Unsteady dynamics of bubble columns

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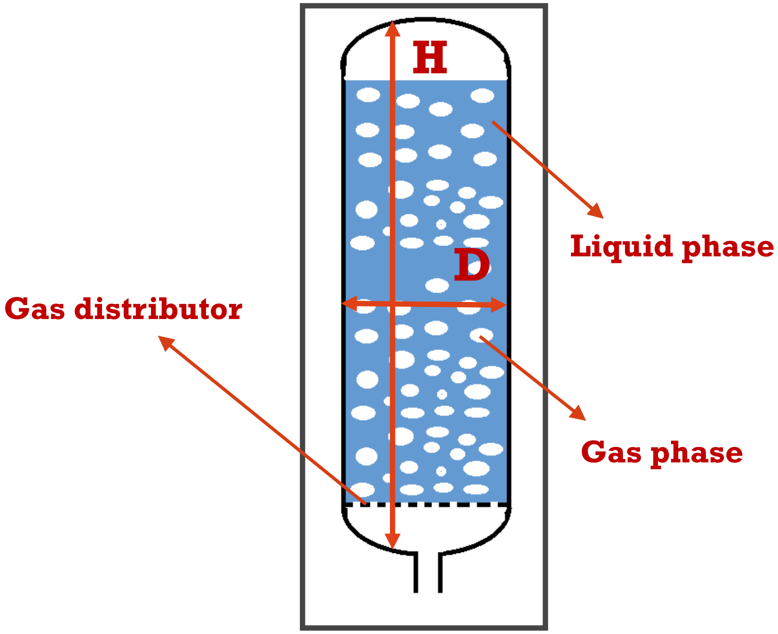
Bubble column reactors

Bubble column reactors, where gas is injected at the bottom of an initially stagnant liquid, are widely used in chemical engineering

- Hydrogenation (Fischer-Tropsch synthetic fuels production)
- Wet management (wet oxidation)
- Flotation units (deinking of paper, extraction of rare metals)

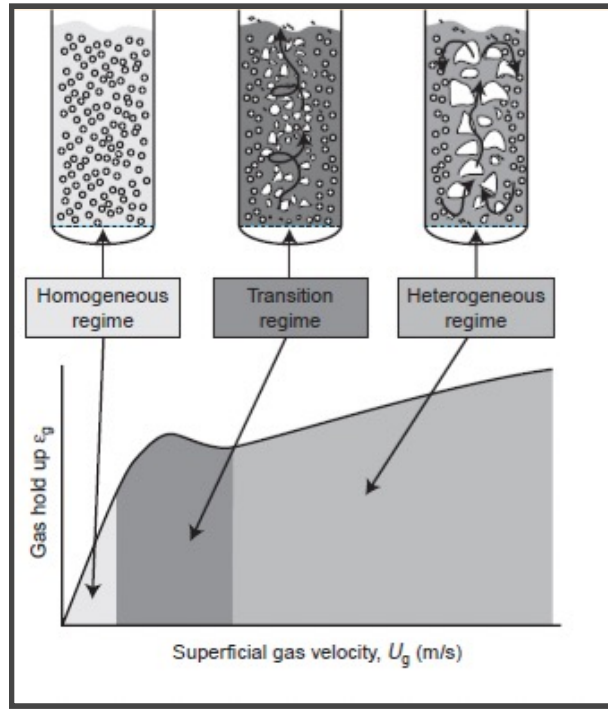


Bubble column reactors

1. **The homogeneous regime is reached at low gas velocities**
   - Presents a quasi-lineal relation between void fraction versus the gas superficial velocity

2. **No clear consensus in the transition between homogeneous and heterogeneous regime**
   - Recurrently linked with the existence of bubble coalescence

3. **The heterogeneous regime occurs at larger gas velocity conditions**
   - Gas hold-up experiences a slower increase than in the homogeneous regime



Forret et al, Oil & Gas Science and Technology-Revue de l'IFP, 2006

$$v_{sg} = \frac{Gas\ flowrate}{Column\ surface}$$

$\boldsymbol{\varepsilon_g}$: global gas hold-up

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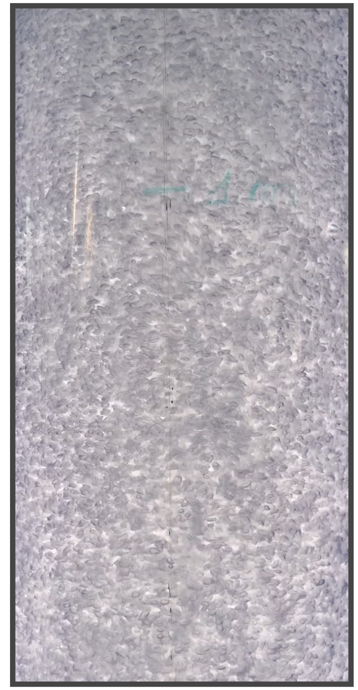

- Usually, the transition is considered to be caused by coalescence between bubbles
- However, some authors such as Chaumat *et al.* (Chem Eng Sci., 2005) have not detected the presence of large bubbles in the heterogeneous regime
- An alternative mechanism will be the agitation generated by the shear between clusters of bubbles

Up-scaling issues in the heterogeneous regime

Several numerical and experimental studies look for scaling laws of relevant parameters (ε_g, v_G, v_L) that can be **extrapolated to industrial reactors**:

- Experiments are performed in relatively small bubble columns ($D < 1\ m$)
- Numerical simulations

Current state of the art

- No consensus over scaling laws of involved quantities
  - Besagni et al. (2016) reviews 37 scaling laws only for the global void fraction
- Ad hoc closures are still needed in numerical simulations:
  - To quantify the void fraction ε_g, it is possible to tune the bubbles size distribution (coalescence) and/or the drag coefficient

$$v_{sg} = \frac{Q_{gas}}{S_{Section}}$$

ε_g: global void fraction

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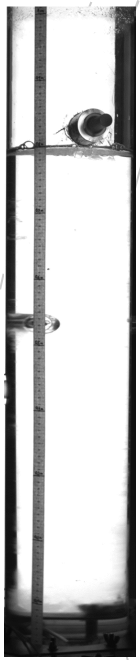
No attention has been paid to time-dependent parameters

Unsteady operation of bubble columns

Case 1
Startup and shutdown



Startup times

The time that takes the bubble column to reach a statistically steady regime

Unsteady operation of bubble columns

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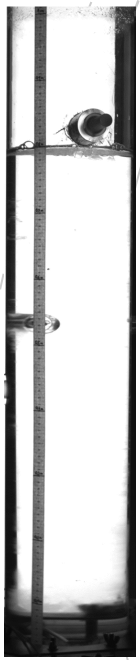
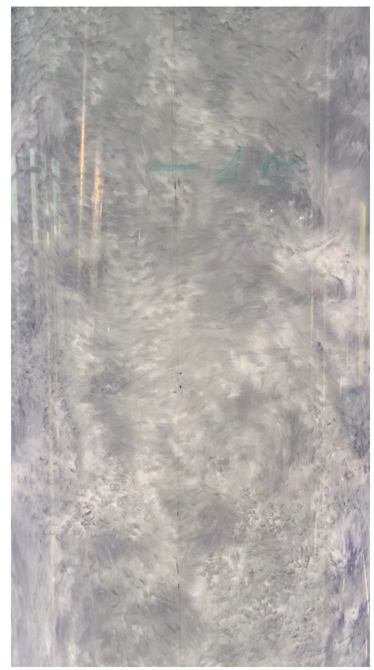


Startup times

The time that takes the bubble column to reach a statistically steady regime

Case 2
Fluctuations in the steady regime

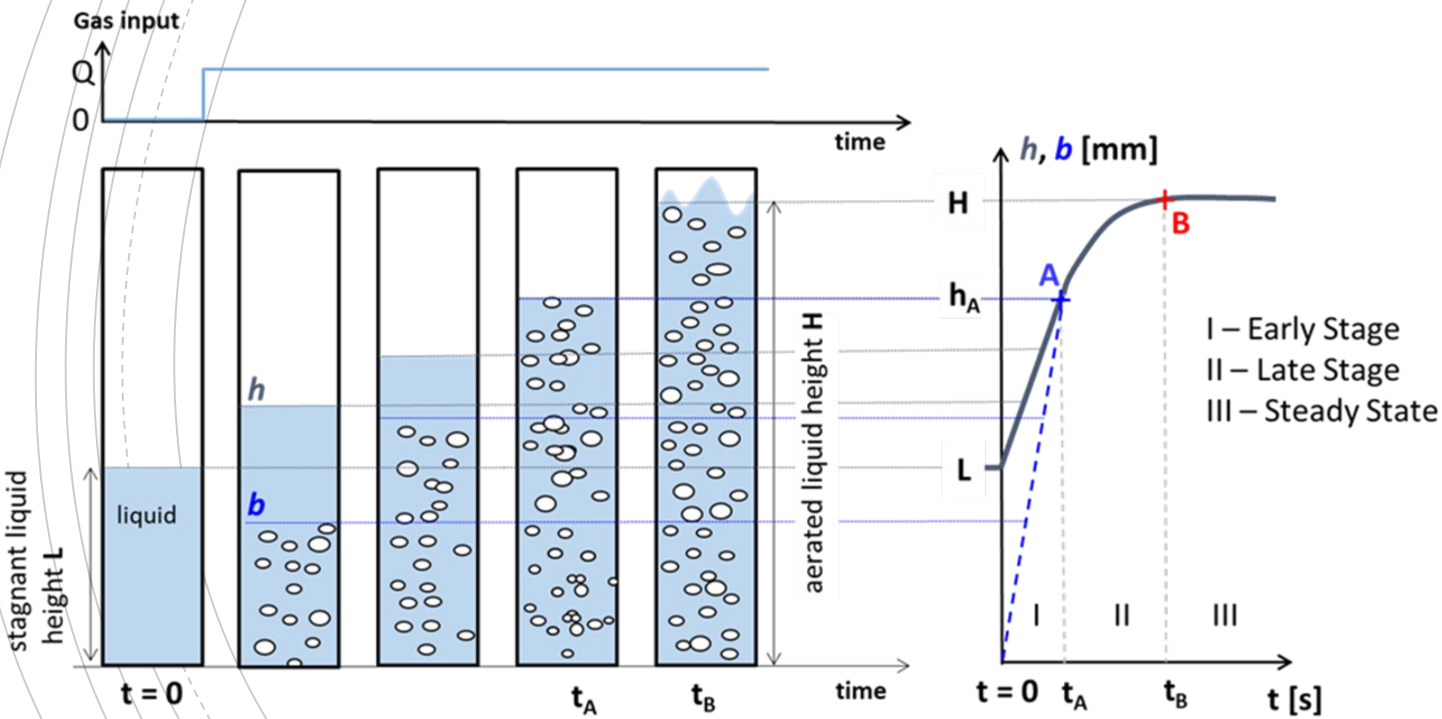


Turbulent fluctuations

The fluctuations of the flow within a statistically steady regime

Unsteady operation of bubble columns – Case 1

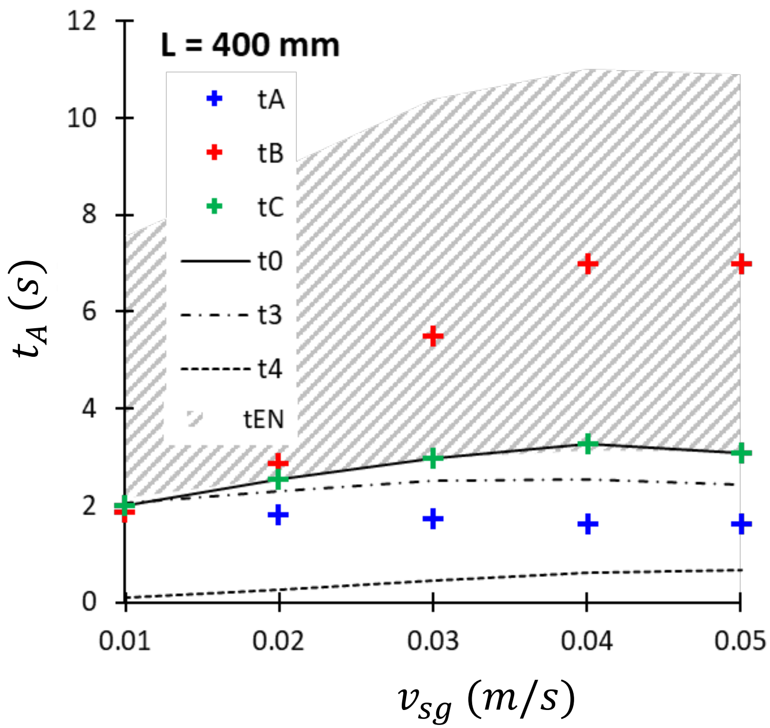
- A recent work quantified start-up and shutdown times in the homogeneous regime (low v_{sg})
- Quantified through early and late-stage times (t_A and t_B)
- The free surface is recorded and different initial heights tested



Ruzicka & Orvalho, CES 2023

Unsteady operation of bubble columns – Case 1

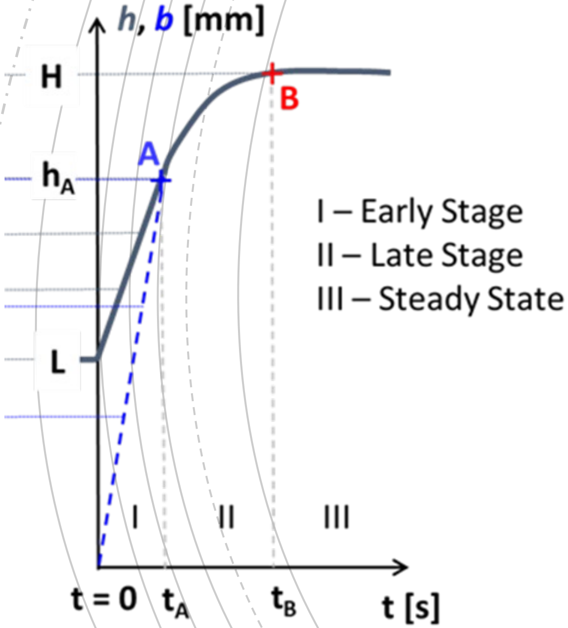
- A recent work quantified start-up and shutdown times in the homogeneous regime (low v_{sg})
- Quantified through early and late-stage times (t_A and t_B)
- The free surface is recorded for a bubble column with $D = 0.14m$



Ruzicka & Orvalho, CES 2023

Unsteady operation of bubble columns – Case 2

- An optical probe resolves in time the local void fraction
- A moving average produces a time-resolved continuous time signal
- The turbulent nature of the flow implies the presence of large fluctuations even in steady operating regimes



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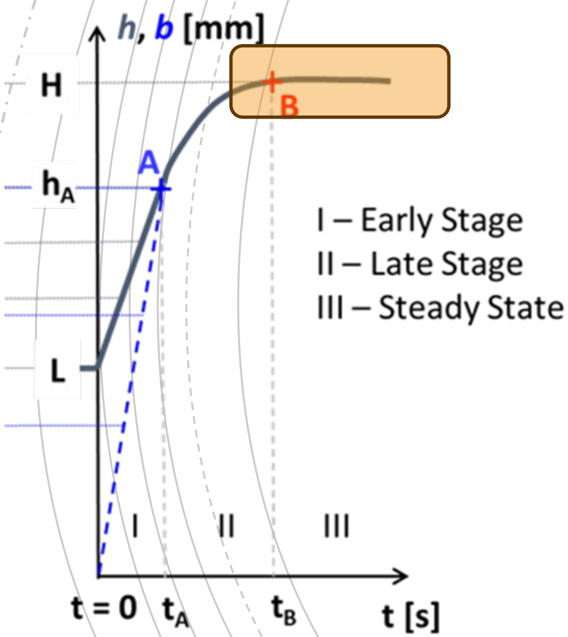

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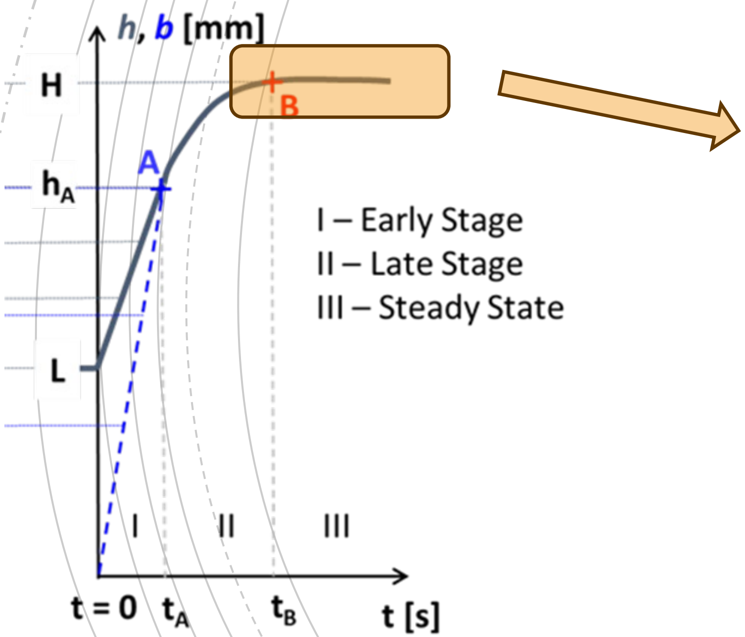

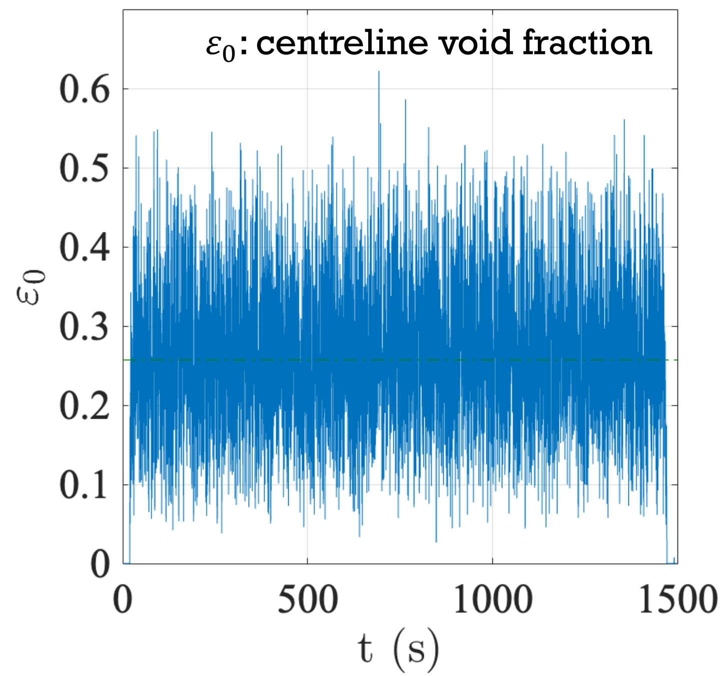

This talk

1. Quantify startup times (homogeneous and heterogeneous regimes)

2. Study the local time-resolved void fraction

3. Spectral analysis, autocorrelation, etc…

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Experimental strategy:

- Tests in bubble columns with different diameters ($0.08\text{m} < \text{D} < 1m$)
- Use optical probes with similar properties
- Comparison with the literature

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1. Quantify startup times (homogeneous and heterogeneous regimes)

2. Study the local time-resolved void fraction

3. Spectral analysis, autocorrelation, etc…

Label	Column diameter (m)	Distributor orifice (mm)	v_{sg} (cm/s)	Regimes
Pr8	0.08	0.5	1.3-20.1	3 Regimes
Pr14-1	0.14	1.6	1.3-20.1	Heterogeneous
Pr14-2	0.14	1.6	1.3-20.1	Heterogeneous
Pr14-3	0.14	1.0	1.3-20.1	3 Regimes
Pr14-4	0.14	0.5	1.3-20.1	3 Regimes
Pr19	0.19	0.5	1.3-20.1	3 Regimes
Pr40	0.40	0.5	1.3-20.1	3 Regimes
LEGI40	0.40	1.0	1.3-16.0	3 Regimes
IFP100	1	2.0	3.0-35.0	Heterogeneous

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Label	Column diameter (m)	Distributor orifice (mm)	Liquid height (mm)	Probe height (mm)
Pr8	0.08	0.5	800	560
Pr14-1	0.14	1.6	800	560
Pr14-2	0.14	1.6	800	280
Pr14-3	0.14	1.0	800	560
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Pr19	0.19	0.5	800	560
Pr40	0.40	0.5	800	560
LEGI40	0.40	1.0	2000	1450
IFP100	1	2.0	4000	2500

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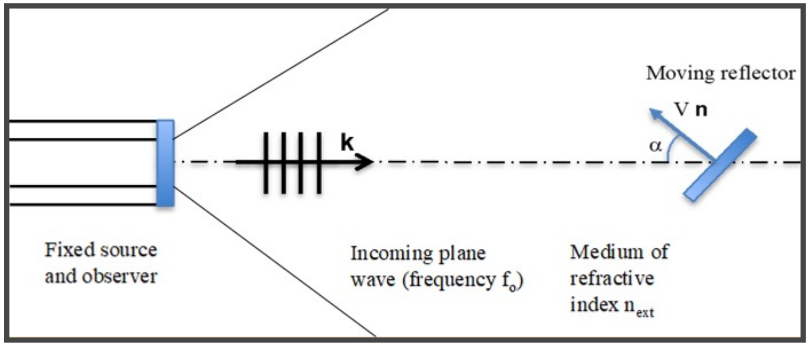
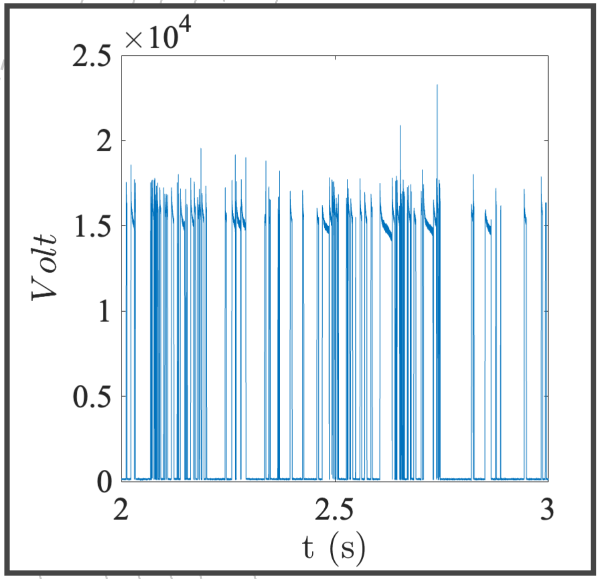
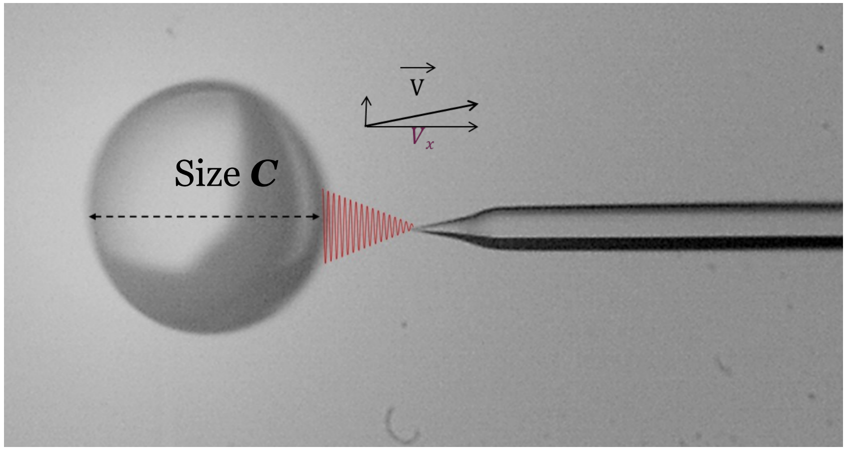
Doppler optical probes

Principle: Doppler shift with an optical fiber

$$f_D = 2\frac{V\,|\mathbf{n}\bullet\mathbf{k}|}{\lambda_0 / n_{ext}}$$



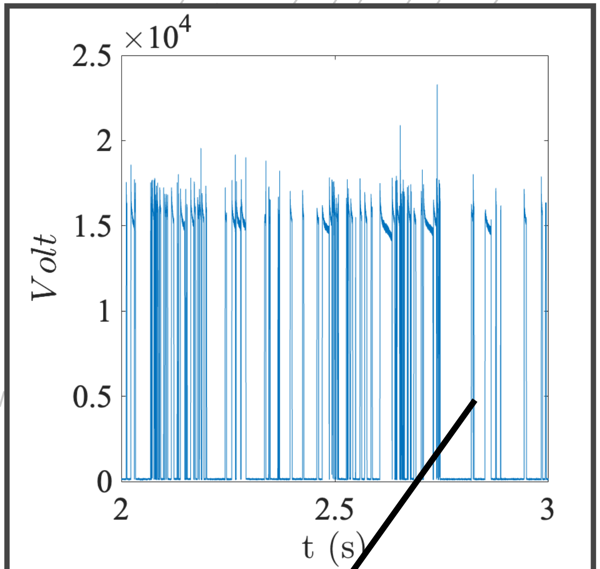


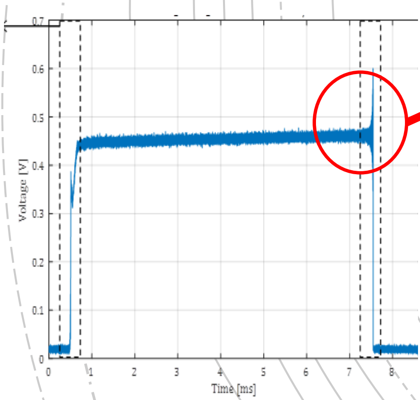


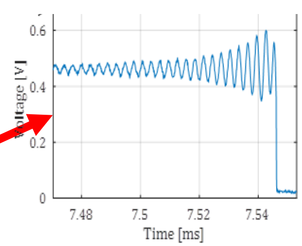
A2 Photonic Sensors

Doppler optical probes

Measurement principle and signal processing







→ T_g, T_a for each bubble → $< \varepsilon_g > = \frac{\sum T_g}{T_{total}}$

Local gas hold-up

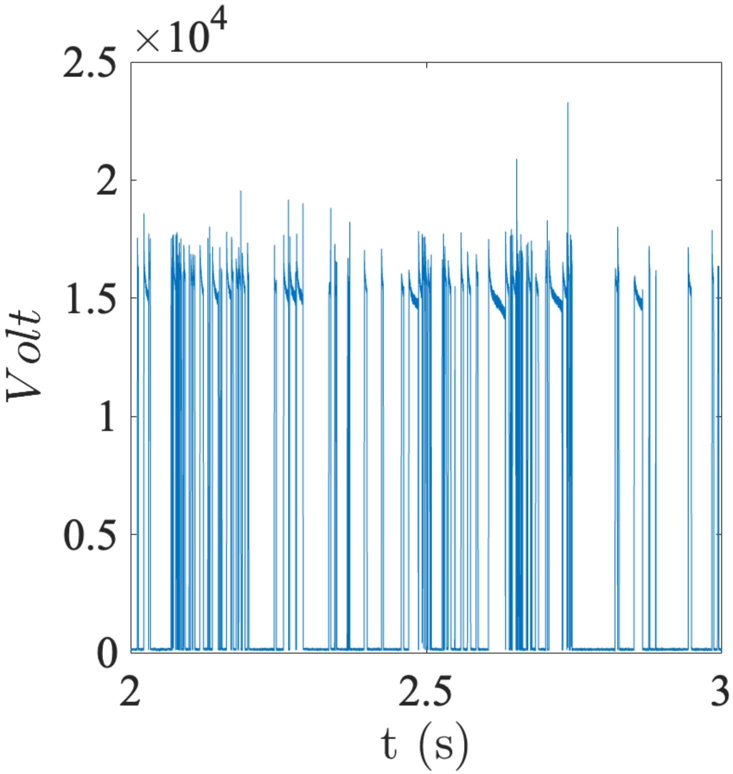
→ Gas velocity → **Gas velocity statistics**

Selection criteria:
- Number of successive periods n
- Period homogeneity ϵ

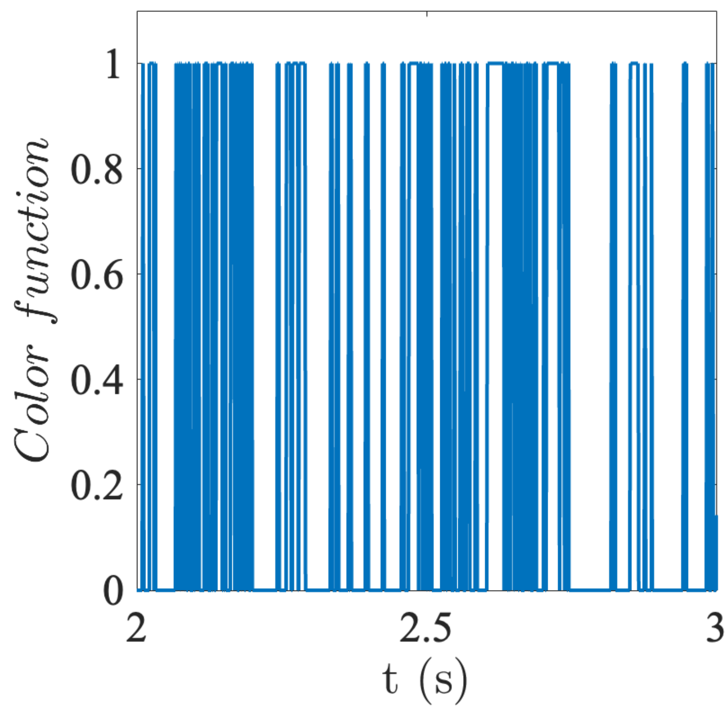
Lefebvre, Mezui, Obligado, Gluck and Cartellier, CES, 2022

Time-resolved void fraction estimation

Step 1: the raw signal is binarized ($CF = 1$ in air)



$\langle CF \rangle = \langle \varepsilon_0 \rangle$



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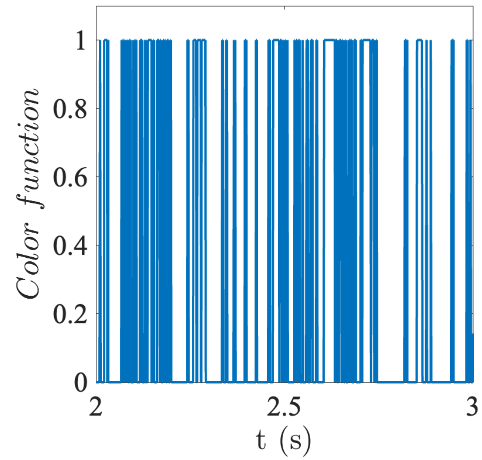
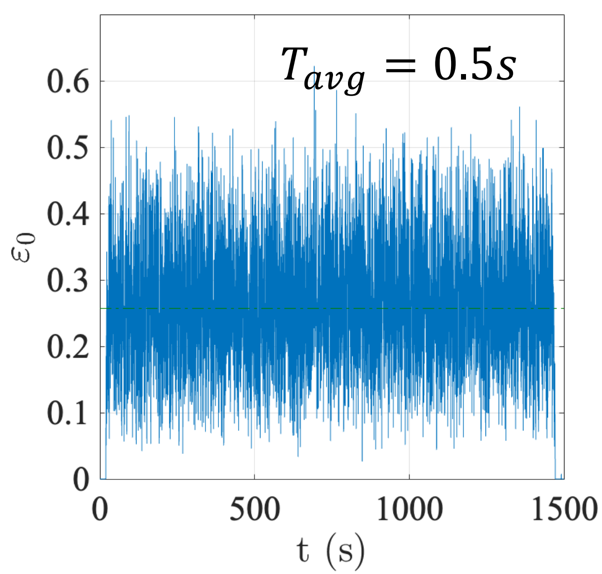
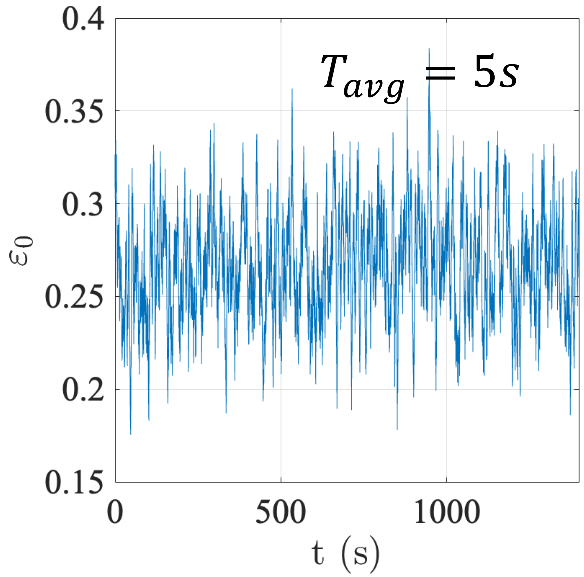


Step 2: a moving average produces $\varepsilon_0(t)$

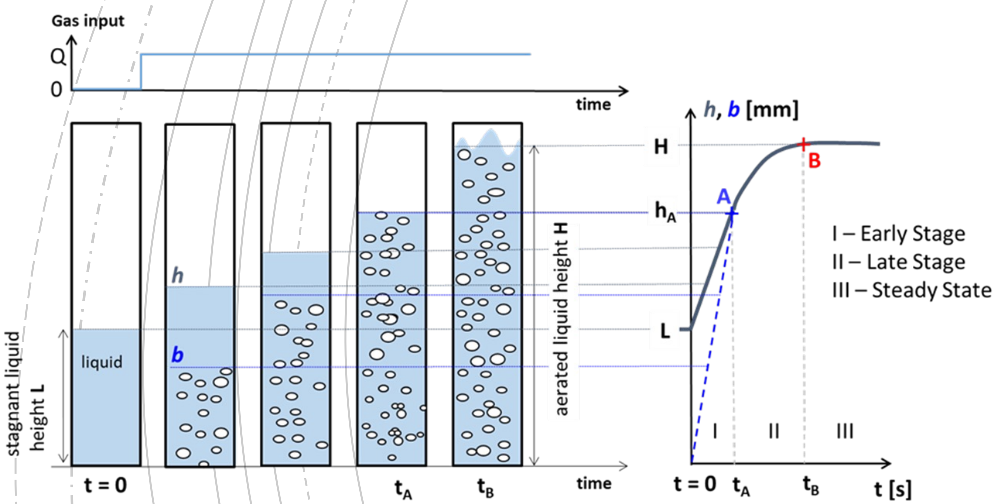


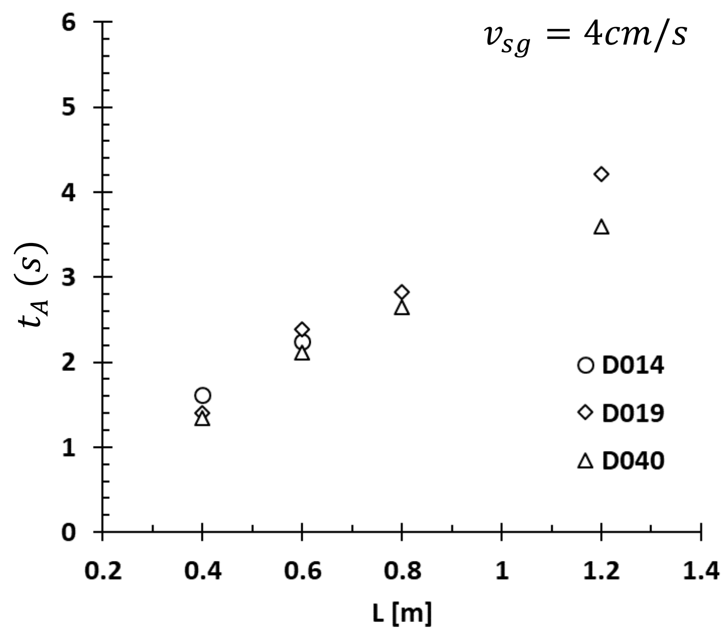


Results: startup times (case 1)

- A stopwatch was used to measure the rising time

- Effect of the column diameter, and liquid height L on t_A





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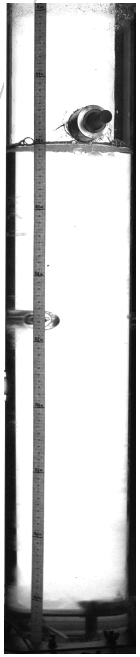

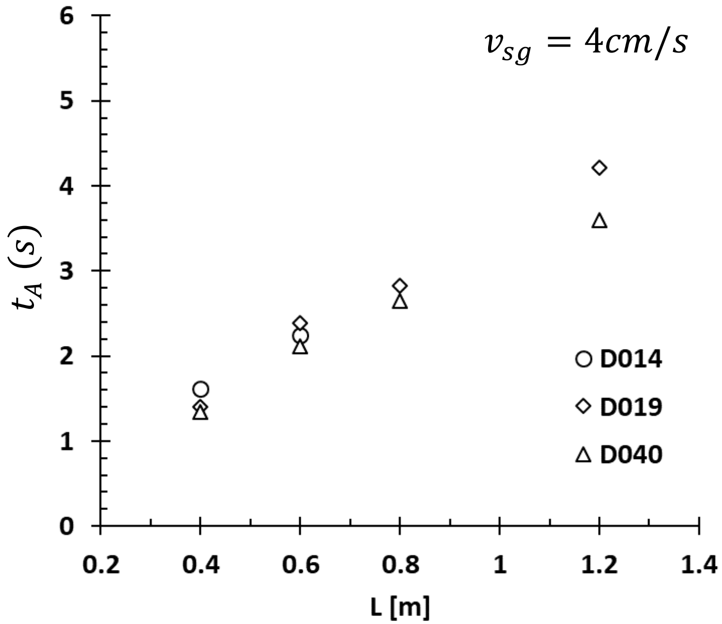

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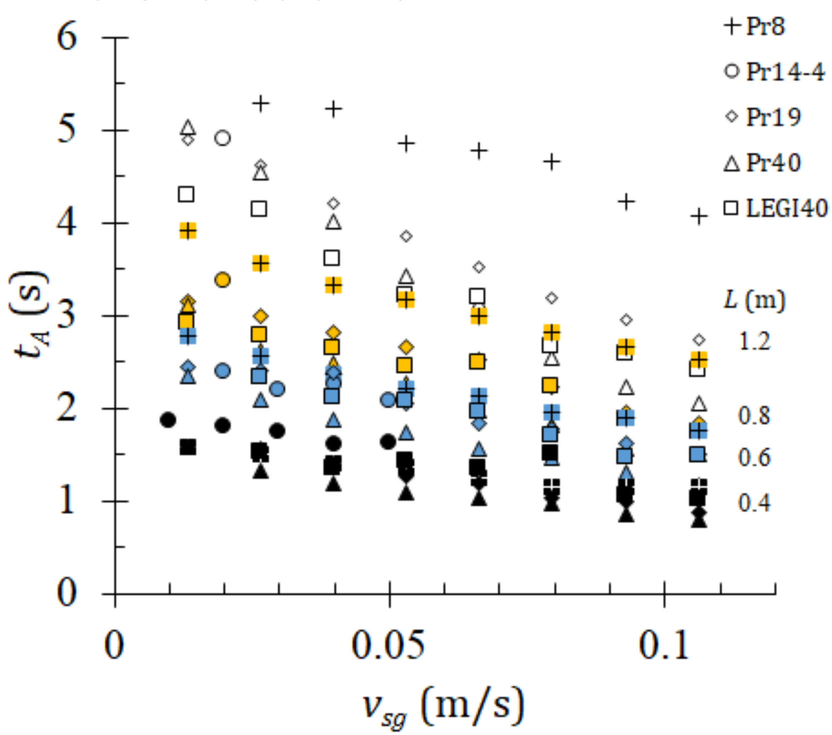
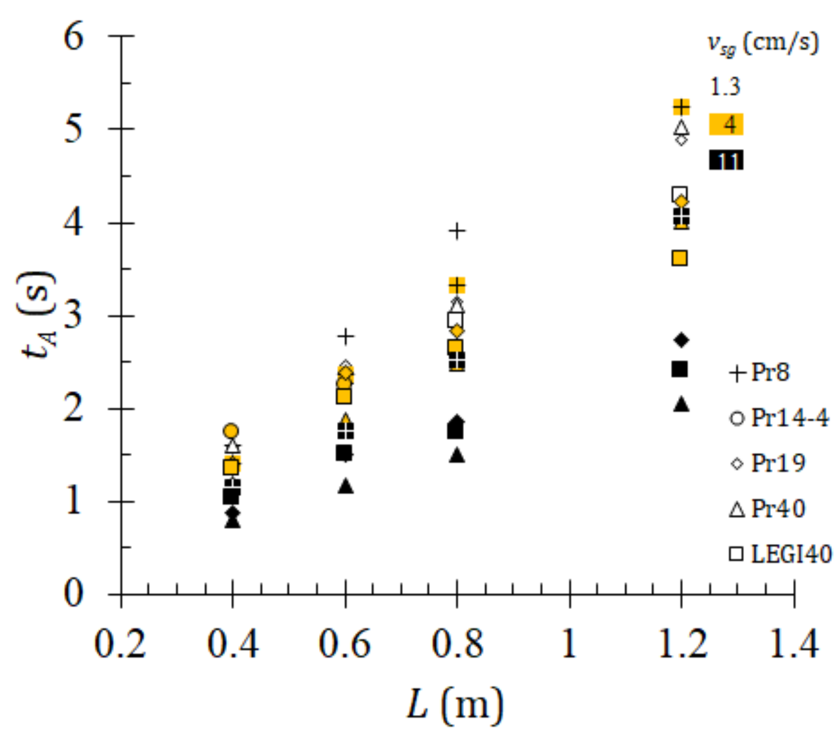
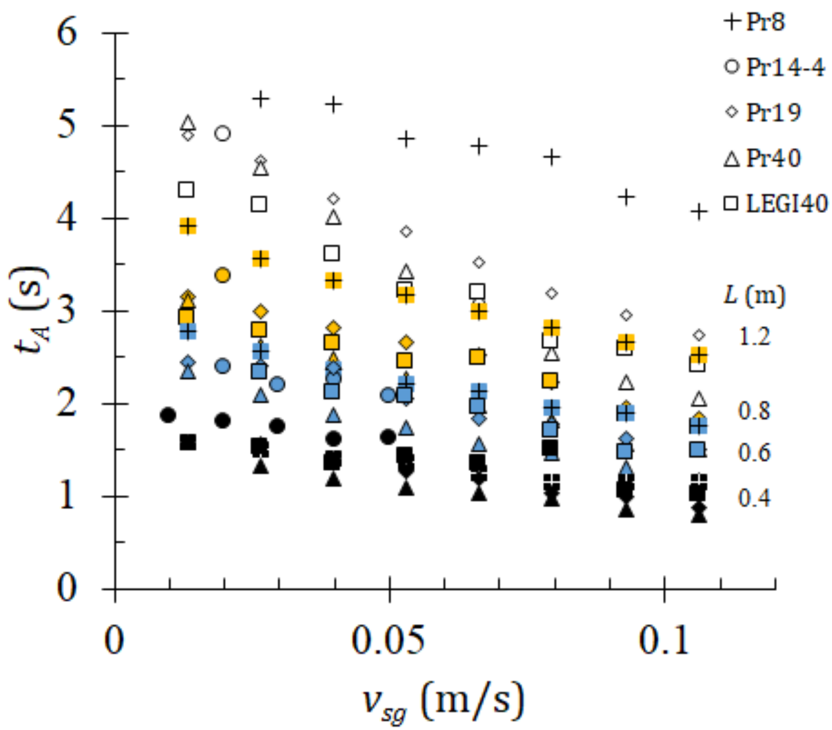
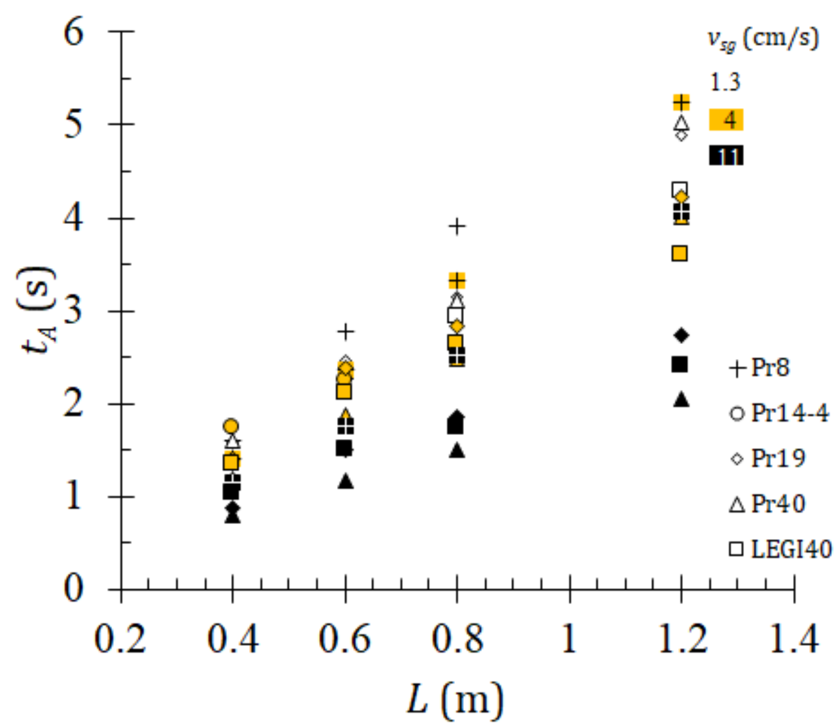




Results: startup times (case 1)

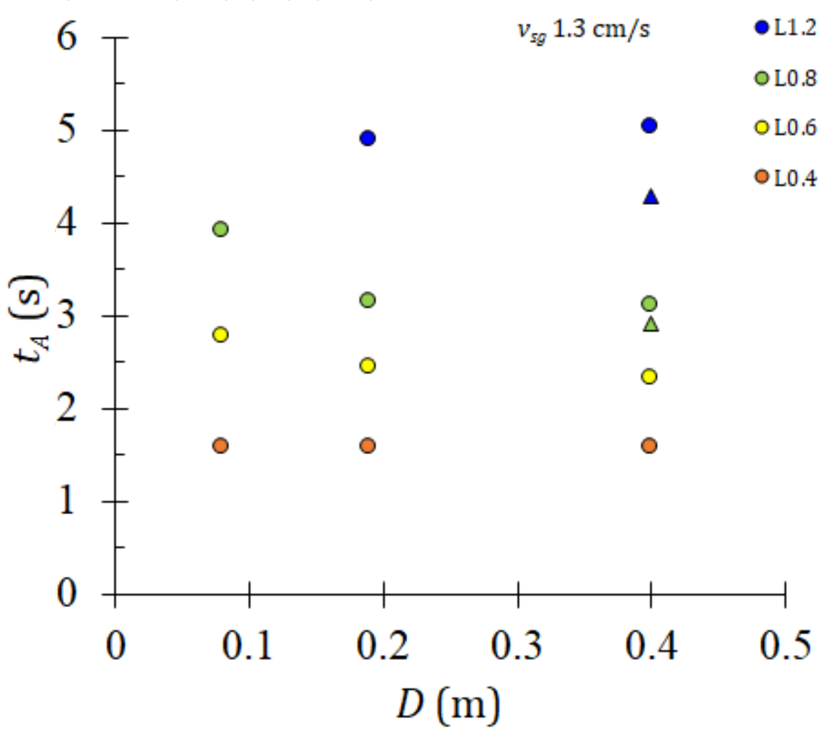
- The startup time has a dependency with the diameter
- A linear trend is observed, independently of the regime

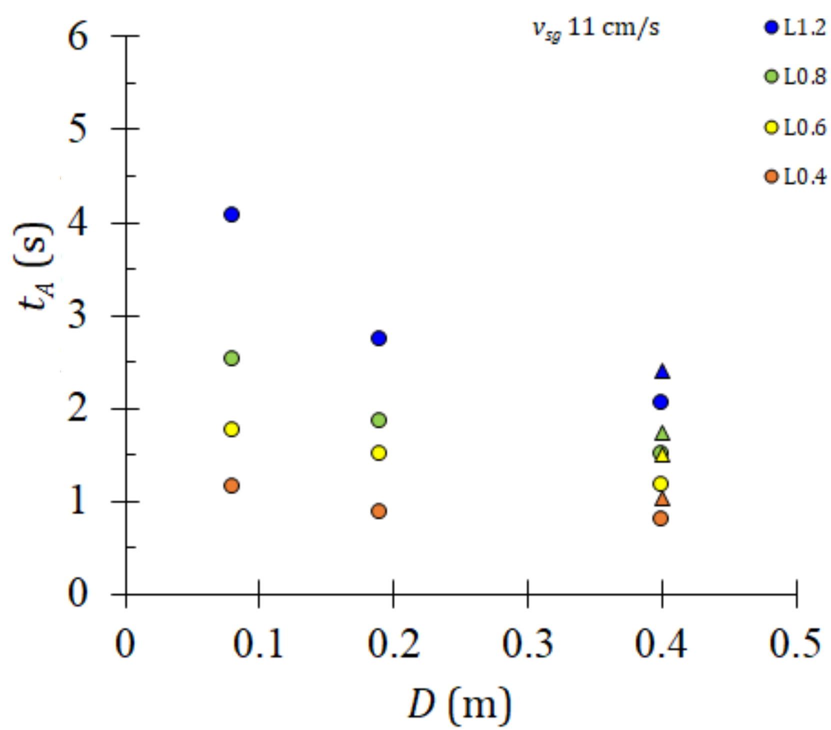




Results: startup times (case 1)

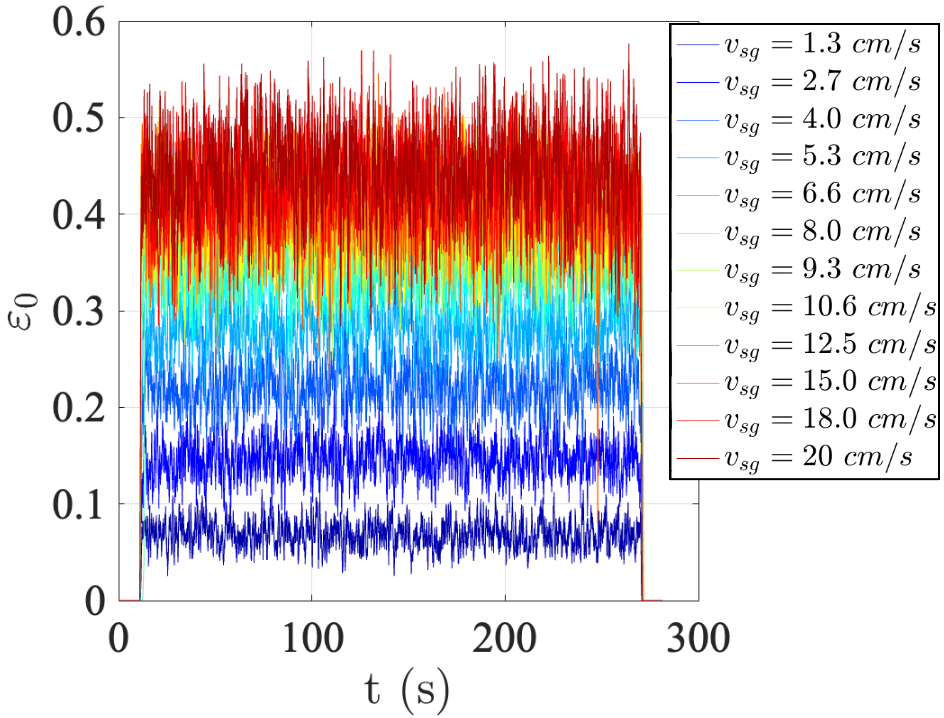
- The startup time has a dependency with the diameter
- The dependency is only relevant in the heterogeneous regime

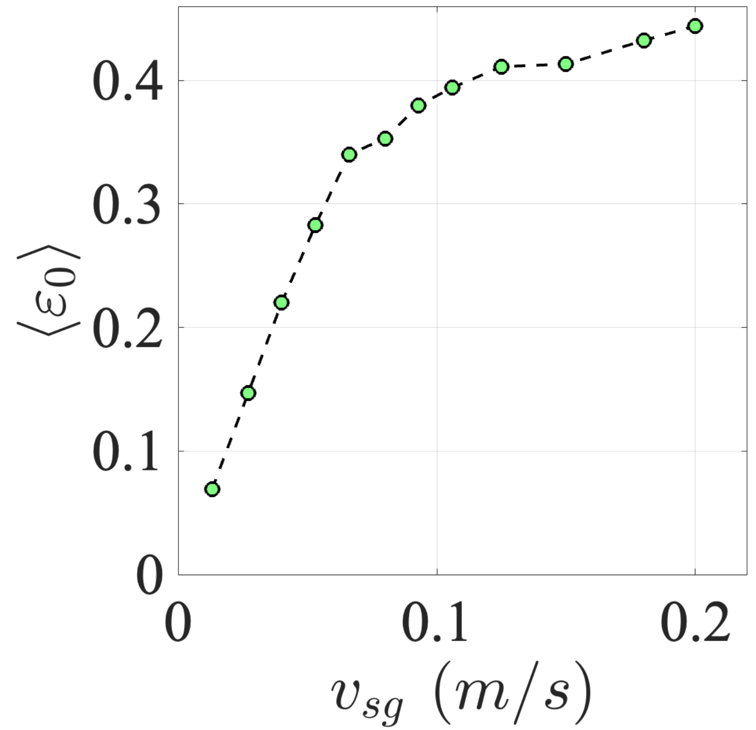




Results: turbulent fluctuations (case 2)

Example: Centreline measurements, $D = 14cm, v_{sg} \in [1.3,20]cm/s$





The transition between homogeneous and heterogeneous regime is captured ($v_{sg} \sim 5cm/s$)

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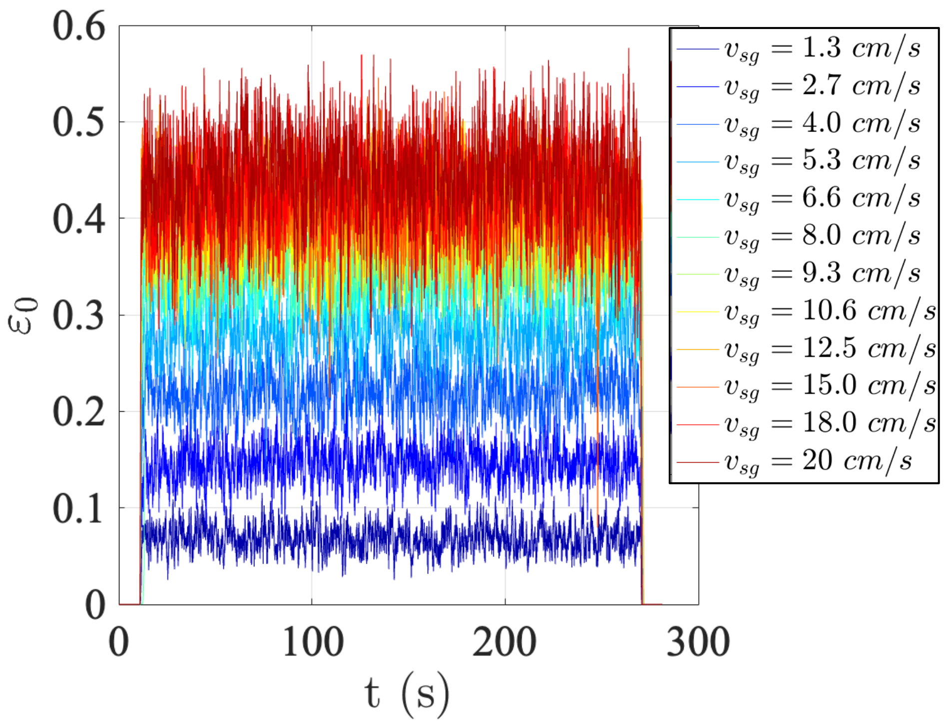

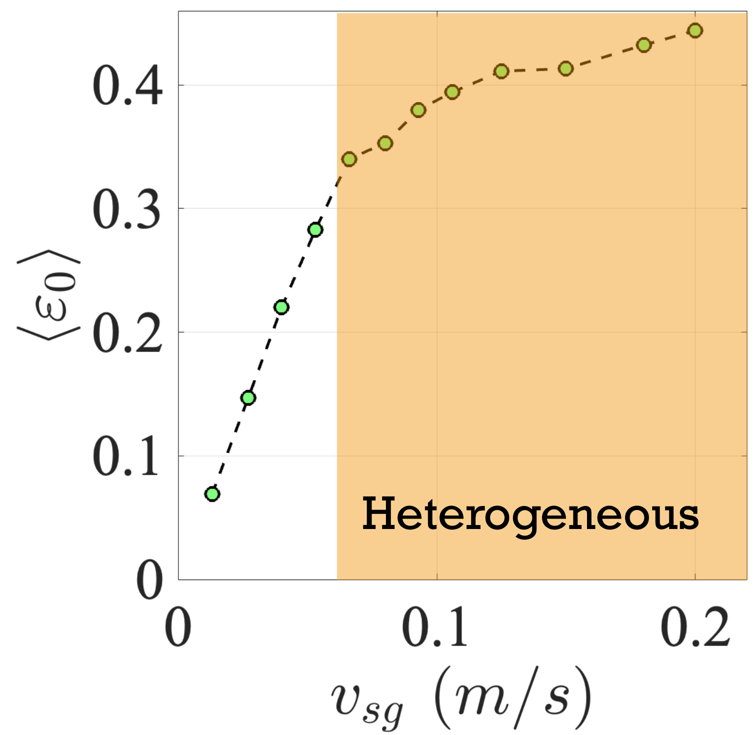

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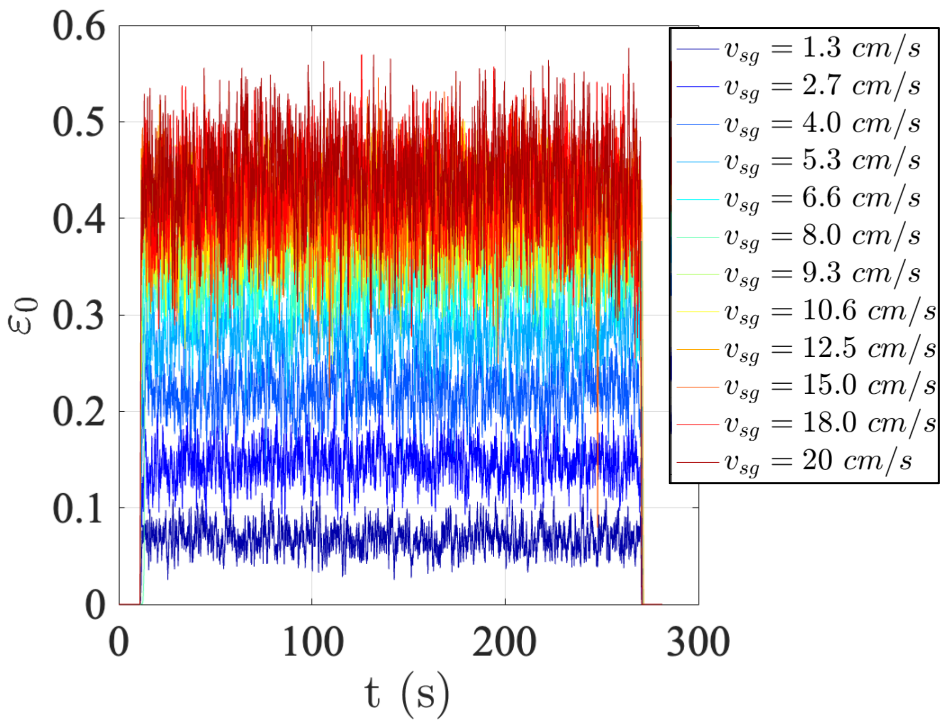

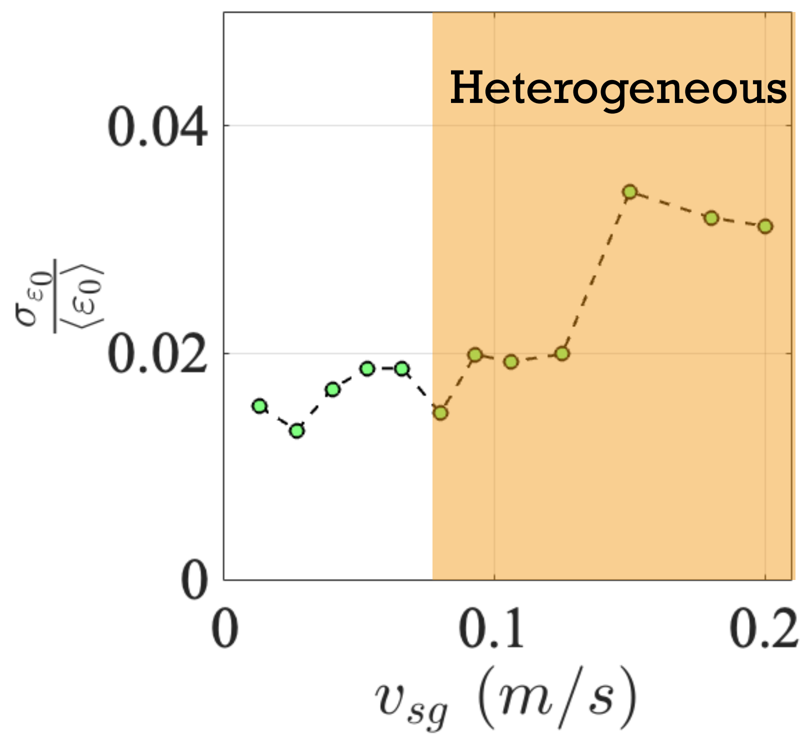

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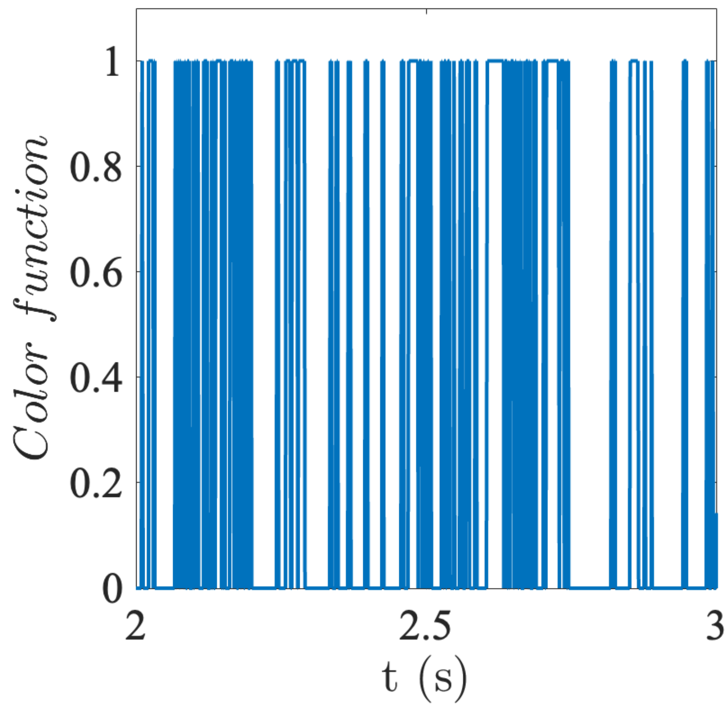

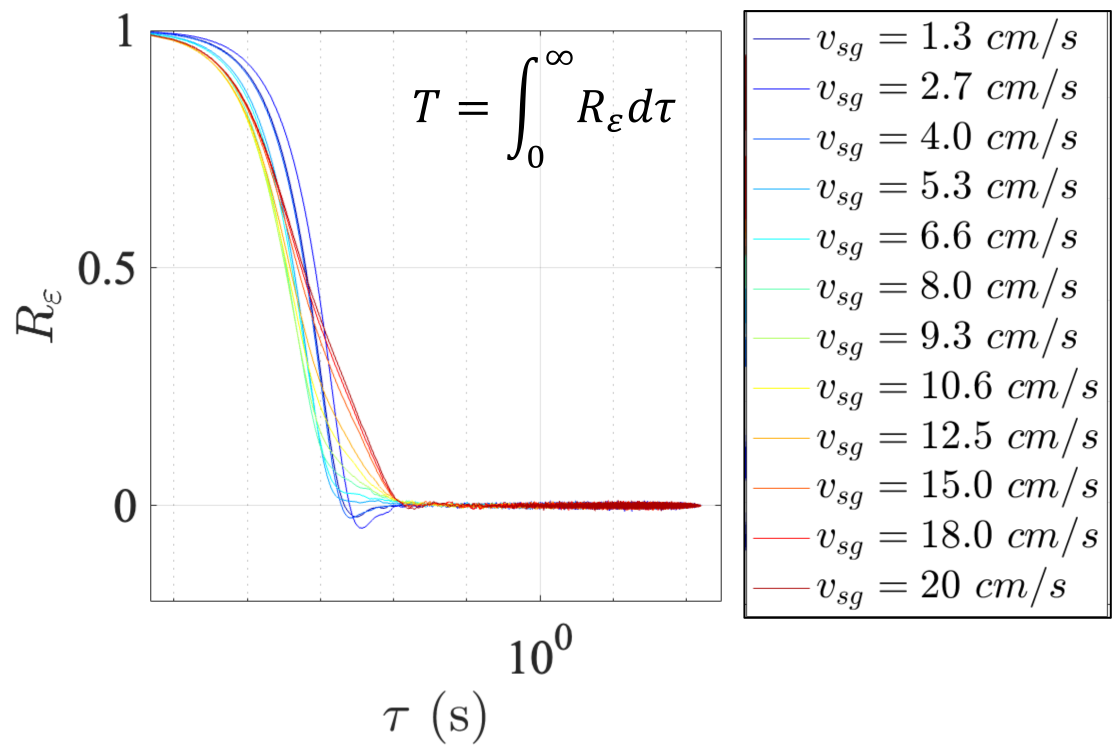

Two time scales can be extracted:

- Correlation time T
- Average time between bubbles ΔT_b

Results: turbulent fluctuations (case 2)

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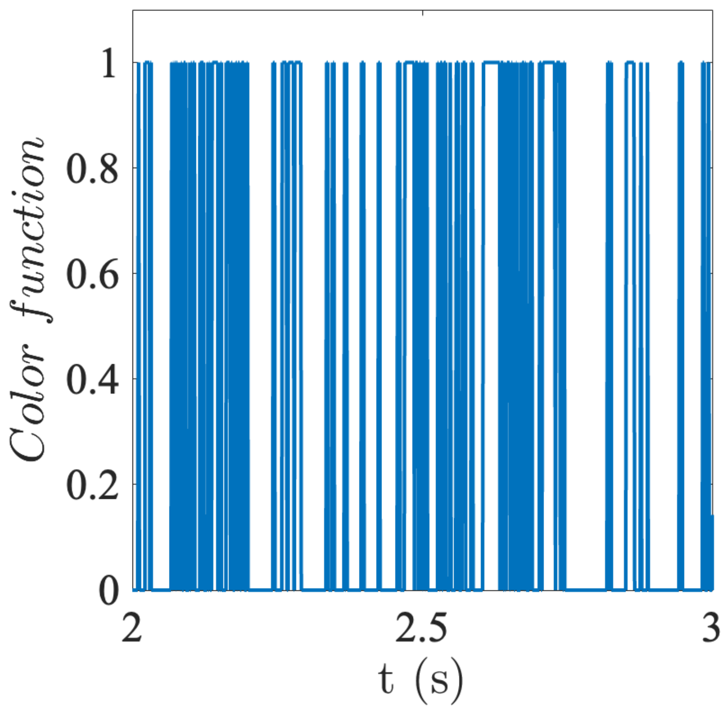

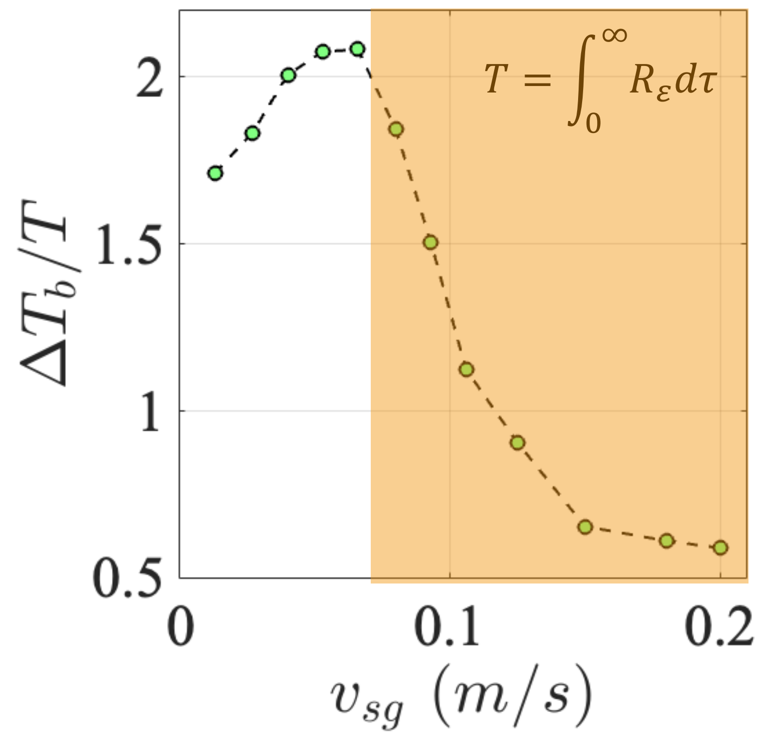

The heterogeneous regime presents $\Delta T_b < T$

Results: turbulent fluctuations (case 2)

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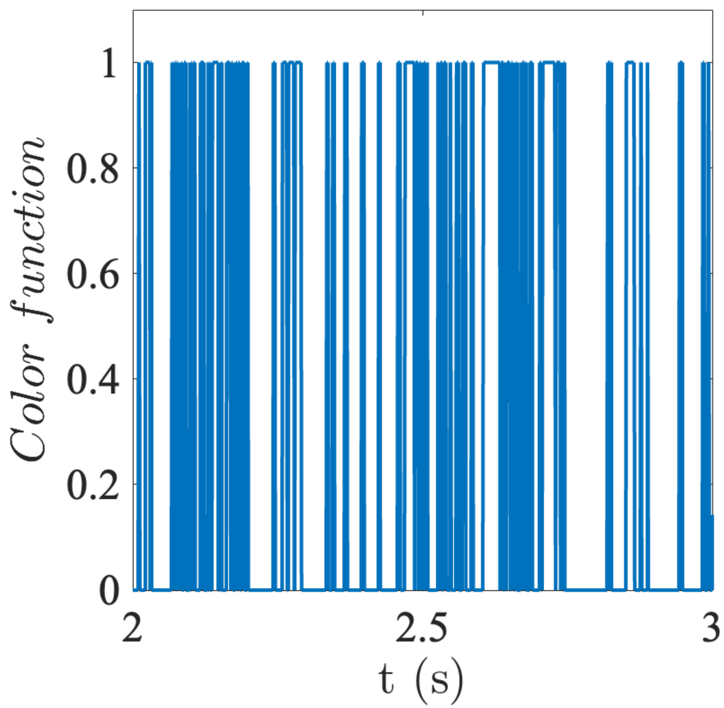

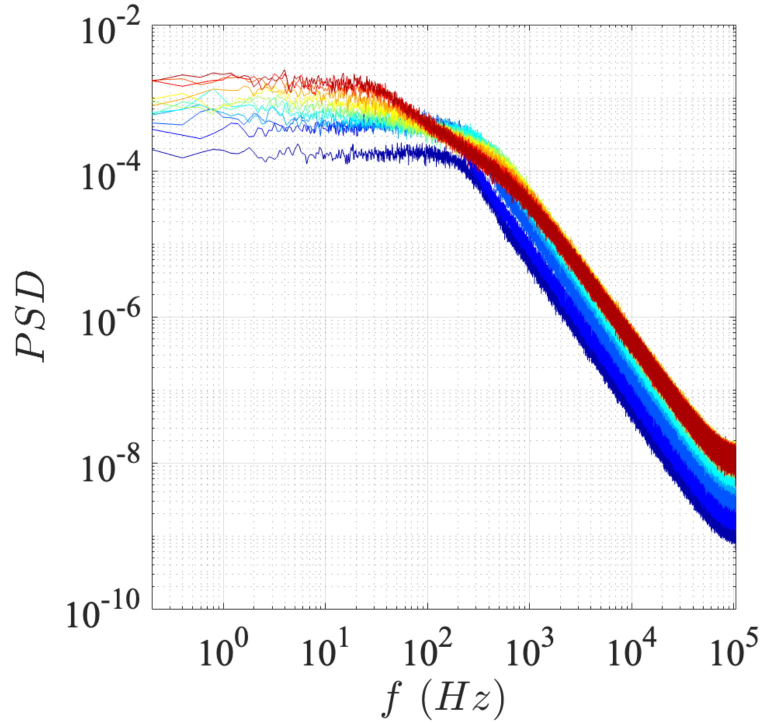

All spectra present two regimes:

1. A plateau at low frequencies
2. A f^{-2} power law (low-pass filter)

Results: turbulent fluctuations (case 2)

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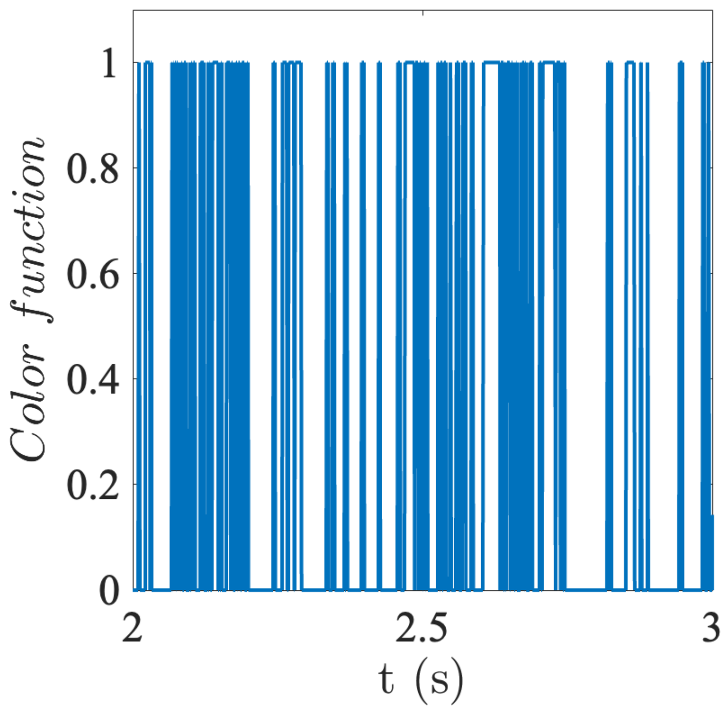
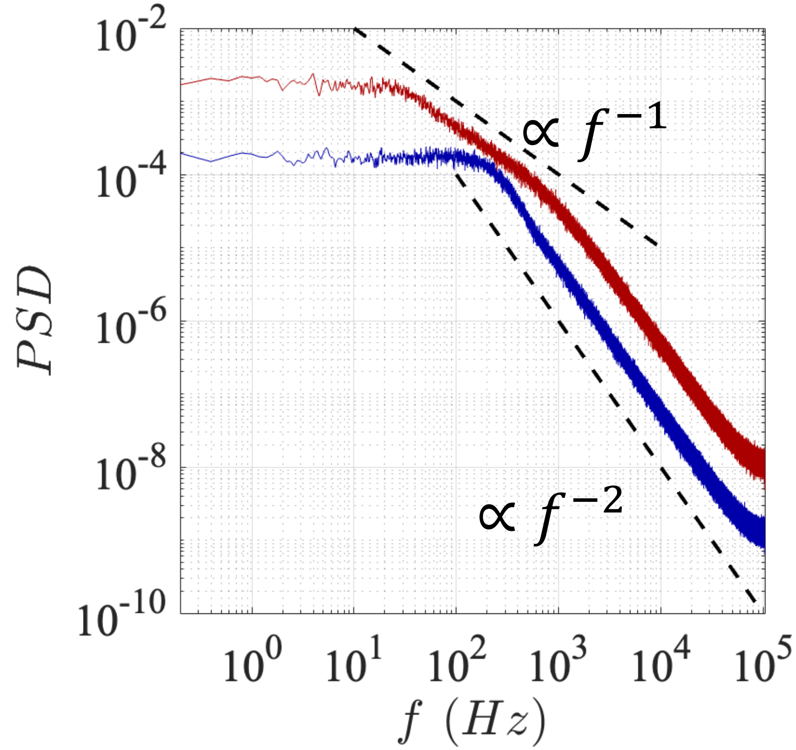


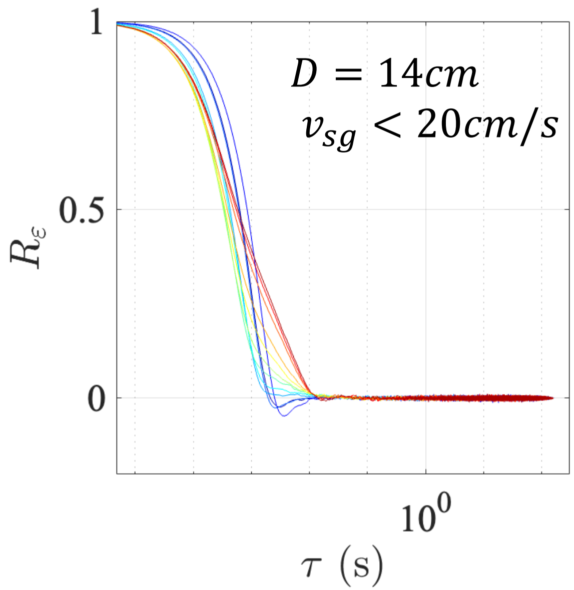


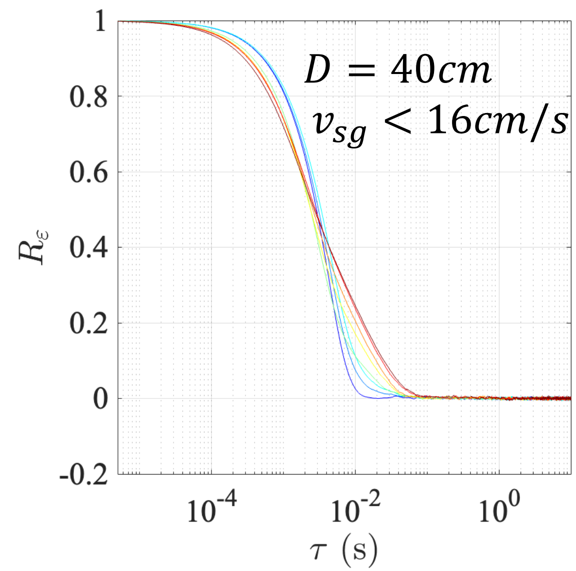
Only in the heterogeneous regime:

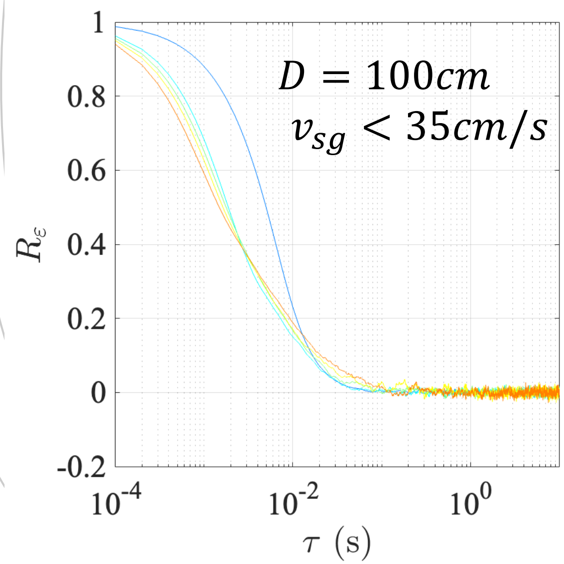
1. A plateau at low frequencies
2. A f^{-2} power law (low-pass filter)
3. An intermediate f^{-1} power law (meso-scale structures)

Results: turbulent fluctuations

All diameters studied



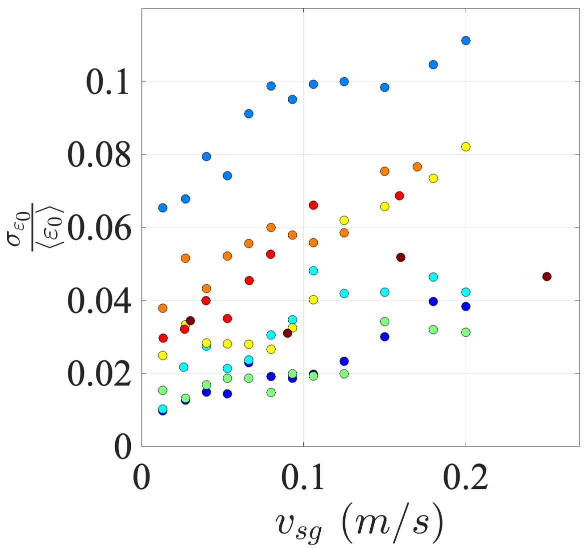


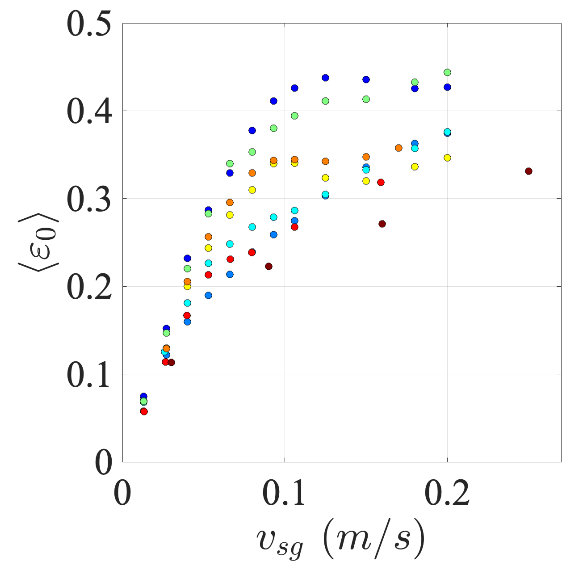


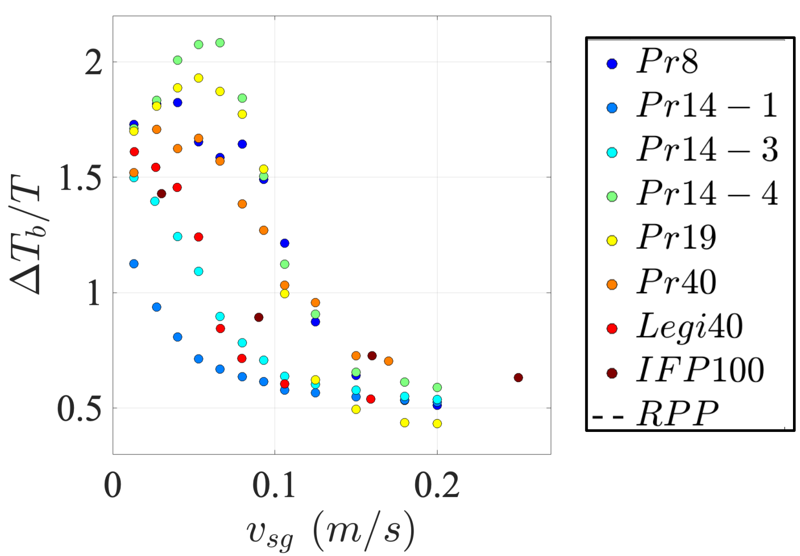
The same functional form is observed for the autocorrelation functions $R_\varepsilon(\tau)$

Results: turbulent fluctuations

All diameters studied



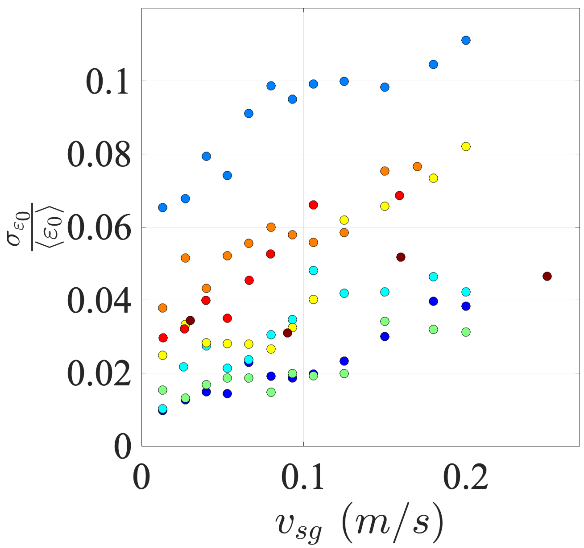


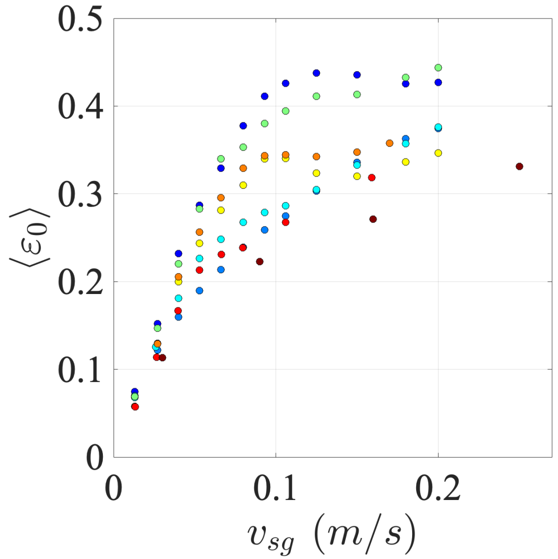


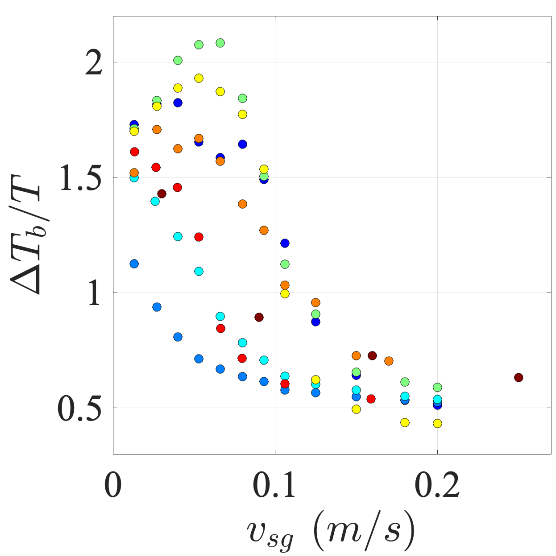
Label	Column diameter (m)	Distributor orifice (mm)
Pr8	0.08	0.5
Pr14-1	0.14	1.6
Pr14-2	0.14	1.6
Pr14-3	0.14	1.0
Pr14-4	0.14	0.5
Pr19	0.19	0.5
Pr40	0.40	0.5
LEGI40	0.40	1.0
IFP100	1	2.0

Results: turbulent fluctuations

All diameters studied







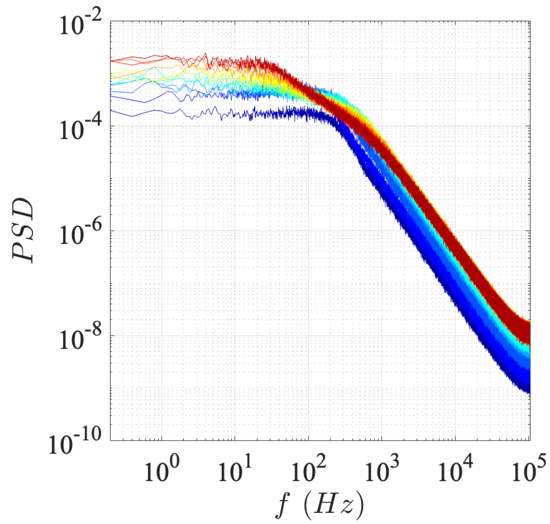
- The same trend is observed for all diameters
- A peak is observed for $\Delta T_b/T$ only for some cases

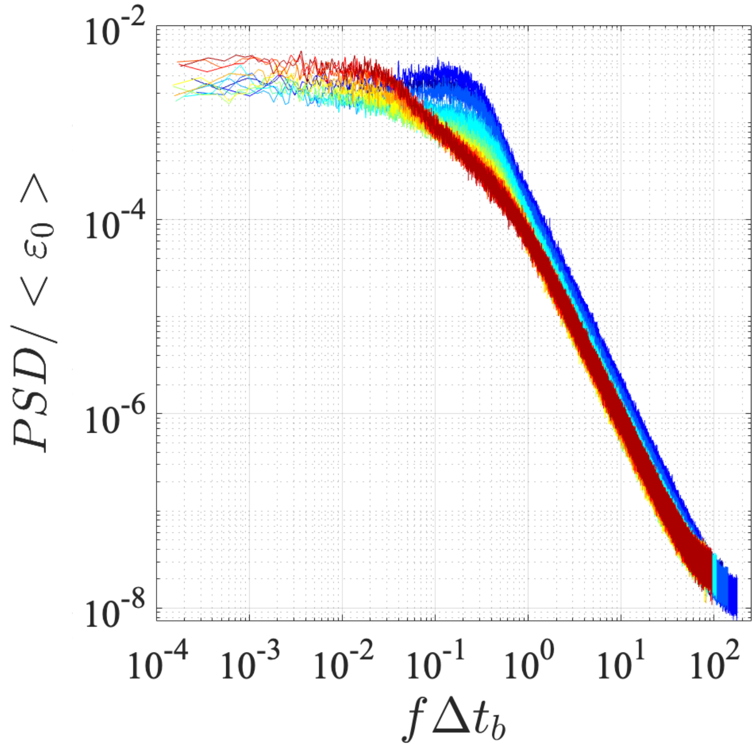
Results: turbulent fluctuations

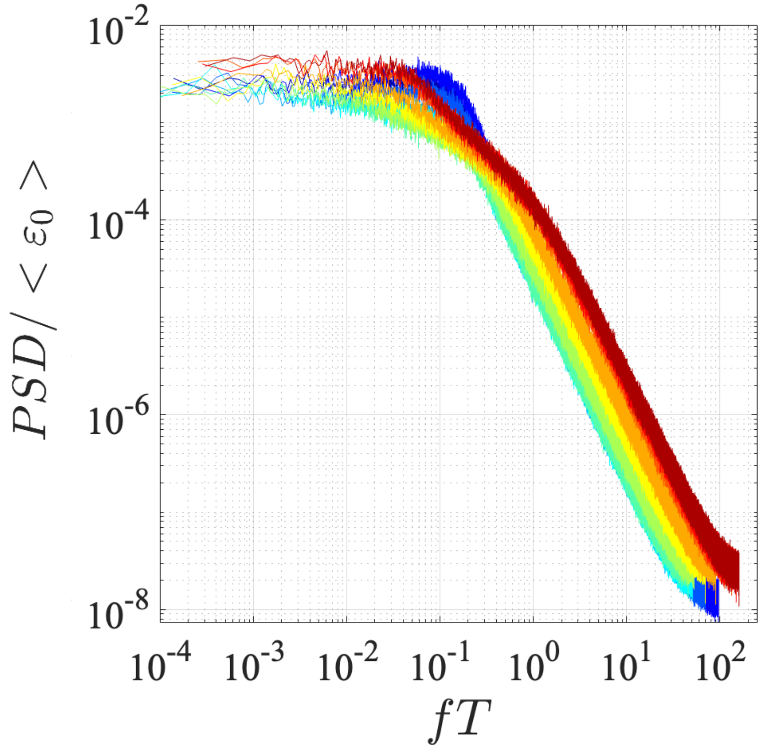
All diameters studied: spectral analysis

Two possible normalisations: ΔT_b and T

Results for $D = 14cm$





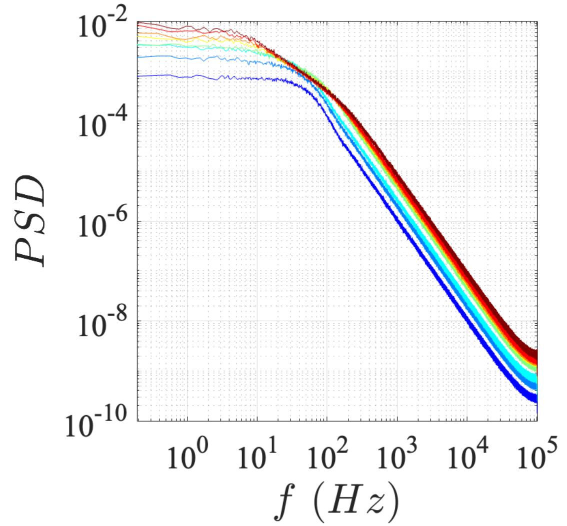


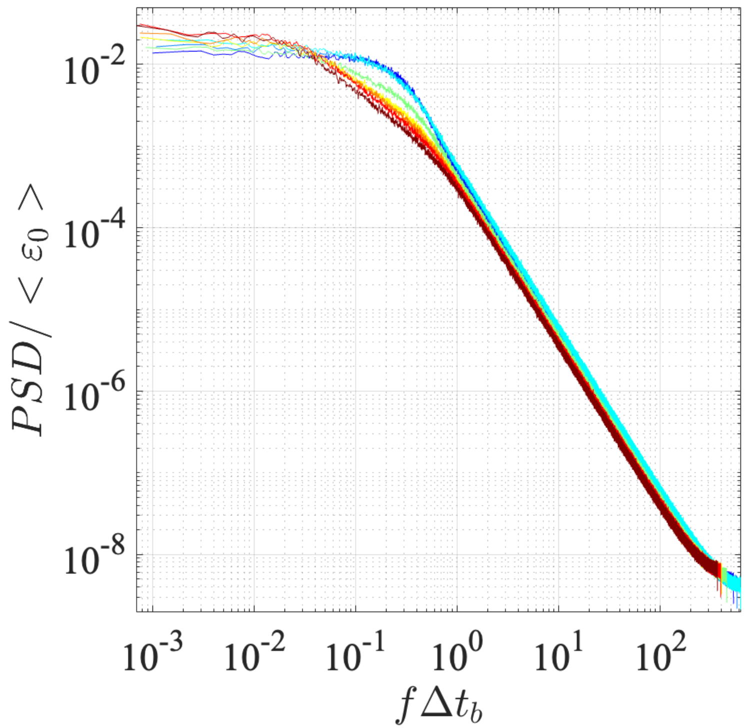
Results: turbulent fluctuations

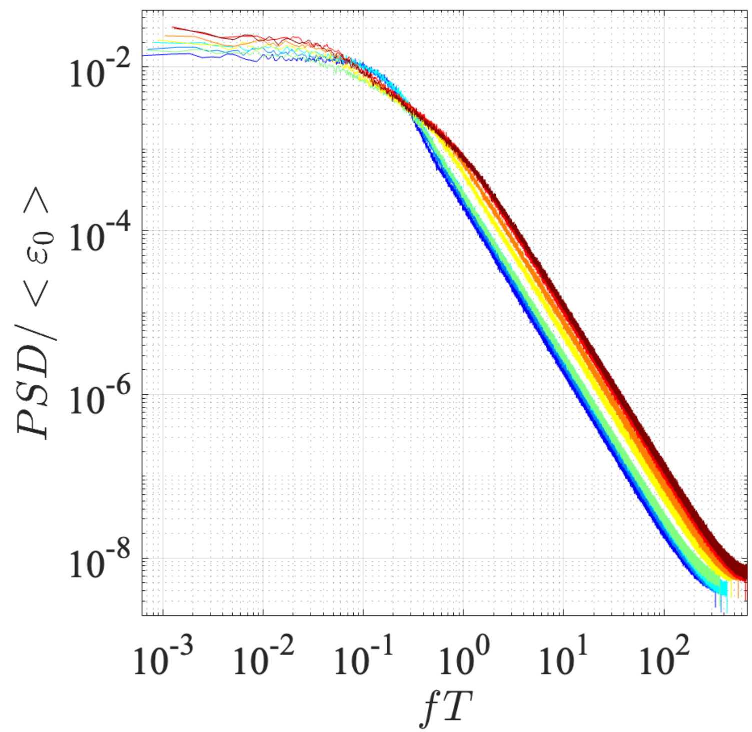
All diameters studied: spectral analysis

Two possible normalisations: ΔT_b and T

Results for $D = 40cm$





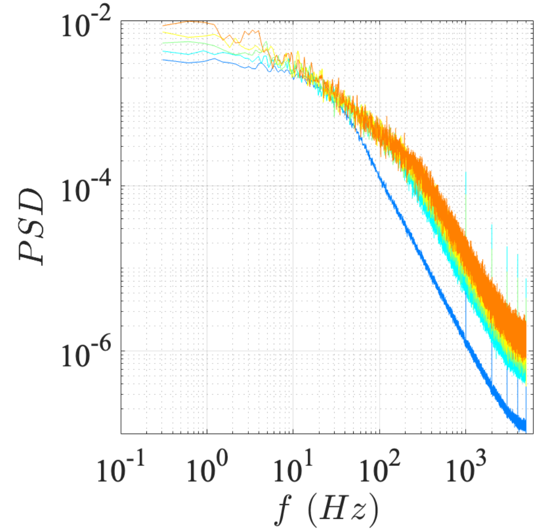


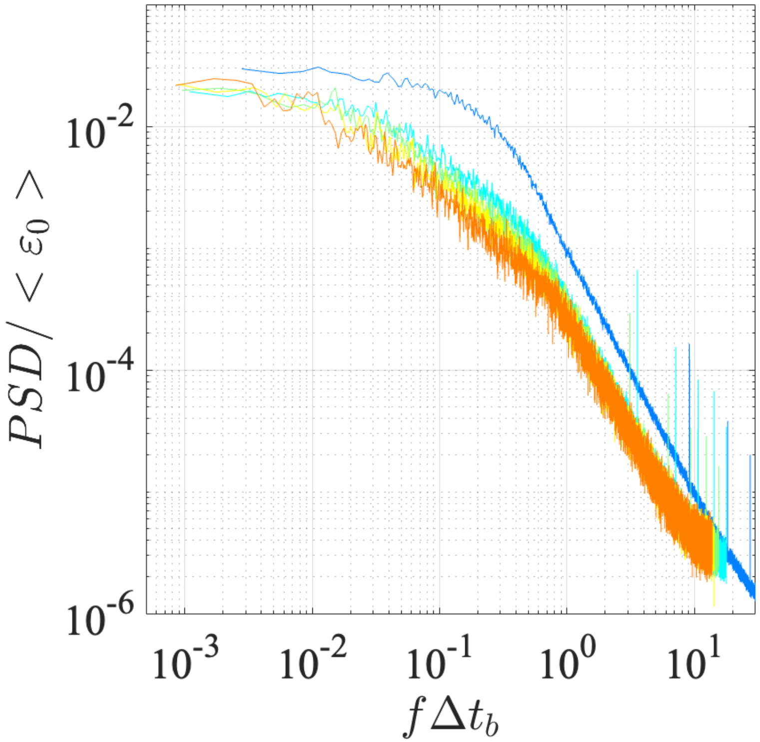
Results: turbulent fluctuations

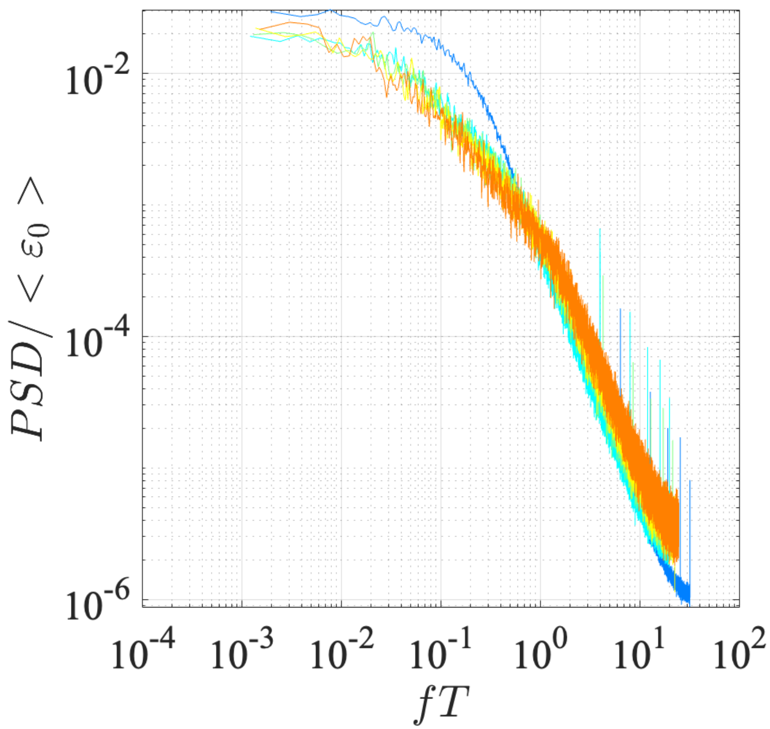
All diameters studied: spectral analysis

Two possible normalisations: ΔT_b and T

Results for $D = 100cm$



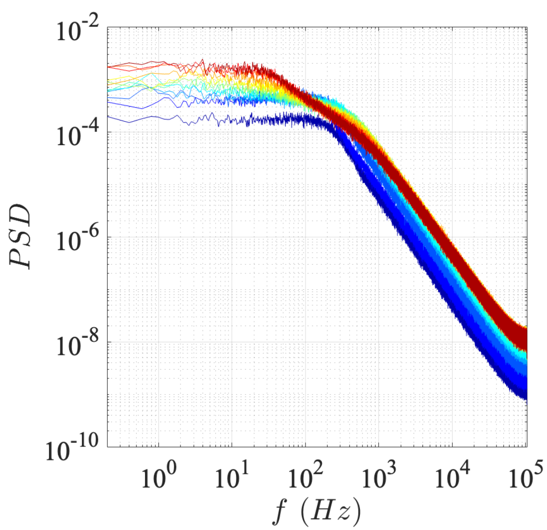




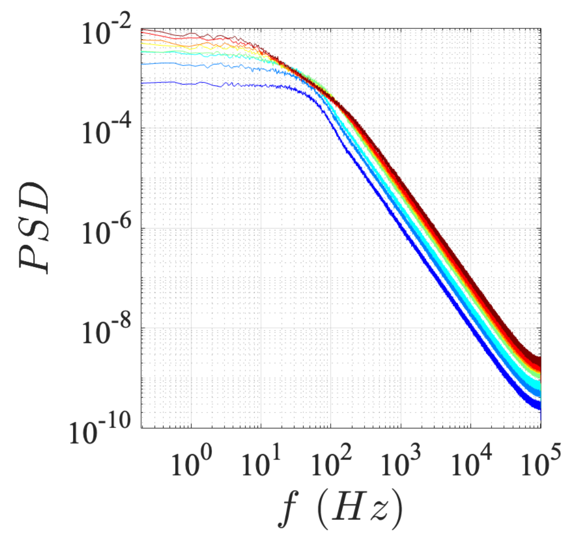
Results: turbulent fluctuations

All diameters studied: spectral analysis

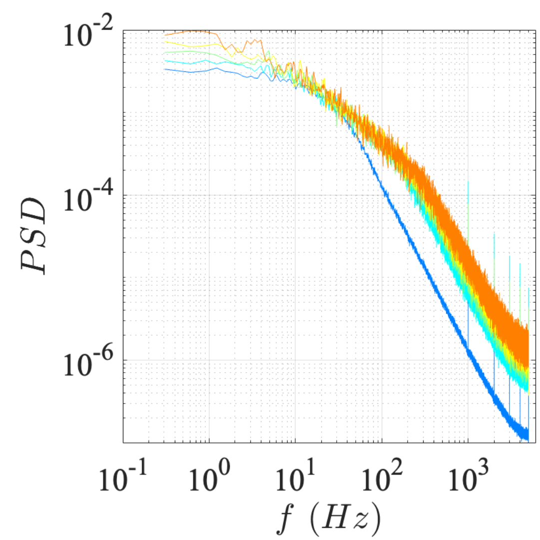
- **All spectra present the same regimes**
- **Large frequencies are collapsed by Δt_b**
- **Mesoscales are collapsed by T**



$D = 14cm$



$D = 40cm$



$D = 100cm$

Results: relation between scales

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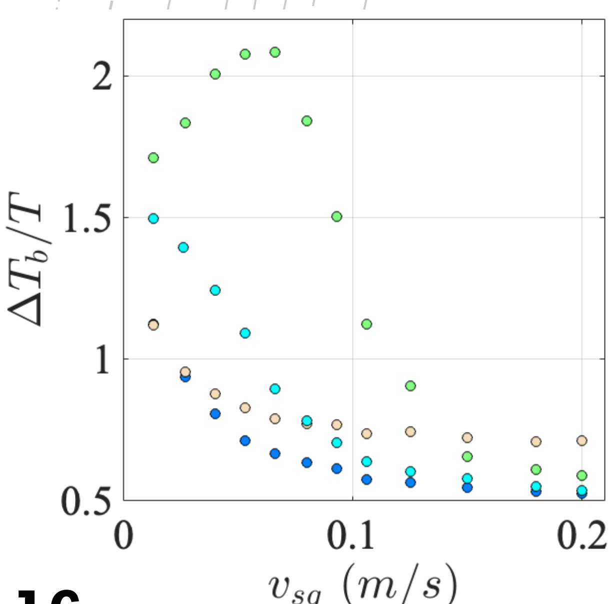
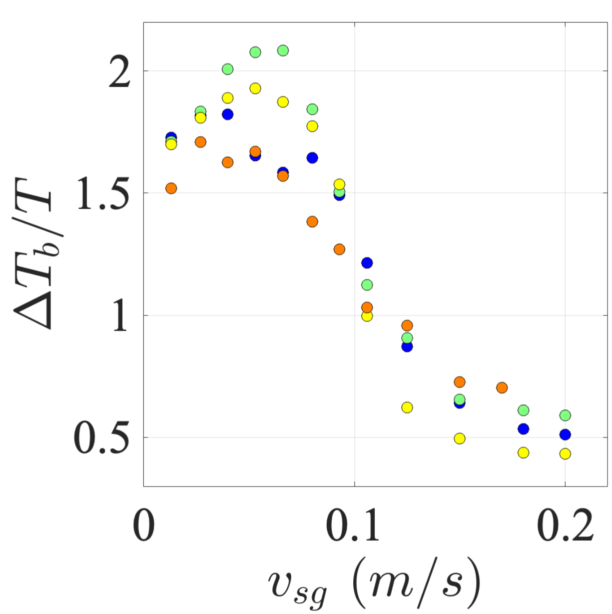
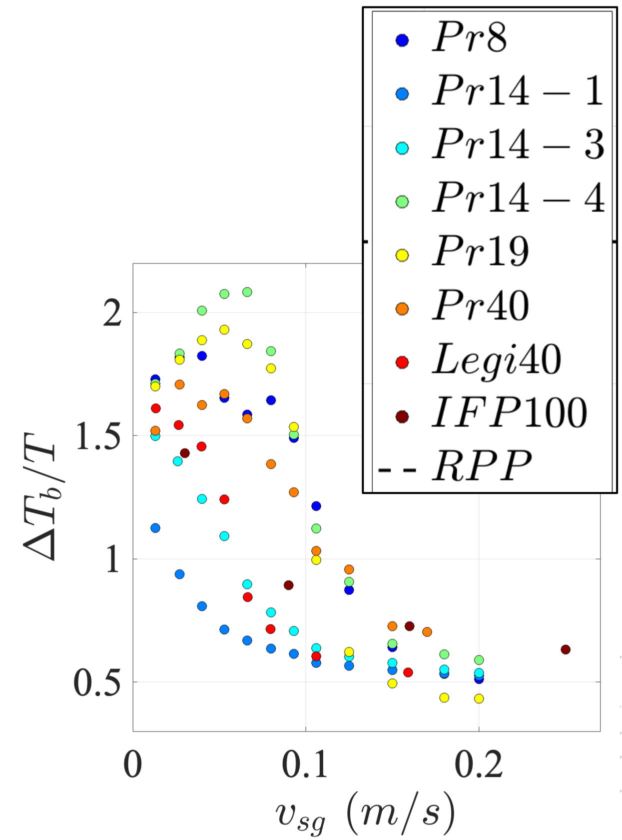
IFP100	1	2.0

- A peak appears only for some cases
- The distributor seems to play a significant role
- The heterogeneous regimes is characterized by $\frac{\Delta T_b}{T} < 1$







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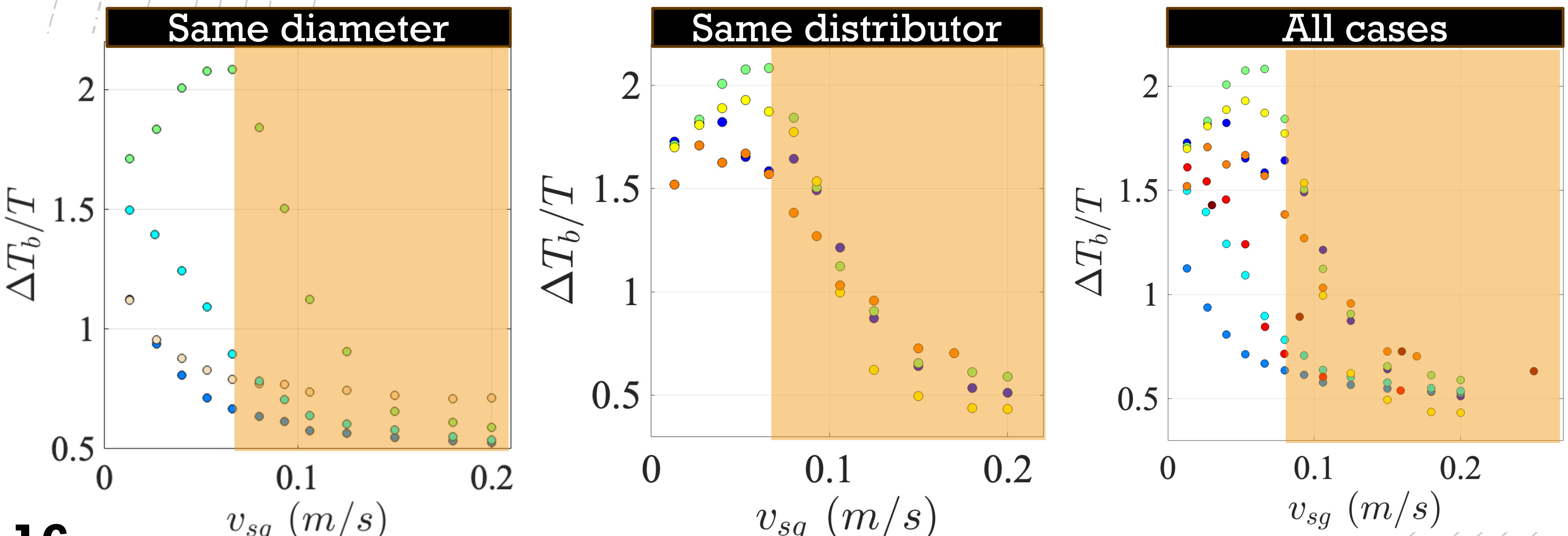
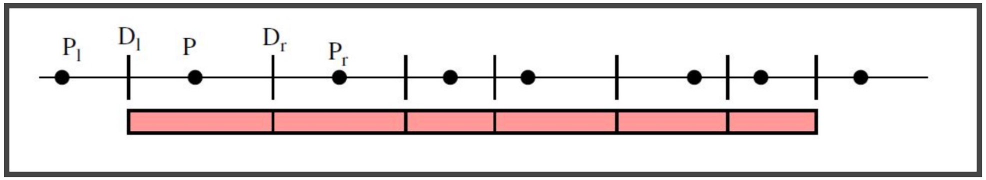
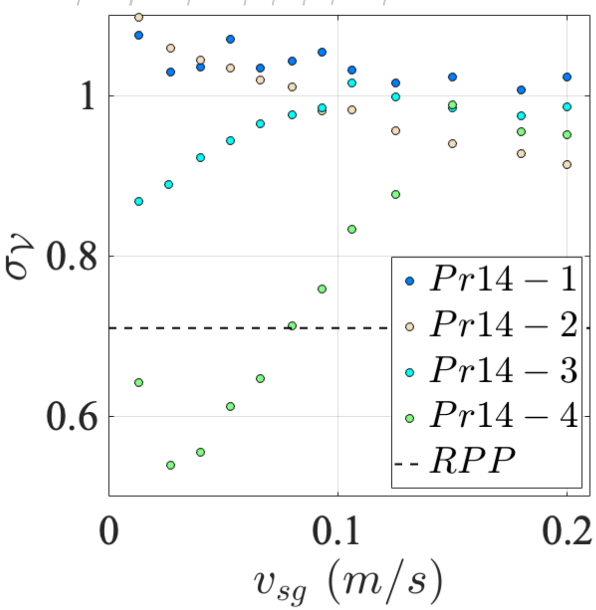


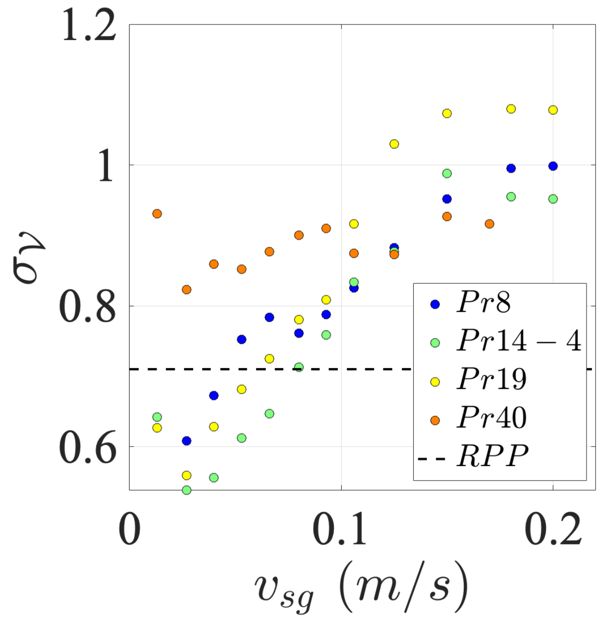
Results: clustering

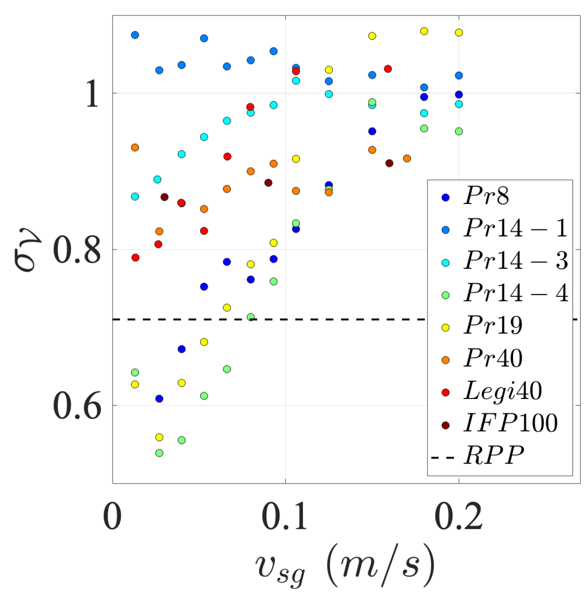
Voronoï tessellations



- Voronoi tessellations can detect the presense of mesoscale structures (or clusters)
- Standard deviations of cells durations above 0.71 imply clustering
- The heterogeneous regime always presents meoscale structures

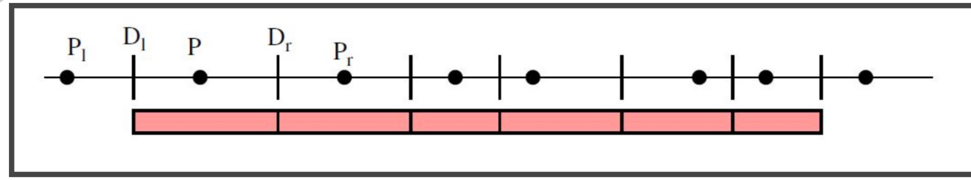






Results: clustering

Voronoï tessellations



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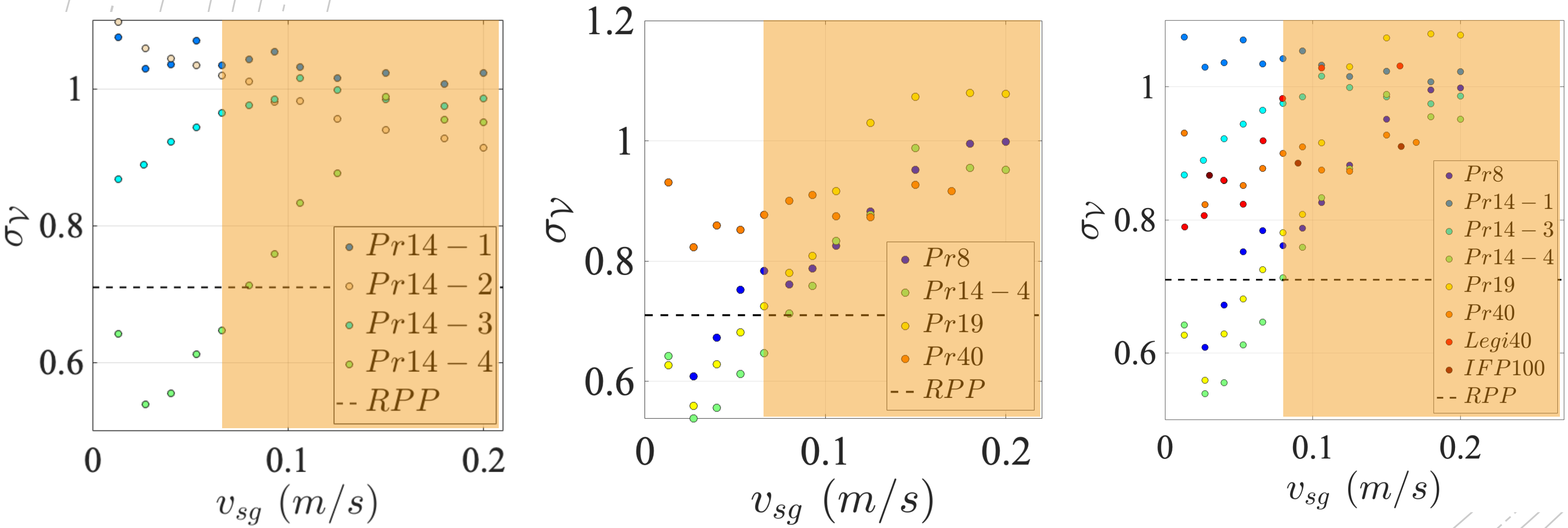

Conclusions

- Startup times are independent of D with similar trends for both regimes
- The colour function from the optical probe can be used to extract time-resolved parameters and their statistics
- The heterogeneous regime is characterized by a correlation time larger than the averaged waiting time
- The spectra of the void fraction presents a f^{-1} power law when mesoscale structures are present

Conclusions

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Perspectives

- Analyse the conditioned velocity
- Free surface measurements
- Testing different mixtures

Thanks for your attention