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Daniel Odens Mora, Alberto Aliseda, Alain H. Cartellier, Martin Obligado

To cite this version:

Daniel Odens Mora, Alberto Aliseda, Alain H. Cartellier, Martin Obligado. Pitfalls Measuring 1D Inertial Particle Clustering. iTi Conference in Turbulence 2018, Sep 2018, Bertinoro, Italy. pp.221-226, 10.1007/978-3-030-22196-6_35. hal-02067048

HAL Id: hal-02067048
https://hal.univ-grenoble-alpes.fr/hal-02067048v1

Submitted on 27 Jan 2025

Pitfalls Measuring 1D Inertial Particle Clustering

Daniel Odens Mora, A. Aliseda, Alain Cartellier and M. Obligado

Abstract We perform 1D Voronoï analysis on a time series from an optical probe detecting the passage of particles in a homogeneous. isotropic turbulent flow. The Voronoï analysis is unable to identify clustering in the particle locations along the measuring "line", despite the flow being almost identical in terms of the Reynolds number based on the Taylor scale (Re_λ), and Stokes (St) numbers to previous experiments in which 2D Voronoï analysis successfully detected and measured this phenomenon [8]. The optical probe accurately measured the particle average global concentration, and size distribution. This result stemmed from the *sub-kolmogorov* measuring volume of the probe, and seems to be in agreement with previously reported studies under totally different conditions [7] that referred to this issue as *sub-poissonian* events. If the instrument measurement window size is 'large' enough -but not too large to smooth out all correlations-, and the data satisfyies statistical convergence, 1D Voronoï diagrams effectively capture evidence of clustering, and constitute a reliable proof of preferential concentration within the flow.

1 Introduction

The study of inertial particles clustering in turbulent flows has received a large amount of attention over the last three decades. This increased interest stems from its potential applications, for instance; aerosol pollutant modelling, and rain droplets formation [8]. Several techniques have been employed to characterize particle-clusters, for example Voronoï tessellations is an increasingly popular tool in either numerical or experimental studies (see [8] and references therein). These 2D/3D Voronoï diagrams have successfully quantified the deviation from randomness (from a Random Poisson Process distribution, RPP) in the inertial particles spatial organization. From

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D. O. Mora (✉) · A. Cartellier · M. Obligado
Univ. Grenoble Alpes, CNRS, Grenoble-INP, LEGI, 38000 Grenoble, France
e-mail: daniel.mora@univ-grenoble-alpes.fr

A. Aliseda
Department of Mechanical Engineering, University of Washington,
Seattle, WA 98195-2600, USA

an experimental point of view, it is interesting to explore whether lower dimensional techniques (1D), such as optical probes [3] are able to recover the clustering signature found in 2D/3D studies. Using these 1D measurements, along a line in space leads towards 1D Voronoï analysis. However, quantifying preferential concentration by means of unidimensional measurements, as described by Shaw [7], might lead to wrong conclusions if caution is not taken, i.e. the absence of evidence of preferential concentration might be due to a faulty method of analysis, or inadequate resolution of measuring instrument. In this context, we explore these biases where the absence of preferential concentration by means of unidimensional Voronoï analysis (1DVOA) could not discard its existence within the flow.

2 Experimental Setup and Methods

The experiment was conducted in a close-circuit wind tunnel at the LEGI-Grenoble laboratory. This wind tunnel has been extensively used to study particle clustering under homogeneous isotropic turbulent conditions [5, 8]. Turbulence is produced by means of an active grid, downstream of which a rack of 36 spray nozzles generate inertial water droplets, see [8]. The grid was operated in two different modes. In the first one, the grid is actuated with time-varying rotation rates and directions, which are chosen randomly (random grid). The second one consists in keeping the grid static and completely open (open grid). The global volume fraction ϕ_v was varied in a range $\in [1-5] \times 10^{-5}$ to avoid turbulence modulation by the droplets. The turbulence within the measuring region has been experimentally found to be very close to a statistically isotropic state [5, 8] under the same experimental conditions (Re_λ, and η). The signal to compute 1DVOA was acquired by means of an monofiber optical probe described in [3]. An example of the signal acquisition record is shown in Fig. 1. The probe diameter δ was well below the Kolmogorov lengthscale η ($\delta \ll \eta$). To compute the 2DVOA, a high speed camera collected 4500 images of the light scattered by the water droplets from 1 mm thick laser plan illumination, and these images were subsequently post-processed to identify the location of the centers of the droplets. The average number of droplets per image was 4000, and the illumination was normalized to remove biases, following [8]. All experimental parameters from both experiments are summarized in Table 1.

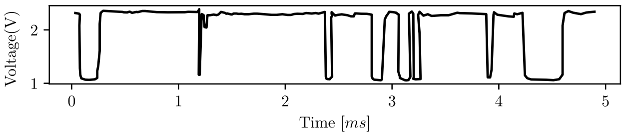


Fig. 1 Probe raw signal example. The signal reaches its maximum amplitude when the probe is surrounded by air, and whenever a droplet interacts with the probe tip, there is a sharp decrease in voltage. For details, see [3]

Table 1 ϕ_v is the volume fraction, $\lambda = \sqrt{15\nu/\varepsilon}u'$ is the Taylor length scale, and $\nu \sim 1.5 \times 10^{-5}$ $[m^2 s^{-1}]$ is the air viscosity, $Re_\lambda = u'\lambda/\nu$, D_p is the value of the most probable diameter which was used to compute the Stokes number $St_\eta = \frac{(D_p/\eta)^2}{36}(1 + 2\rho_p/\rho_f)$, see [8]. ρ_p/ρ_f is the density ratio between the particles, and the carrier phase. ε, and $\mathcal{L}$ is the carrier dissipation, and integral length scale, respectively, and OG/AG stands for open/active grid mode, respectively

Dataset	Grid mode	Re_λ	St_η	$\varepsilon\mathcal{L}^4/\nu^3$	D_p/η	$\mathcal{L}/\eta$	λ/η	ϕ_v	ρ_p/ρ_f
EXP-1D-OG	Open	105	1.4	1.0×10^8	0.125	110	20	1.0×10^{-5}	800
EXP-2D-AG-A	Random	250	0.9	4.3×10^8	0.125	175	35	1.2×10^{-5}	800
EXP-2D-AG-B	Random	250	0.9	4.3×10^8	0.125	175	35	2.3×10^{-5}	800
EXP-2D-AG-C	Random	250	0.9	4.3×10^8	0.125	175	35	4.7×10^{-5}	800

3 Results

Following [1], a unidimensional Voronoï analysis (1DVOA) was performed on the signal extracted from the optical probes. Figure 2 illustrates the diagram construction. Droplets were solely characterized by their arrival time. Considering previous 2D Voronoï analysis (2DVOA) have shown evidence of particle clustering [5, 8], it was rather surprising to find the signature of a Random Poisson Process (RPP) in the distribution of the inter-particle distance from the 1DVOA. This denotes the absence of preferential concentration (see Fig. 3a), despite the probe's accuracy in capturing global variables, such as liquid volume fraction or droplet size distribution. This result appeared to be consistent for the different vertical locations sampled in the measurement region, as well as for different values of injected droplet diameters, turbulence intensities, or the type of probe employed (single or triple cone [3]).

To discard the possibility that the underlying working principle of the probe or an incorrect configuration were responsible for the unexpected result found in Fig. 3a, 2D experimental images (see Table 1) were virtually sampled, aiming to emulate a 1D measurement to check whether the probe size δ had an impact on the 1DVOA outcome. These images were analyzed by 2DVOA, which confirmed the presence of preferential concentration in the droplet spatial distribution in this flow, as shown in Fig. 3b where the PDF shapes deviates from the corresponding RPP. This 'virtual' 1D projecting procedure was conducted as follows (see also Fig. 4a):

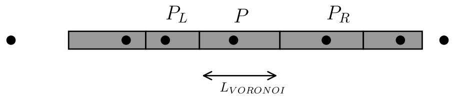
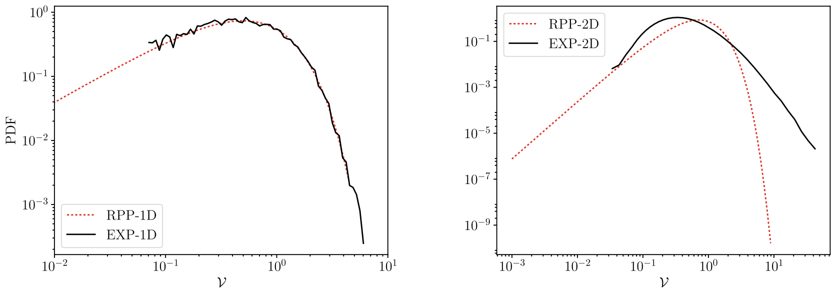


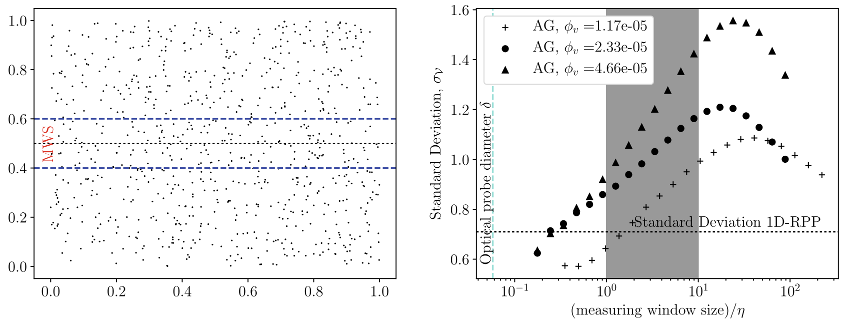
Fig. 2 For a given point **P** with left, and right neighbours points P_L, and P_R respectively, the length of the Voronoï cell is given by $L_{VORONOI} = |P_R - P_L|/2$. The time of the sharp decline in signal (droplet arrival time) illustrated in Fig. 1 was taken as the **P** point shown in this sketch



(a)

(b)

Fig. 3 **a** PDF of normalized Voronoï lengths by 1DVOA, $\mathcal{V} = L_{Vorono\ddot{\imath}}/\langle L_{Vorono\ddot{\imath}}\rangle$, from our experimental data acquired by an optical probe. 2D analyses detected clustering under similar experimental conditions $Re_\lambda \sim 100$, see Fig. 3b. **b** PDF of normalized Voronoï areas by 2DVOA[4], $\mathcal{V} = A_{Vorono\ddot{\imath}}/\langle A_{Vorono\ddot{\imath}}\rangle$ for the experimental data (EXP-2D-AG-C) found in Table 1. Here, it is clearly seen that the experimental data PDF follows a different trend than the RPP



(a)

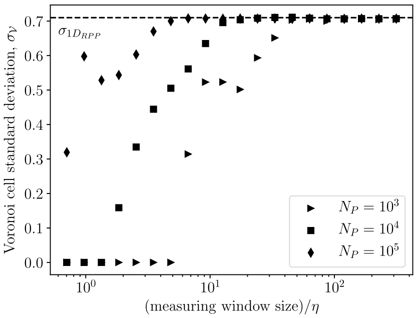
(b)

Fig. 4 **a** Illustration of the procedure taken to uni-dimensionally sample the 2D experimental data $2D \rightarrow 1D$ The measuring window size (MWS) was varied to obtain the Fig. 4b. **b** Standard deviation, $\sigma_{\mathcal{V}}$ against measuring window size for the experimental data found in Table 1. Shaded region denotes the sizes of interest for several '1D' measuring instruments, e.g., PDI [6]

1. A random vertical coordinate was generated, and a measuring window or detection threshold was defined.
2. All the points/droplets *centers* that lay within this measuring strip were projected into a line, i.e., their horizontal coordinates are taken, which is basically invoking the Taylor's frozen flow hypothesis.
3. 1DVOA was performed over the projected points.

Figure 4b illustrates how the standard deviation ($\sigma_{\mathcal{V}}$) of the normalized Voronoï cells, which serves to quantify clustering via 1DVOA or 2DVOA [4, 5], varies with the measuring window size (MWS). The plot exhibits a *non-monotonic* behavior with the MWS, and shows that if it is too narrow, the signature of clustering might be lost. This "decorrelating" effect from the small probe window size is the origin

Fig. 5 'Virtual' ($3D \rightarrow 1D$) 1DVOA standard deviation evolution versus measuring window size from 1D sampling of artificially generated 3D data using a random distribution. N_P stands for the number of points inside the 3D domain



of the false negative result reported here (see Fig. 3a) and, therefore, a signal coming from an optical probe would not be able to capture the preferential concentration that exists in the flow via 1DVOA, i.e., $\sigma_{\mathcal{V}} \sim 0.71$. For completeness, the same algorithm was applied to a "cloud" of 3D points generated by a random distribution (RPP) employing the different number of particles to check the impact of particle concentration. Interestingly, for the random cloud virtual set (see Fig. 5), even with 100 times more snapshots than the actual data, there is an evolution of the inter-particle rms with the concentration as seen in Fig. 4b, that is proportional to the number of events detected and, therefore, increases the convergence of the statistics. This plot confirms the role of convergence and projections, suggesting that *sub-poissonian* events are only a consequence of lack of convergence. More importantly, it shows that a sensitivity analysis of this type for an RPP distribution will not produce evidence of spurious clustering, or $\sigma_{\mathcal{V}} > 0.71$. The impact of volume fraction ϕ_v in $\sigma_{\mathcal{V}}$ follows previous trends found [8].

Similar studies with the radial distribution function (RDF) noticed attenuation in the 1D-RDF at lengths below the characteristic length of the instrument employed, and explained its origin by loss of information [2] due to the projection. This related phenomenon, which has been previously reported under different conditions to the ones here ($St \ll 1$, [7]), had a similar bias at small scales, with *sub-poissonian* events occurring as a result of the instrument resolution and droplets finite size. This supports the hypothesis that the optical probe actually recorded uncorrelated events, explaining the false negative result found. Hence, if the evaluation of preferential concentration by means of 1DVOA is made by comparing the standard deviation of the signal's $\sigma_{\mathcal{V}}$ against the corresponding RPP's σ_{RPP}, a positive result ($\sigma_{\mathcal{V}} > \sigma_{RPP}$) indicates without doubt the presence of clusters within the flow, whereas the opposite is not necessarily true, namely, $\sigma_{\mathcal{V}} \approx \sigma_{RPP}$ does not prove that a lack of clusters. Furthermore, our results from the optical probe and the analysis from Fig. 5 suggest that, rather than a loss of information, *sub-poissonian* events are the consequence of a lack of convergence.

4 Final Remarks

A sensitivity analysis might be required when evidence of preferential concentration by means of 1DVOA is not recovered. Conversely, when clustering is found in the 1DVOA, it is a reliable proof of its existence within the particle-laden flow. However, there are some open interesting questions concerning what is the optimal measuring window size to capture preferential concentration, and what is the impact of this analysis variable on cluster characterization.

Acknowledgements This work has been partially supported by the LabEx Tec21 (Investissements d'Avenir - Grant Agreement # ANR-11-LABX-0030).

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