van Hout, 2010, 2013). These near-wall structures come as packets (Zhou et al., 1999) having considerable streamwise extent (~300 wall units). As a result, particle accumulation in longitudinal streaks with transverse spacing of ~100 wall units was observed (Kaftori et al., 1995). Only a few investigations on particle dispersion have been performed in square duct flows (Phares and Sharma, 2006; Yao and Fairweather, 2010; Rabencov et al., 2014) that are characterized by Prandtl's secondary motions of the 2nd kind. It has recently been shown that these are induced by streamwise, near wall coherent structures (Uhlmann et al., 2007; Pinelli et al., 2010).

Voronoï tessellation has recently been used to study particle clustering in homogeneous turbulent flows (Fenerc and Néda, 2007; Monchaux et al., 2010; Tagawa et al., 2012). Voronoï analysis produces a "Voronoï diagram" dividing space into "Voronoï cells", defined around a "seed" (e.g. bead position). Any point within the Voronoï cell is closest to the corresponding seed. The Voronoï cell area, *A*, is the inverse of the local bead concentration and therefore equivalent to the local concentration distribution. Unlike other methods evaluating clustering such as "box counting" (Aliseda et al., 2002), Voronoï analysis does not require an a-priori chosen length scale.

The aim of this short communication is to apply Voronoï analysis to beads suspended in an inhomogeneous turbulent square channel flow and characterize clustering.

## Experimental setup and methodology

Experiments were performed in a closed loop, horizontal, square water channel facility (Fig. 1) made of glass ensuring optical access. The test section bulk velocity, $U = 0.38 \pm 0.03$ m/s, corresponded to a Reynolds number, $Re_h = 10{,}602$, based on channel half height, $h = 25$ mm, and $u_\tau = 0.021$ m/s. Fully developed, turbulent flow was achieved at $l/h = 52$, where $l$ is the distance from inlet to measurement position.

Single view, digital in-line holography was used to track beads in a volume of interest (VOI) of $50.0 \times 17.4 \times 17.4$ mm$^3$ at the channel bottom. Polystyrene beads (specific gravity 1.05, Microbeads AS) with mean diameter, $\langle d_p \rangle = 141 \pm 2$ µm (TS140, $\tau_p^+ = 0.502$), were added to particle filtered (<5 µm), deionized water ($T = 25.90 \pm 0.05$ °C) giving an average number density, $\langle \#_d \rangle = 167$beads/VOI. In addition, few larger beads ($\langle d_p \rangle = 583 \pm 14$ µm) were present at two orders of magnitude lower

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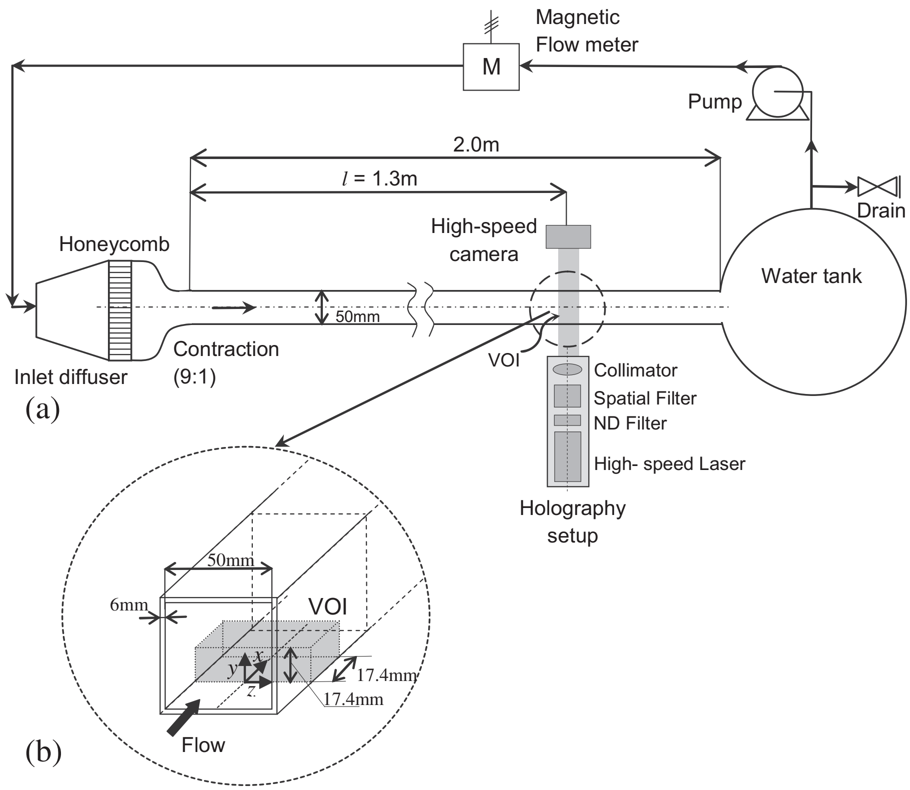


**Fig. 1.** Schematic layout of (a) water channel/holography setup, and (b) VOI.

$\langle \#_d \rangle \approx$ 1bead/VOI. In the following, only TS140 beads are discussed assuming no interaction between small and large beads (based on the large difference in $\langle \#_d \rangle$). Further note that the latter did not change mean and turbulent flow field characteristics (van Hout, 2010). Holograms created by interference between diffracted object and reference beams at the camera's sensor (Vikram, 1992) were acquired at 1 kHz; Every 50th hologram (total 164 holograms) was analyzed to obtain independent bead position data. Streamwise, wall-normal and transverse directions are denoted by $x$, $y$, $z$, respectively; $\langle .. \rangle$ denotes average.

To determine bead locations, holograms were numerically reconstructed by solving the Fresnel diffraction formula (Schnars and Jüptner, 2005). Beads' ($z$)-positions were determined by gradient operator (Langehanenberg et al., 2008) while ($x$, $y$)-positions were based on the beads' centers of mass. Useful data was obtained for $y^+ = yu_\tau/\nu > 20$. For more information on the experimental setup and hologram reconstruction, see Rabencov et al. (2014).

## Voronoi analysis

To obtain insight in bead clustering/segregation in wall-bounded turbulent flow, Voronoï tessellation was performed after collapsing 3D bead coordinates onto $y^+$–$x^+$ and $y^+$–$z^+$ planes (Fig. 2). Data collapse was necessary due to low $\langle \#_d \rangle$ hindering 3D tessellation as many Voronoï volumes would not be closed by physical boundaries (i.e. the channel walls). Furthermore, based on recent planar PIV experiments (van Hout, 2010, 2013) in the same channel and conditions, beads do not change their $z^+$ position much during passage of the VOI. Note that collapsing the 3D volume onto a 2D plane sort of "artificially" increases the number of beads at the collapsed cross-sectional slice assuming no bead interaction and negligible transverse drift in the streamwise direction. Dots and lines indicate beads and perpendicular bisectors to lines connecting them, respectively. $\langle \#_d \rangle$ in the $y^+$–$z^+$ plane (Fig. 3) indicates that beads are absent near the side walls/corners corresponding to Yao and Fairweather (2012) who showed that particles having $\tau_p^+ < 6.43$ deposit near the channel bottom center. The latter is likely the result of secondary flows (Phares and Sharma, 2006; Yao and Fairweather, 2012; Rabencov et al., 2014). Note, the corresponding $\langle \#_d \rangle$ in the $y^+$–$x^+$ plane is uniform (not shown).

Randomly distributed particles are described by 2D Poisson distribution (Ferenc and Néda, 2007):

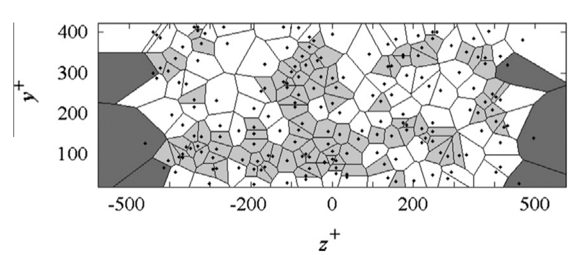


**Fig. 2.** Voronoi diagram (Approach I). – Cell edges, • "seeds". Clusters: light gray, Voids: dark gray.

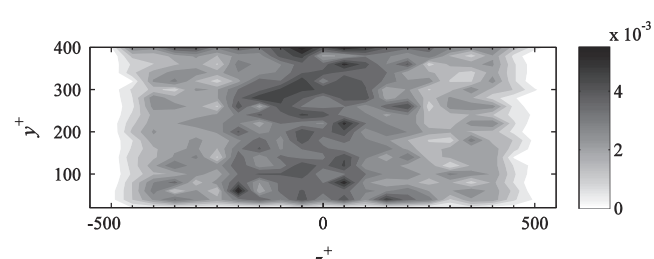


**Fig. 3.** Average bead number density.